ENERGY FOUNDATION
能源基金会

Synthesis Report 2020 on China's Carbon Neutrality

China's New Growth Pathway:

From the 14th Five-Year Plan to Carbon Neutrality

Acknowledgments

This report is the product of a collaborative effort between Energy Foundation China and a multi-team research consortium. The research consortium is coordinated by the Energy Foundation China and the University of Maryland Center for Global Sustainability and includes both Chinese and international research institutions.

Energy Foundation China and the project team would like to thank the Energy Foundation China's Long-term Strategy for Decarbonization Task Force Advisory Roundtable, stakeholders, and reviewers that provide suggestions for improving the framing and analysis of this report.

Reviewers (Listed by alphabetical order of last name)

Sonia Aggarwal	Vice President, Energy Innovation
Rongchun Bai	Deputy Director, National Energy Standardization Committee
Richard Baron	Executive Director, 2050 Pathways Platform
Jae Edmonds	Chief Scientist and Battelle Fellow, Pacific Northwest National Laboratory's (PNNL) Joint Global Change Research Institute
Michael Greenstone	Milton Friedman Distinguished Service Professor in Economics, the College, and the Harris School, University of Chicago
Cameron Hepburn	Professor of Environmental Economics and Director of Smith School, University of Oxford
Frank Jotzo	Professor, Crawford School of Public Policy; Director, Centre for Climate and Energy Policy
Kejun Jiang	Senior Researcher, Energy Research Institute (ERI) of the National Development and Reform Commission
Elmar Kriegler	Acting Head of the Research Department "Transformation Pathways", Potsdam Institute for Climate Impact Research
Amory Lovins	Co-founder and Chairman Emeritus, Rocky Mountain Institute
Junfeng Li	Professor & Former Director General of National Center for Climate Change Strategy and International Cooperation
Xiaojiang Li	Former President，China Academy of Urban Planning and Design
Qiang Liu	Director of Programs, China, Children's Investment Fund Foundation
Bert Metz	Climate Policy Expert, UN IPCC Mitigation Co-chair for TAR & AR4
Artur Runge-Metzger	Head of Unit Climate Strategy, International Negotiation and Monitoring of EU Action, DG Environment, European Commission
Lord Nicholas Stern	Chair, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science
Ronan Palmer	Programme Leader, Third Generation Environmentalism (E3G)
Jonathan Pershing	Program Director of Environment, William and Flora Hewlett Foundation; former U.S. Special Envoy for Climate Change
Jim Skea	Professor, Research Councils UK Energy Strategy Fellow at Imperial College London, Co-chair of IPCC working group III
Antonio Soria	Head of Unit, European Commission, Joint Research Centre, Unit C.6 - Economics of Climate Change, Energy and Transport
Robert Stowe	Executive Director, Harvard Environmental Economics Program and Co-Director of the Harvard Project on Climate Agreements
Massimo Tavoni	Professor of Climate Change Economics, Politecnico di Milano,Director, RFF-CMCC European Institute on Economics and the Environment
Lord Adair Turner	Chair, Energy Transitions Commission; Senior Fellow, Institute for New Economic Thinking
Yi Wang	Vice President, Institutes of Science and Development, Chinese Academy of Sciences, Member of the Standing Committee of National People's Congress
Zhixuan Wang	Secretary General，China Electricity Council
John Ward	Managing Director, Pengwern Associates
Matthias Weitzel	Project Officer, European Commission, Joint Research Centre
Harald Winkler	Professor, Energy Research Centre of University of Cape Town, Coordinating Lead Author of IPCC Sixth Assessment Report WGIII
Chunping Xie	Policy Fellow, Grantham Research Institute on Climate Change and the Environment
Dadi Zhou	Executive Vice President, China Energy Research Society; former Director General of the Energy Research Institute; Member of the State Expert Advisory Committee to China's 14th FYP; Deputy Group Leader, Expert Group to the National Energy Development of China's 14th FYP
Rong Zhou	Green finance expert, International Finance Corporation

China's New Growth Pathway:

From the 14th Five Year Plan to Carbon Neutrality

December 2020

RESEARCH CONSORTIUM AND AUTHOR TEAM

Coordinating lead authors

- Energy Foundation China: **Sha Fu, Xuan Du**
- University of Maryland: **Leon Clarke, Sha Yu**

Lead authors (Listed by alphabetical order of institutions and authors)

- China Academy of Transportation Sciences: **Zhenhua Feng, Xuecheng Wang**
- Energy Foundation China: **Lingyan Chen, Zhuoxiang Yang**
- Harbin Institute of Technology, Shenzhen: **Junling Liu**
- Innovative Green Development Program: **Li Yang**
- International Institute for Applied Systems Analysis: **Nicklas Forsell, Fei Guo, Volker Krey**
- Renmin University of China: **Minpeng Chen, Ke Wang**
- Tsinghua University: **Qimin Chai, Qiang Zhang**
- University of Maryland: **Ryna Cui, Nathan Hultman, Jiehong Lou, Jiawei Song**

Suggested citation

Energy Foundation China (2020). "Synthesis Report 2020 on China's Carbon Neutrality: China's New Growth Pathway: from the 14th Five Year Plan to Carbon Neutrality." Energy Foundation China, Beijing, China. Available at: https://www.efchina.org/Reports-en/report-lceg-20201210-en.

FOREWORD

This September, President Xi Jinping announced an ambitious, first-ever post-2030 climate target: that China will strive to achieve carbon neutrality before 2060. The announcement is hugely significant—perhaps the biggest positive climate development globally since the 2015 Paris Agreement. However, achieving the carbon neutrality target will be immensely challenging.

Energy Foundation China (EF China) is a non-profit charitable organization that has been working in China since 1999. We are committed to promoting prosperity, sustainable development, and climate security for China and the world. Three years ago, EF China launched our first and highest priority flagship initiative—the Long-Term Strategy for Decarbonization Task Force (LTS). Over the past three years, we have steadily built capacity and strategically supported research to make the case for a new, low-carbon growth model toward sustainable prosperity and carbon neutrality. In June 2019, we finalized our LTS strategy, including overall goals to achieve carbon neutrality by 2060 and climate neutrality by 2070. That same week, at the annual meeting of the China Council for International Cooperation on Environment and Development in Hangzhou, we first presented this vision for China's long-term climate targets to senior Chinese policymakers. For over a year, we have steadily engaged climate and energy experts, as well as those in economics and development, to make the case for the feasibility and opportunity of net zero.

In support of our vision for a carbon neutral China, EF China has invested considerable efforts both domestically and internationally. Early on, our LTS Task Force initiated a joint research project with Institute of Climate Change and Sustainable Development (ICCSD) at Tsinghua University on China's long-term low carbon development strategy and pathways, engaging 24 top think tanks in China. In parallel, to introduce international perspectives, EF China engaged the several international leading think tanks including International Institute for Applied Systems Analysis, University of Maryland, Joint Research Centre (European Commission), and other experts to advise on China's Mid-Century Strategy, and cooperated with the International Energy Agency, Potsdam Institute for Climate Impact Research, 2050 Pathway Platform, and E3G in LTS modelling and technical discussions. Through these wide-ranging partnerships, EF China cultivated a network of international and domestic modelers, powered the exchange of knowledge in the climate and energy research field, and created a multilateral open intellectual platform for cooperation. Meanwhile, to popularize the notion of carbon neutrality, EF China organized international advisory roundtables and Economists Dialogues to showcase solid evidence for decarbonizing. Finally, EF China has been facilitating decarbonization pilot programs at sectoral and local levels to demonstrate and catalyze real changes on the ground.

Today, we are excited to release our first synthesis report based on multi-model comparison research and other knowledge sources—a major milestone for the LTS Task Force. The report features comprehensive views from prestigious research teams in China and abroad and helps fulfill EF China's role as a strategic advisor, facilitator and regrantor leveraging comprehensive insights to inform policymakers.

The report sets out the broad outlines of decarbonization, identifies key elements of strategy across the economy and within individual economic sectors, and points toward continued research needs to support China's success in meeting its 2060 pledge and long-term goals for growth and development. The publication of this synthesis report may contribute to build the narrative of 14th Five-Year Plan, would not be possible without China's growing willingness to lead and cooperate with the international community in global climate agenda in a confident and open manner, laying the foundation for multilateral solutions to global issues.

China is poised today to accelerate its movement onto a new growth pathway toward a clean and vibrant economy that provides broadly shared benefits across China. EF China will continue to support research for an "all-win" pathway for deep decarbonization in China, facilitate the green and low-carbon transition of the Chinese economy, and help "tell the China New Growth Story."

2020 has been a rollercoaster of a year. We hope this report is a gift at this moment. Our author team has spent innumerable hours writing this report around the clock and even through lockdowns. I would like to extend my deep gratitude and big congratulations to the amazing and world-class author team and appreciate all the efforts from everyone on the advisory roundtable, who spent valuable time among their super busy agenda. My special thanks go to my dream team in EF China, who are creating a miracle. Without your great efforts and help, we would not have been able to produce this gift. Thank you!

Zou Ji

CEO & President of Energy Foundation China

Table of Contents

List of Figures

1. INTRODUCTION

China sits today at the confluence of a number of important changes – rapid technological, energy, and industrial revolutions, increasing Chinese international leadership, a growing and increasingly prosperous middle class, and slowing domestic economic growth. In the near term, these trends are intersecting with the global economic downturn as well as the health and social implications of the COVID-19 pandemic. Layered on all of these is the challenge of climate change and the need for the global community to address this urgent planetary crisis. Together, these changes present a set of challenges as China looks to both its immediate and its long-term future.

It is possible to respond to these challenges in a way that navigates a new path toward growth in China, even as the economy moves toward carbon neutrality before 2060. This is the new growth pathway that will enable China to strengthen its economy, create new sources of employment, foster new innovation and industrial competitiveness, and in doing so, reach the goal of an "ecological civilization."

Even as China creates this new growth pathway for its own economy, it will create broader benefits for addressing global climate change. China's role in climate mitigation is critical. China is currently the world's largest greenhouse gas (GHG) emitter, second only to the United States in cumulative emissions. China's contribution to global emissions reductions is absolutely critical for limiting global temperature change within scientifically informed global goals of 1.5°C or well-below 2°C. Achieving the new growth pathway would also further advance China's emerging international leadership. The signals that China sends to the rest of the world with its actions are increasingly important and influential. China's approach to climate change will communicate this leadership to the world during a time of genuine global need.

Avoiding the worst impacts of climate change calls for warming to be limited to well below 2°C, and the global community holds hope that warming can be limited to 1.5°C. This is a daunting challenge. Net global CO_2 emissions must decline to zero by around mid-century to have a meaningful chance of limiting temperature change to 1.5°C; they must decline to zero around

2070 to limit temperature change to 2°C. China's new growth pathway to carbon neutrality will make a significant contribution to the global ability to achieve these goals. It also implies substantial, rapid, and far-reaching transitions in Chinese energy, land, urban, and industrial systems.

China is uniquely qualified to take on this challenge. Throughout its history, China has committed to deliberate and forward-looking national planning. This commitment has allowed China to undertake large-scale public works from the Great Wall to giant aqueducts that move water from the south to the north. It has also allowed China to maintain decades of rapid economic development and industrialization, leading to its position in the global economy today. 14th FYP on climate change will be out in Autumn 2021, and the supporting plan on climate change will be finalized later in Fall at the same year. In addition, as a party to the Paris Agreement, China is also called upon to update its nationally determined contributions and produce a long-term mid-century strategy for reducing GHG emissions. China's recent pledge to reach carbon neutrality before 2060 and to peak emissions before 2030 is an important step toward both of these.

Against this backdrop, the Energy Foundation China has commissioned top Chinese universities and think tanks along with leading international research institutions and experts to initiate a program of new analyses to identify low-emissions development pathways for China. This is an ongoing project meant to inform China's near-term needs for its mid-century strategy and 14th Five-Year Plan and to build a network of top researchers to continue to meet the needs for information and analysis over the coming decade.

This report is the first of what will be a series of multi-institution reports in support of China's new growth pathway and carbon neutrality goal. It aims to provide an overview of pathways designed to meet these mutually-reinforcing goals and the issues that might arise along the way; present and synthesize both existing and new transition scenarios from multiple modeling and research teams; and identify a set of long-term sectoral strategies and near-term sectoral actions that can be taken today to put China on a successful, low-emissions growth pathway. As the first in what is intended to be a series of synthesis reports, it also identifies critical knowledge gaps that need to be addressed to support China's efforts to navigate its growth agenda and carbon neutrality goal.

BOX 1-1. MODELING SCENARIOS USED IN THIS REPORT

This report synthesizes a number of quantitative scenarios from energy models, integrated assessment models, and agricultural models. It includes a set of scenarios, primarily from the CD-LINKS project, used in this report primarily to understand the nature of China's carbon neutrality goal in a global context. This includes scenarios produced using GCAM-China, IMAGE 3.0.1, MESSAGEix-GLOBIOM 1.0, POLES CD-LINKS, REMIND MAgPIE 1.7-3.0, and WITCH-GLOBIOM 4.4. This report also relies on a broader set of scenarios from multiple models to explore the details of China's economy-wide and sectoral transitions. This includes scenarios from economy-wide models that are used to explore both sectoral and cross-sectoral strategies – C-GEM, DPEC, ERI-LEAP, GCAM-China, IPAC-AIM/technology, MESSAGEix-GLOBIOM, PECE V2.0, PECE_LIU_2019, and POLES-JRC 2019 version. It also includes several sectoral models – AGHG-INV (agriculture and land use), CBEM (buildings), ERI-Industry (industry), ICCSD-LoMLoG (electric power), and Transportation-CATS (transportation) – that are used to provide details on specific sectoral transitions. Some of these scenarios can be found in the published literature, while others were constructed specifically for this report. The scenarios are used selectively throughout the report to support conclusions and to illustrate key elements of future pathways. As the first report in this series, scenarios are largely reported here in their "native" states – that is, only minimal efforts have been made to harmonize baselines, sectoral accounting approaches, or other methodological concerns that can influence comparability across models. Greater harmonization will be undertaken in future reports.

2. CHINA'S NEW VISION FOR GROWTH AND DEVELOPMENT

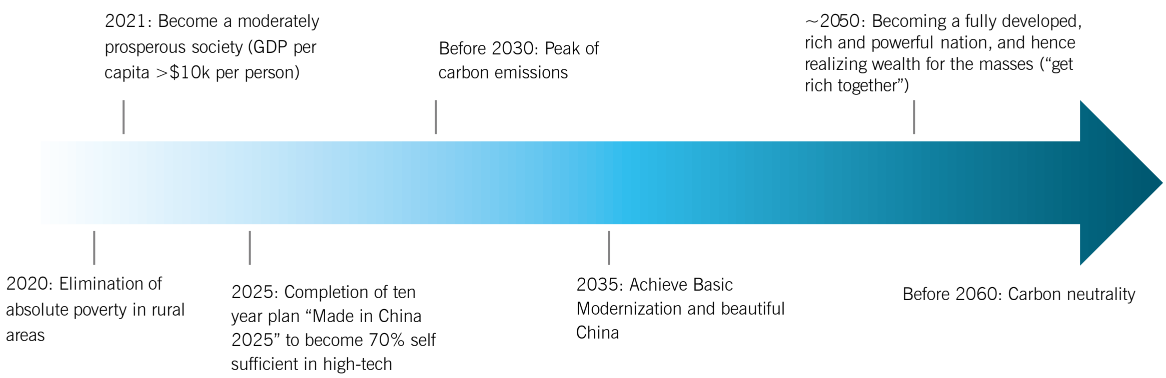
The world is changing. Revolutions in science, technology, and how we relate to each other are driving increasing connectivity and substantial changes to economic productivity. Developments in information technology, including artificial intelligence, big data, and quantum information are driving changes in how we live, work, and interact. Clean energy technologies such as batteries, solar cells, and electric cars, have advanced far more rapidly than anyone expected even a decade ago. These trends have created entire new industries, economic opportunities, and business models that are fundamentally changing global development. The next decades will be crucial as these new global drivers of growth and development replace the old ones.

China is also changing. Since the reform and "opening up," in 1978, China has achieved an annual average GDP growth rate of almost 10% and lifted more than 850 million people out of poverty (World Bank, 2020). China is now the world's second largest economy, with expanding global influence through trade, investment, international leadership, and ideas. As China looks forward, a range of forces – China's evolving relationships with the rest of the world, uncertainties on trade and investment, and domestic economic structural changes – present both challenges and opportunities. China's high growth, driven by resource-intensive and highly-polluting manufacturing, export and investment, and low-cost labor, is proving unsustainable. Structural constraints, such as declining productivity and declining labor force growth, have already reduced China's economic growth. China's long-term economic expansion is also highlighting institutional and social questions. In the short-term, China faces challenges from the COVID-19 pandemic and disputes over trade. In the long-term, slowing growth within the current paradigm could create challenges for an expanding middle-income population increasingly yearning for a life of safety, health, well-being, and equality. Transitioning to steadier and more sustainable development can unlock new possibilities.

In this context of rapid domestic and global change, China has adopted a new vision for growth and development that is built around improving people's livelihoods and well-being. China's own policy processes have highlighted this clearly. China has begun to work toward an "ecological civilization" that integrates sustainability into development—a vision that is viewed as central to sustaining China's long-term growth and development. As part of this process, the Chinese government has committed to the "Beautiful China" initiative, an integrative approach for creating and implementing new systems for environmental protection, developing eco-friendly growth models and ways of life, and contributing to global ecological security. China's carbon neutrality goal can be seen in this broader context of steady progress toward a vision for an "ecological civilization". It adds a specific structure to the overall process and will serve as a foundation for China's new vision for growth and development.

FIGURE 2-1. TIMELINE OF IMPORTANT NATIONAL GOALS.

(Sources: President Xi's speech delivered at the 19th National Congress of the Communist Party of China; Proposals for formulating the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035; President Xi's speech at the General Debate of the 75th session of the United Nations General Assembly)

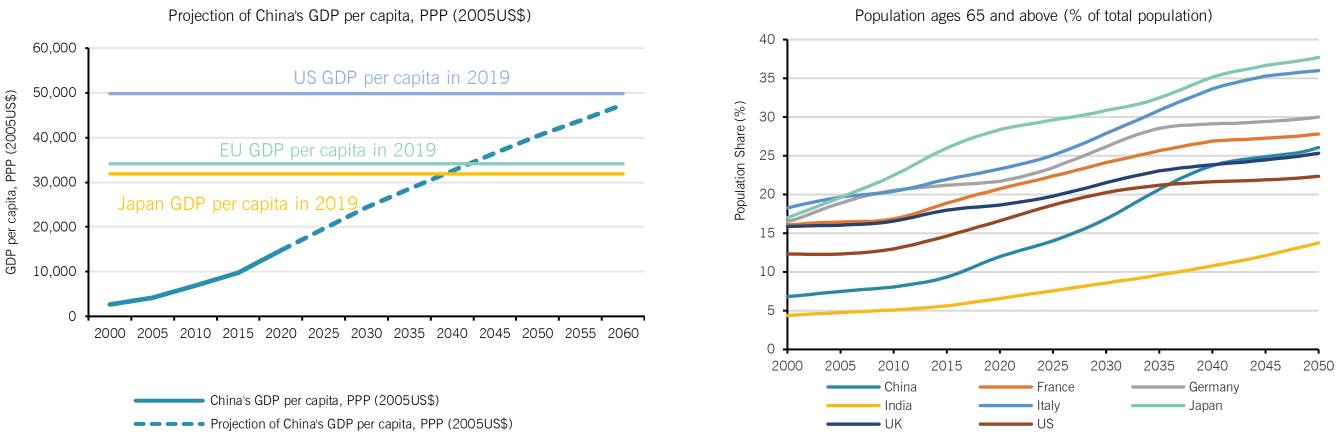


This new vision for growth and development is built on a model of sustainable development featuring greener, more efficient, and sustainable consumption and production that can help promote living standards and a healthier ecosystem—in other words, the "ecological civilization". Part of this vision involves moving from a focus solely on GDP growth to a more integrative view of higher quality development. President Xi, for example, framed this as "innovative, coordinated, green, and open development that is for everyone." This is reflected in China's "Two Centenary Goals," namely "building a moderately prosperous society in all respects by 2021; and building China into a great modern socialist country that is prosperous, strong, democratic, culturally advanced, harmonious, and beautiful by 2050." The new vision for growth and development embedded in these formal statements focuses on better quality, and more open, inclusive and cohesive economic, political and social systems (see Box 2-1).

Importantly, the new growth pathway must aim at the China of the future, not the China of today. By 2060, China will have changed in many ways. China's standard of living will be roughly in line with that of the most advanced economies today (Figure 2-2A), and its population will be older than it is today (Figure 2-2B). China's population is also expected to continue to become more urbanized, with its urbanized population projected to be 80% of total population by 2050 (UN-DESA, 2018).

FIGURE 2-2. PROJECTION OF CHINA'S GDP PER CAPITA AND CURRENT GDP PER CAPITA IN SELECTED COUNTRIES IN 2019 (PANEL A) AND PROJECTION OF SHARE OF POPULATION ABOVE 65 YEARS OF AGE IN SELECTED COUNTRIES (PANEL B).

(Source Panel A: projection data from Dellink R. et al, 2017; historical data from World Development Indicators, 2020; source Panel B: UN-DESA, 2019)



BOX 2-1. CONNECTING CHINA'S 2060 CARBON NEUTRALITY GOAL TO CHINA'S LONG-TERM DEVELOPMENT GOALS THROUGH 2035

The new growth pathway implied by China's carbon neutrality goal will be rooted in existing goals and policies that have been articulated by China. One recent and salient example is the connection between China's new development objectives and its overall technological context and growth strategy. The proposals for formulating the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035, adopted in 2020, outline China's major development goals for the next 15 years. Notable features of these goals include:

- Becoming a global leader in innovation by making major breakthroughs in core technologies in key areas.
- Building a modernized economy through "new industrialization, digitalization, urbanization, and agricultural modernization".
- Advancing eco-friendly ways of work and life across all areas of society.
- Achieving a "Beautiful China" with steadily declining carbon emissions and a fundamental improvement in the environment.
- Improving overall lives of its citizens, focusing on well-rounded human development.
- Strengthening across diverse areas, including but not limited to the economy, health, per-capita GDP, inter-regional equity, and technology.

Overall, these goals for 2035 are clearly resonant with the strategies for carbon neutrality before 2060. The next phases of discussion and planning in China will focus on the policies and programs needed to connect today's situation to these 2035 goals and continue this transition to 2060.

BENEFITS OF CHINA'S NEW GROWTH PATHWAY

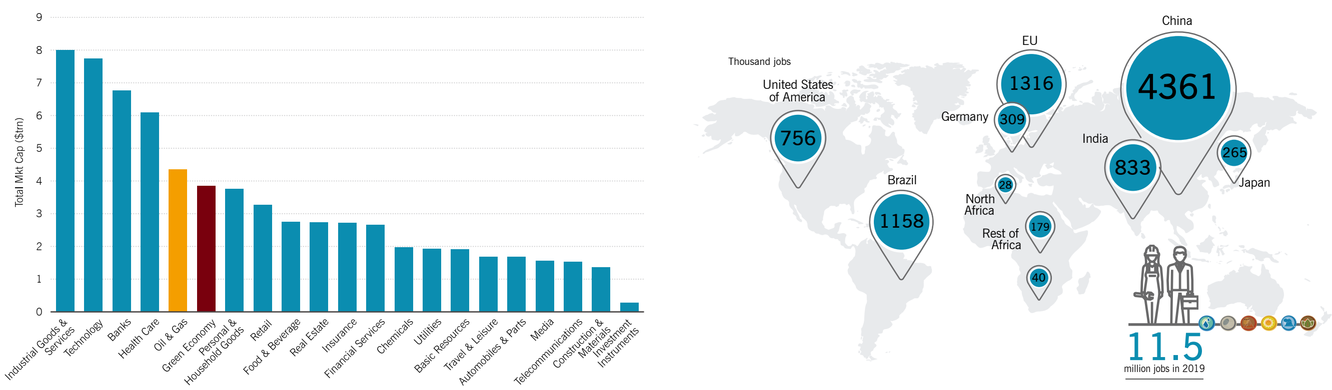
The economic transformation embodied in the concepts of ecological civilization, beautiful China, and China's carbon-neutrality goal can be seen as a blueprint for a new growth pathway. This pathway can deliver industrial expansion and competitiveness, jobs, economic restructuring, and improved health and a cleaner environment through reduced air pollution.

Industrial expansion and competitiveness. China is already a leader in technologies of the emerging global green economy, such as solar photovoltaic cells, batteries, and electric vehicles—and is poised to become a global leader in 5G technology and artificial intelligence. If structured well, China's new growth pathway will lead to accelerated innovations and development in these emerging industries. Investing knowledge and human capital in low-carbon industries will accelerate innovation and development in sectors that will drive the emerging global green economy. This will also allow China to solidify its position as a leader in the science and technologies of the 21st century, leveraging them into a beneficial industrial transformation domestically and into long-term economic competitiveness in the global green economy (see Box 2-3).

Jobs and prosperity. The economic transformation reflected in the carbon neutrality goal can promote strong employment and broadly shared economic prosperity. The size of the global green economy is comparable to that of the oil and gas sector (Figure 2-3A). China's current strength in the global green energy economy is already paying dividends and can be expanded rapidly. For example, between 2010 and 2019, China attracted $818 billion of investment in the renewable sector, making it the world's largest market for both solar PV and solar thermal energy. 38% of all global renewable energy jobs are in China, reaching 4.3 million jobs in 2020 (Figure 2-3B). While China's progress toward carbon neutrality will raise important challenges as it transitions away from fossil-based economic activities (see Box 2-3), it will also create expanded job opportunities across the spectrum of industrial activity, including battery production, renewable energy, construction (e.g. retrofitting existing buildings), and related services (e.g. shared mobility) (Huang et al., 2020). China's leadership in key technologies underpinning the evolving international energy industry will put the country in a position for strong job growth and industrial gains in these industries (see Box 2-3).

FIGURE 2-3. SIZE OF GLOBAL GREEN ECONOMY IN 2017 (PANEL A) AND GLOBAL RENEWABLE ENERGY SECTOR EMPLOYMENT IN 2019 (PANEL B).

(Source: FTSE Russell, 2018; IRENA, 2020)



Structural reform. The carbon neutrality goal will facilitate China's industrial structural reform as it shifts away from polluting, carbon-intensive industries to low-carbon industries. The low-carbon transition will increase industrial total factor productivity, change production methods, and cultivate new business models, therefore helping to achieve China's goal of structural adjustment, optimization, and upgrade.

Enhanced energy security. As one of the world's largest crude oil consumers, China surpassed the U.S. to become the world's largest importer of crude oil in 2018 (IEA, 2020). China is also the world's largest consumer and importer of coal. In 2019, China consumed 2,870 Mtce of coal comprising 53% of the global consumption and imported 21% of the coal in the international market (IEA, 2020). The heavy reliance on imported fossil fuels undermines

China's energy security. China's progress toward carbon neutrality will allow it to install more domestic renewable energy capacity, reducing its reliance on imported fossil fuels and leading to enhanced energy security.

Improved health, cleaner air. The carbon neutrality goal will improve the health of citizens, save lives, and improve China's natural environment by reducing air pollution. Implementing a low-carbon transition strategy will decrease the reliance on coal across the economy – in electricity generation, industry, and buildings – and support a new generation of low-pollution vehicles. These actions will dramatically reduce health risks associated with fine particulates ($PM_{2.5}$), SO_2, and NO_X emissions. Current air quality standards are insufficient to meet long-term goals, but combining these standards with the low-carbon development implied by China's carbon neutrality goal will put China on a path to meet the highest WHO air quality standards (see Box 2-2).

As the old growth and development strategy comes to its end, China has identified a new vision for growth and development. Now is a critical moment to move forward on this vision. China's carbon neutrality goal will serve as a foundation for this new vision. It will promote greener, more efficient, and sustainable consumption and production with better quality, more open, inclusive and cohesive economic, political and social systems and an "ecological civilization" that is more harmonious with the natural ecosystem.

BOX 2-2. THE MUTUALLY-REINFORCING GOALS OF HEALTH, AIR QUALITY, AND CLIMATE MITIGATION

Because emission sources of air pollutants are highly linked to those of GHGs, Strategies to reduce GHG emissions can significantly improve air quality and public health, and vice versa. Air pollutants are often co-emitted from major sources of GHGs, including fossil-fuel combustion, industrial processes, waste disposal, agriculture, and land-use change (IPCC, 1990). In addition, most air pollutants (e.g. black carbon, sulfate, nitrate, ozone) have an effect on the climate. The effective forcing from aerosol-radiation interactions and overall aerosol forcing can be as high as -0.45 (-0.95~+0.05) W/m^2 and -0.9 (-0.95~+0.05) W/m^2 respectively (IPCC, 2014).

Over the past decade, China has made significant improvements in air quality. However, China is still confronted with challenges rooted in air pollution and public health. This is especially true in the context of an aging population that will be more susceptible to air quality and associated health concerns.

Numerous studies have demonstrated that addressing GHGs and air pollutants simultaneously will be easier and cheaper than addressing them individually (e.g., Li et al., 2019). Nam et al. (2013) estimated if China reduced SO_2 and NO_X emissions by 8%–10% per five year during 2015–2050, a total of 20 Gt CO_2 emissions could be decreased in 2050. Tong et al. (2020) found that if China fulfilled the Nationally Determined Contribution (NDC) pledges and current clean air actions, major air pollutant emissions (e.g. SO_2, NO_X, primary $PM_{2.5}$, and VOCs) would decrease by 29% to 52% during 2015-2030. With more strict climate mitigation actions to limit warming to well-below-2ºC warming and best end-of-pipe control measures, these major air pollutant emissions would further decrease by 36%-61% between 2030 and 2050. (Tong et al., 2020). Li et al. (2018) found that a carbon price along with an annual 4% reduction in carbon intensity could decrease China's population-weighted $PM_{2.5}$ concentration by 12%, avoiding 94,000 $PM_{2.5}$-related premature deaths in 2030 compared to what would happen without these climate mitigation actions. Li et al. (2019) found that a 2ºC-consistent energy transition combined with the best air pollution control could reduce China's population-weighted $PM_{2.5}$ concentration to nearly 16 μg/m3 in 2050. Importantly, research has shown that current air pollution policies will deliver only small air quality improvements after 2030. Combining ambitious climate targets with air pollution control, China's $PM_{2.5}$ air quality could come close to or well below the WHO Guideline of 10 μg/m3 in 2050 (Cheng et al., 2020).

Coal-fired power plants have long been a dominant source of China's air pollution and carbon emissions. Effective "co-governance" of pollution and carbon emissions within the power sector needs to focus on low-carbon structural adjustments and power efficiency improvements. Structural adjustments focus most heavily on increasing the share of renewable power generation. Efficiency improvements include upgrading existing units, closing down outdated power plants, and reducing coal consumption per unit of power generation through the combination of the first two. Previous studies have demonstrated these measures can deliver significant benefits for both air pollution and carbon emissions. Yang et al. (2018) found that if the solar photovoltaic power capacity reaches 400 GW in 2030, CO_2 emissions would decline by 4.2%, and 1.2% air pollution-related premature deaths would be avoided. Lu et al. (2019) found that 9.3% CO_2 and 12% $PM_{2.5}$ emissions reductions from 2015 levels could be obtained by replacing 1,050 TWh of coal-fired electricity generation with coal-fired bioenergy gasification systems with carbon dioxide capture and storage (CBECCS). Power sector efficiency can be increased by shutting down small and inefficient plants, thereby increasing the fraction of China's large power units (with capacity larger than 600MW) to 80% in 2030. This would reduce the CO_2 and SO_2 emissions by 25% and 5% respectively (Tong et al., 2018).

The industrial sector also plays a central role in both carbon emissions and air pollution. Control measures for the industrial sector mainly include curtailing industrial energy demand through technological upgrades and increasing low-carbon energy shares by eliminating and substituting for fossil fuels. For example, research shows that with 640 million tonnes of steel demand in 2030, an increase of 50% in the scrap recovery rate could lead to 190 million tonnes of recovered steel and reduce CO_2, SO_2, NO_X and PM_{10} emissions by 67.7 million tonnes and 110,000, 20,000, 30,000 tonnes. This could prevent 30,000 to 70,000 air pollution-related premature deaths and reduce economic losses by $386-854 million (Ma et al., 2016).

With the rapid growth of car ownership, energy consumption in the transportation sector has increased dramatically in recent years, resulting in commensurate air pollution and GHG emissions. Energy efficiency improvements, switching to low-carbon fuels, and mode shifting are major measures to reduce carbon emissions and improve air quality. Liu et al (2018) showed that 38% and 35% CO_2 emission reductions could be achieved in 2050 by improving transport energy efficiency and increasing the use of electricity in the fleet. These two measures could avoid more than 120,000 and 102,000 air pollution-related premature deaths (Liu et al., 2018).

In residential buildings, improved living quality is leading to higher service demands and associated environmental pressures. Substituting clean and low-carbon fuels (e.g. electricity from grid or building-integrated PV (BIPV) and new biomass energy) for bulk coal in China's vast rural and urban areas will be necessary for residential pollution and CO_2 co-control. Cost-benefit assessments have demonstrated remarkable climate, air quality, and health co-benefits from transitioning away from residential coal and traditional biomass. Liu et al (2019a) found that clean residential fuels replacement could avoid 4% of outdoor air pollution-related mortality. Co-benefits on indoor air pollution-related health impacts are more significant, with a 31% reduction in mortality compared with the baseline (Liu et al., 2018).

BOX 2-3. EMPLOYMENT IN THE NEW ECONOMY

China's transformation to a low-carbon economy can promote strong employment growth across a broad range of industries and deliver broadly shared economic prosperity. In this transition, employment will shift away from fossil fuels and toward the emerging industries of the 21st century. Emerging analysis increasingly highlights the positive employment effects of these technologies, and underscores the natural transition toward new technologies as they become cheaper and more effective than older ones. Countries that embrace such changes quickly have the opportunity to lead in the global economy of the 21st century.

Current employment in the low-carbon sectors. China's current strength in the global green energy economy is already paying dividends through new jobs, and these can be expanded rapidly. Employment in low-carbon technology and service sectors has increased rapidly over the past decade and will continue to do so driven by the transformation to a low-carbon economy. Between 2010 and 2019, China attracted $818 billion investment in the renewable sector and became the world's largest market for both solar PV and solar thermal energy. Today, 38% of all global renewable energy jobs, or 4.4 million jobs, are in China (IRENA, 2020).

In fact, China already leads the world in employment in at least four major renewable energy industries. China accounts for 59% of PV employment worldwide, with 2.2 million jobs; 44% of offshore and onshore wind employment worldwide, with 500,000 jobs; 29% of hydropower employment, with 600,000 jobs; and 81% of solar heating and cooling employment, with 700,000 jobs (IRENA, 2020).

Future growth in clean energy jobs. China's leadership in the key technologies that underpin the evolving international energy industry will put the country in a position for strong job growth and economic gains in these industries. Global employment in renewable energy is anticipated to grow fourfold by 2050 (IRENA, 2020). China's progress toward carbon neutrality will create expanded job opportunities across the spectrum of industrial activities, including renewable energy and storage, construction, and related services such as shared mobility (Huang et al., 2020). Beyond these direct employment opportunities in the renewable energy-related industries, China's current focus on promoting innovation and identifying key strategic industries as "environmentally friendly, low-carbon, and circular"—such as next-generation telecommunication, artificial intelligence, advanced robotics, and big data—as will not only create other job opportunities in these sectors, but will also support green jobs and the structural economic changes that are part of a transition to a low-carbon economy (MHRSS, 2019).

Policy support. While the overall employment prospects of a low-carbon transition appear positive, there will be near-term job losses in fossil fuel and other carbon-intensive industries. China's specific policy approaches will help to determine the balance between these job losses and employment gains in low-carbon industries and services. If designed well, the current trend of job creation in the low-carbon economy, combined with a dedicated policy framework to address the challenge of job losses while moving away from coal in particular, can support a fair and well-structured transition towards a green economy. There is increasingly robust evidence supporting the possibility for a just transition and job gains in low-carbon industries and services across other countries and regions (Caldecott et al., 2017; Gales and Hölsgens, 2017; Herpich et al., 2018). Additionally, recent research shows the potential for retraining in green industries (OECD, 2019; Bowen et al., 2018). Research also suggests that If job transitions are strategically managed with carefully designed supportive policies, short-run growth can be achieved in the green economy with minimal impacts on workers (Bowen et al., 2018). These supportive policies include skills development and training programs, capacity building, and vocational training programs. Because workers in the coal industry generally have lower education levels and limited employment choices (Fei, 2018), such training programs will be important elements of China's policy strategy to a low-carbon economy.

Despite promising initial research, our understanding of job market dynamics remains somewhat limited, and more research on the employment effects of policy packages, taking into account the specific situation across China, will be needed to improve the knowledge base that climate policy can build upon. Several studies have looked at quantifying the employment effects of China's transformation towards a low-carbon economy, but more research and analysis are needed to elucidate the most important factors that will drive effective policy strategies.


南浦大桥

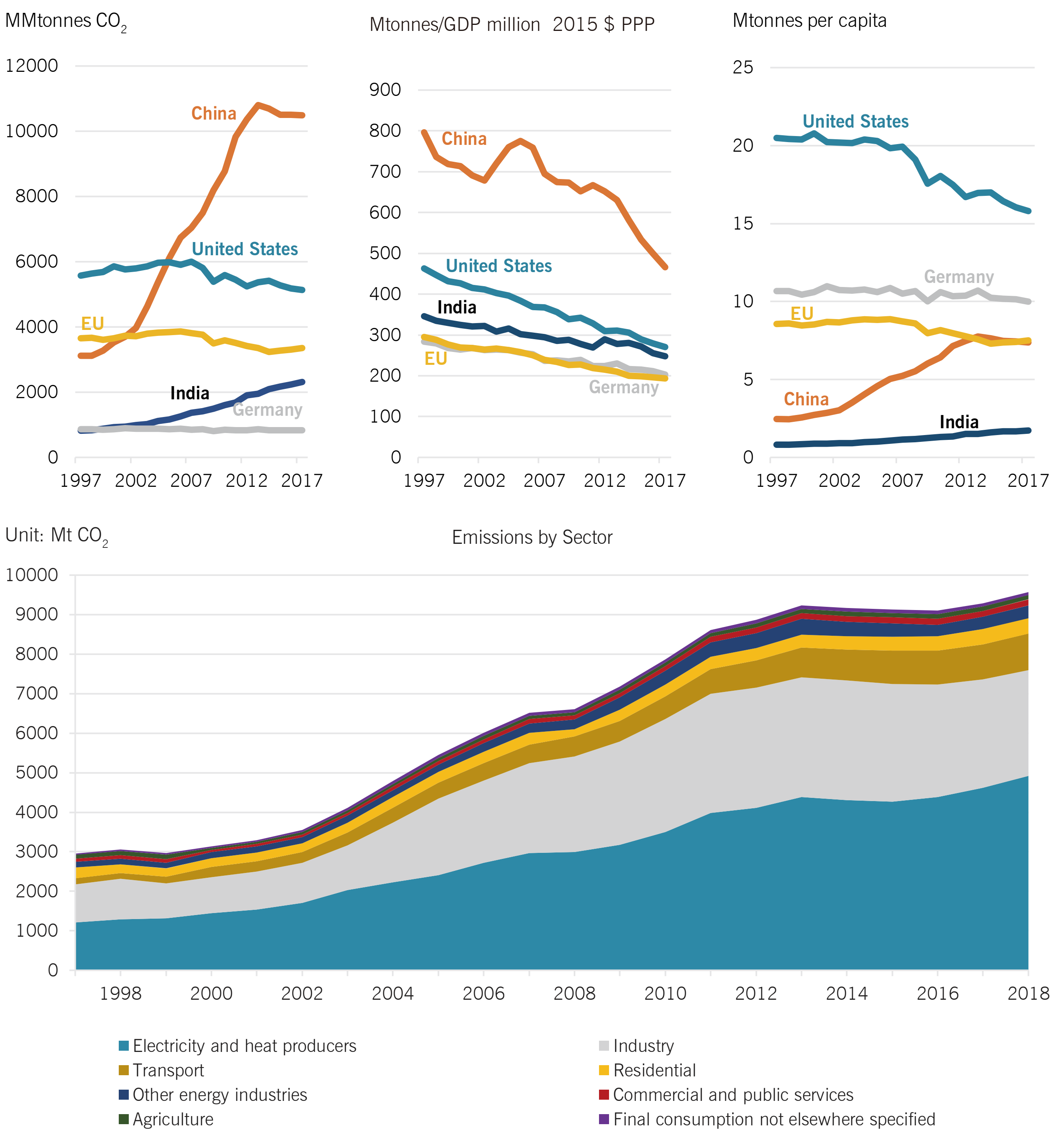
3. KEY ELEMENTS OF A LONG-TERM STRATEGY

In 2015, in Paris, parties to the UN Framework Convention on Climate Change (UNFCCC) reached a landmark agreement to combat climate change. The Paris Agreement has as one of its central goals "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". China's recent announcement of its long-term carbon neutrality goal will make a significant contribution to this global effort. In September of 2020, Xi Jinping pledged to the UN General Assembly that China aims "to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060." China's pledge demonstrates its commitment to global environmental leadership and an understanding of the role that climate mitigation can play in supporting China's vision for growth and development in a rapidly changing world.

China's global leadership on climate change is essential. China is now the second largest economy in the world, and it became the world's largest CO_2 emitter in 2006. At the same time, China's approach to carbon neutrality needs to take into account its unique circumstances. As a growing economy, China's emissions per unit of economic output ranked 16th in the world, and its emissions per capita ranked 49th, or about half that of the United States (Gilfillan et al., 2019; UNFCCC, 2019; BP, 2019). In 2018, China's fossil fuel and industrial CO_2 and GHG emissions stood at 10.1 $GtCO_2$ and 12.7 $GtCO_2eq$ (Global Carbon Atlas). China's CO_2 emissions from fossil fuels and cement grew an average of 1.4% every year between 2010 and 2018. The largest share of emissions came from electricity and heat (51%), followed by industry (28%) and transportation (10%) (IEA, 2020a). Moving away from traditional energy sources will need to be done in a way that ensures new opportunities for broadly shared prosperity.

FIGURE 3-1. HISTORICAL CO_2 EMISSIONS IN SELECTED COUNTRIES (PANEL A); HISTORICAL EMISSIONS INTENSITY (RELATIVE TO ECONOMIC OUTPUT) IN SELECTED COUNTRIES (PANEL B); HISTORICAL EMISSIONS PER CAPITA IN SELECTED COUNTRIES (PANEL C); HISTORICAL EMISSIONS BY SECTOR IN CHINA (PANEL D).

(Data source: EIA, The Global Carbon Project; IEA, 2020a)



Like all countries, COVID-19 has affected China's economy, and its GHG emissions. During the first half of 2020, CO_2 emissions dropped by 3.7%. Emissions dropped most precipitously in February (-18.4%), followed by March (-9.2%). Emissions rebounded, however, and were 5% above 2019 levels by May, 2020 as economic activities resumed (Liu et al., 2020). While the pandemic will undoubtedly influence

China's near-term strategy, the long-term ramifications of the pandemic are not clear. China's long-term strategy needs to address both the nearer-term ramifications of COVID-19 and China's long-term vision for growth and development.

Based on the most recent science, the guidance from the Intergovernmental Panel on Climate Change (IPCC) is that net global CO_2 emissions need to reach zero – that is, carbon neutrality – around 2050 in order to limit warming to 1.5°C and around 2070 or 2080 in order to limit warming to 2.0°C. Emissions of non-CO_2 gases need to be substantially reduced over this same period (IPCC, 2018)*. This guidance from the IPCC is based on a body of research that identifies a much broader range of possibilities for the timing of carbon neutrality. Some scenarios on which this guidance is based reach net zero global CO_2 emissions as early as 2040, and some do not reach net zero global emissions until well after 2060. The different results reflect both uncertainty and strategic choices. Many key drivers of emissions cannot be known with any meaningful certainty today – for example, population and demographic change, economic growth, and the advance of technology. The climate science behind this guidance is also uncertain and continues to evolve. Strategic choices include how much to reduce emissions over the coming decade versus the decades that follow, how much to rely on negative emissions options (e.g., afforestation, BECCS, and direct air capture) in the second half of the century to allow for less ambitious mitigation over the coming decades, and the degree to which non-CO_2 GHGs, aerosols, and aerosol precursor emissions are reduced. In general, the later that net CO_2 emissions reach zero, the greater will be the need for substantial reductions in non-CO_2 GHGs and the greater will be the reliance on negative emissions options in the second half of the century. The IPCC guidance attempts to find a balance between what is achievable today and limiting the use of negative emissions options, particularly in the second half of the century.

In this light, China's pledge to reach carbon neutrality before 2060 is a significant contribution to the international processes for limiting warming to 1.5°C. It is consistent with recent global modeling studies that try to identify the most globally "cost-effective" pathways to 1.5°C (see Figure 3-2). At the same time, the sooner before 2060 that China can reduce its emissions to zero or near-zero, the greater the chance of limiting warming to 1.5°C. While the global goal is to reach carbon neutrality around mid-century, different countries may do so at different times while still giving the world a good chance to limit warming to 1.5°C. Within the context of the Paris Agreement, countries need to build their long-term strategies based on national circumstances such as their domestic low-carbon energy and land resources, their strategies for growth and development, and their ability to sequester carbon and to eke out the final emissions reductions needed to reach zero. Different ways of looking at equity and fairness will also influence perceptions of when different countries should reach carbon neutrality relative to one another. Approaching the question from the perspective of global economic efficiency, for example, leads to different conclusions than asking the same question from the perspective of equity, measured, for example, in terms of per-capita emissions or historical responsibility (e.g., van den Bergh et al., 2020). These various perspectives cannot be reconciled into a single number for any country. They do, however, provide a sense of the range of possibilities.

China intends to achieve carbon neutrality before 2060. Regardless of precisely when China reaches carbon neutrality, it is essential that its CO_2 emissions peak quickly and, depending on the actions of other countries, be brought very close to zero around mid-century in order to limit warming to 1.5°C. China cannot wait to start reducing emissions or continue with substantial emissions through 2060. The concept of carbon neutrality is a valuable organizing framework for international action, but what ultimately matters for limiting warming is the totality of emissions over time – "cumulative emissions" – and not just the emissions at mid-century. Earlier peaking and faster long-term reductions will help to limit China's cumulative CO2 emissions. Indeed, both global and national studies consistently call for China's emissions to peak almost immediately in order to limit temperature change to 1.5°C (Figure 3-2). Scenarios that limit warming to 2°C

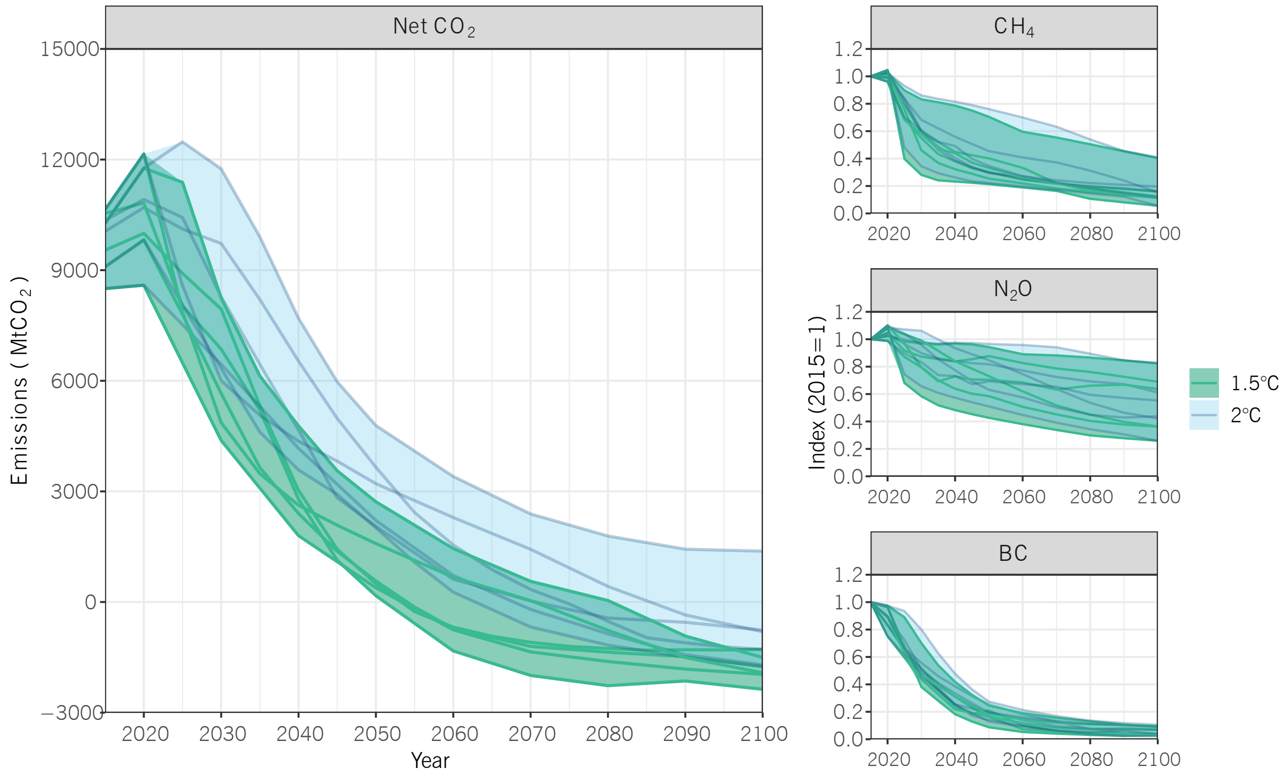
* *Note that neither of these net zero goals guarantees that temperature will be limited to 1.5°C or 2°C. Rather, they are based on a 50% chance of limiting warming to 1.5°C and a 66% chance to limit warming to 2°C.*

may peak toward 2030 (Figure 3-2).

If China's CO_2 emissions do not peak before 2030, not only will its cumulative emissions be higher, it will create substantial challenges for reaching carbon neutrality by 2060 and limiting cumulative emissions because China's economy will be "locked in" to higher emitting assets that will be difficult to move away from, for example, new coal-fired power plants; and it will limit the time for the broader societal, economic, and energy system transitions needed to limit emissions. In other words, delay would put in doubt the prospects for achieving carbon neutrality before 2060.

FIGURE 3-2. CHINA'S CO_2 AND SELECTED NON-CO_2 GHG EMISSIONS FOR 1.5°C AND 2.0°C SCENARIOS FROM SELECTED SCENARIOS.

The table shows full ranges of key variables from the selected scenarios. (Sources: CD-LINKS global scenarios (McCollum et al., 2018; Roelfsema et al., 2020) and national emissions pathways for China from GCAM-China).

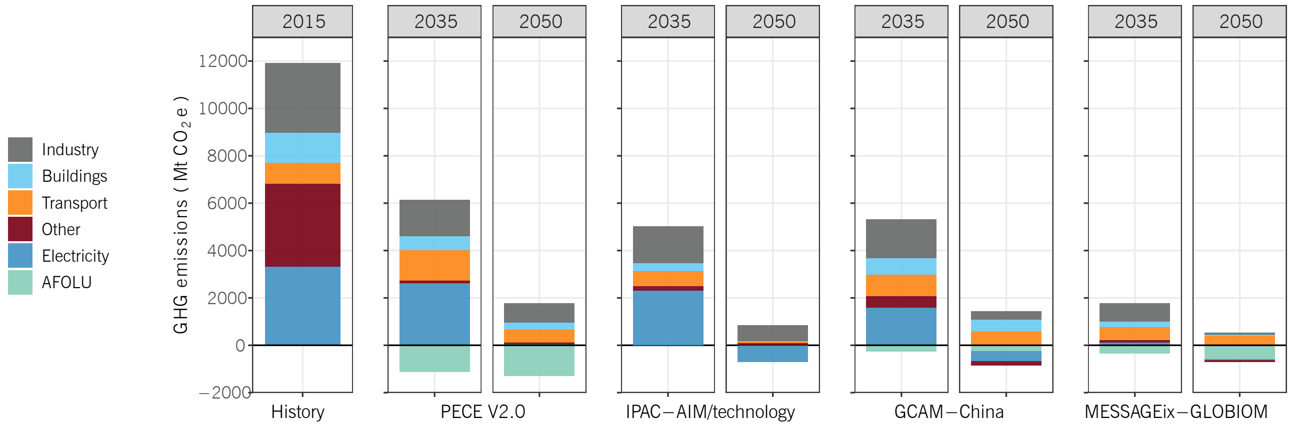


	Cumulative CO_2 emissions (2016-2050) [$GtCO_2$]		fossil CO_2 emission reduction relative to 2015 [%]		GHG emission reduction relative to 2015 [%]		Year of Peak	Year of Neutrality		
	incl. AFOLU	fossil fuels	2035	2050	2035	2050		CO_2 incl. AFOLU	CO_2 fossil fuels	Kyoto GHGs
1.5°C	150-260	120-220	45-65	75-100	45-70	75-90	~2020	2050-2080	2050-2080	2060-2090
2°C	200-330	170-290	10-45	60-80	15-55	55-75	2020-2030	2065-2100	2060-2100	2070-2100

Carbon neutrality is an economy-wide challenge, requiring substantial emissions reductions across all sectors of the economy, including buildings, industry, transportation, electricity generation, refining, agriculture, and forestry. Emissions must be brought to zero even as China's economy continues to grow. Each sector presents its own challenges and opportunities and will not follow a unique timeline (Figure 3-3). Nonetheless, at least two strategic themes emerge both from existing research and the new research supporting this report. First, electricity provides greater near-term opportunities for emissions reductions relative to other sectors, due to the many low-carbon electricity generation options and the increasing competitiveness of wind and solar power in particular. In addition, decarbonization of electricity generation is an important enabling condition for the decarbonization of end-use service sectors via electrification. This does not obviate the need for immediate action across all sectors; it only highlights that it will be possible to achieve substantial emissions reductions in electricity more quickly than in other sectors. Second, there are a number of applications in which low-cost mitigation options do not exist today. This includes, for example, air transport, industrial processes, and high temperature heat. Research typically anticipates that these will be the last sectors to be decarbonized or that they may never be fully decarbonized. For this reason, many studies envision that deep reductions in sectors such as industry and transport may be slower than in other sectors. At the same time, technology is evolving rapidly, and opportunities for mitigation decades from now may be very different than those of today. Effective strategy will therefore make progress on emissions reductions today, leave open options for adjustments as technology evolves, and invest in creating the technological options to address hard-to-decarbonize sectors.

FIGURE 3-3. CO_2 EMISSIONS FROM SELECTED MODELS IN 2035 AND 2050 IN 1.5°C SCENARIOS ALONG WITH ACTUAL CO_2 EMISSIONS IN 2015 (TOP PANEL); SECTORAL CO_2 REDUCTIONS ACROSS MODELS RELATIVE TO 2015 (BOTTOM TABLE).

Note that percentages are calculated based on 2015 numbers from the scenarios rather than from China's inventories, to allow for differences in base year numbers. Differences in base year numbers arise from differences in sectoral accounting methodologies among models. Negative values indicate increases. Note also that subsets of scenarios were used to calculate ranges in each sector. The choice of scenarios included for each sector can be found in Section 4 of this report. Models used in the bottom table include ERI-Industry, GCAM-China, ICCSD-LoMLoG, IPAC-AIM/technology, MESSAGEix-GLOBIOM, PECE_LIU_2019, PECE V2.0, POLES-JRC 2019, and Transportation-CATS. (Source for 2015 data: IEA, 2019b)



Sector	2035		2050	
	1.5°C	2°C	1.5°C	2°C
Electricity	20%~60%	0%~45%	100%~120%	80%~100%
Buildings	0%~70%	0%~50%	50%~95%	20%~80%
Industry	30%~70%	20%~35%	75%~95%	50%~80%
Transportation	-45%~25%	-60%~-5%	40~90%	25%~65%

BOX 3-1. LINKING NATIONAL SCENARIOS TO CHINA'S CARBON NEUTRALITY GOAL AND TO LIMITING WARMING TO 1.5°C

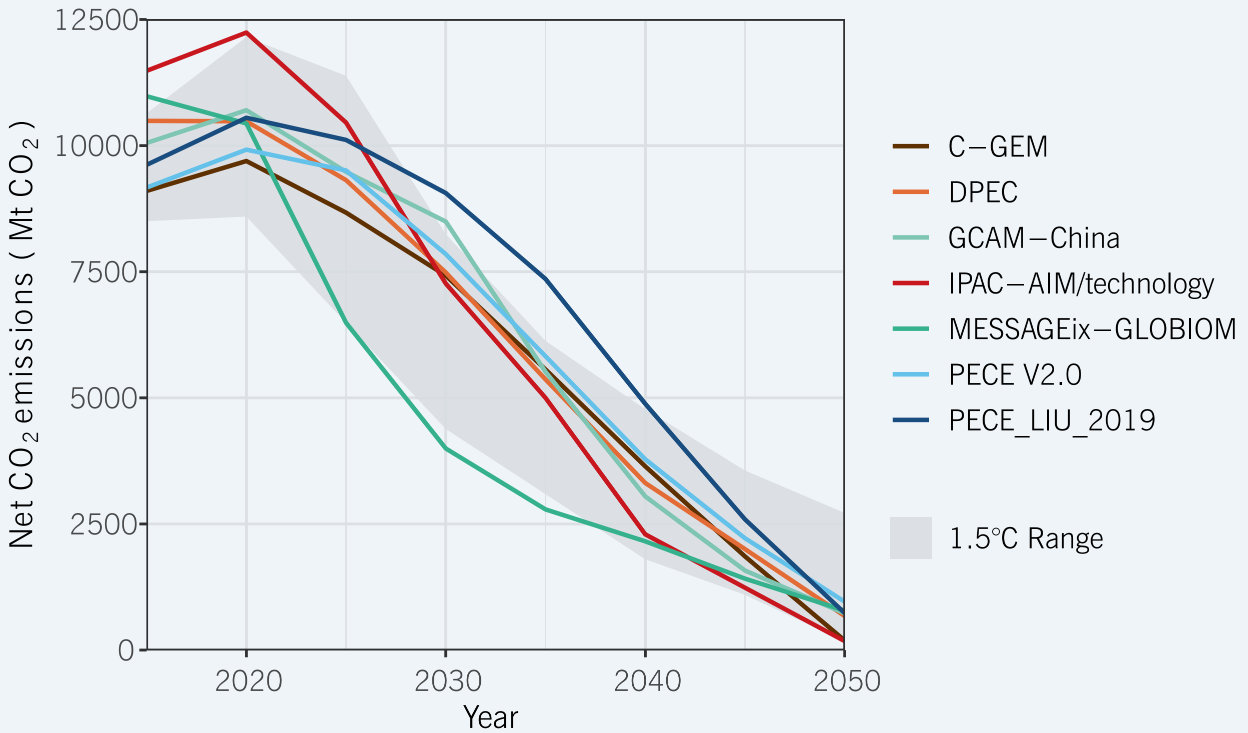
This report explores the national and sectoral transitions necessary to meet China's carbon neutrality goal and limit warming to 1.5°C. Exploring national and sectoral transitions requires modeling and analytical tools with sufficient levels of detail on China and the key sectors within China that will need to transition to low-carbon configurations. All of the national scenarios in this study are consistent with carbon neutrality before 2060, and several are on track to achieve carbon neutrality not long after 2050.

In general, to allow for this sufficient level of detail, these models only represent dynamics in China or in specific sectors in China—that is, they do not represent the transitions taking place in the rest of the world. This narrower focus on China and sectors within China, while advantageous for understanding national and sectoral dynamics, also limits the ability to use these tools, by themselves, to understand whether the scenarios they produce are consistent with long-term temperature goals such as 1.5°C. Because climate change is the result of emissions across the world, only global models are capable of exploring the distribution of emissions reductions across countries. While it is possible to assess the consistency of national scenarios with China's carbon neutrality goal, it is not possible to assess their consistency with broader temperature goals without comparing them to the results of global scenarios.

To assess the consistency of the national scenarios, we have compared their national energy emissions to those emerging from the global models for China. All of the 1.5°C scenarios from national models explored here led to emissions reductions within the range of the global scenarios in 2050, although several temporarily fall out of the range. The national scenarios reach emissions reductions of between 90% and 100% in 2050 relative to 2015 levels. This range of reductions lies at the lower end of the range for China from global scenarios and can therefore be considered as roughly consistent with limiting warming to 1.5°C. All put China in position to reach carbon neutrality before 2060.

FIGURE 1. CO_2 EMISSIONS ACROSS NATIONAL MODELS AND GLOBAL MODELS WITH NATIONAL RESULTS.

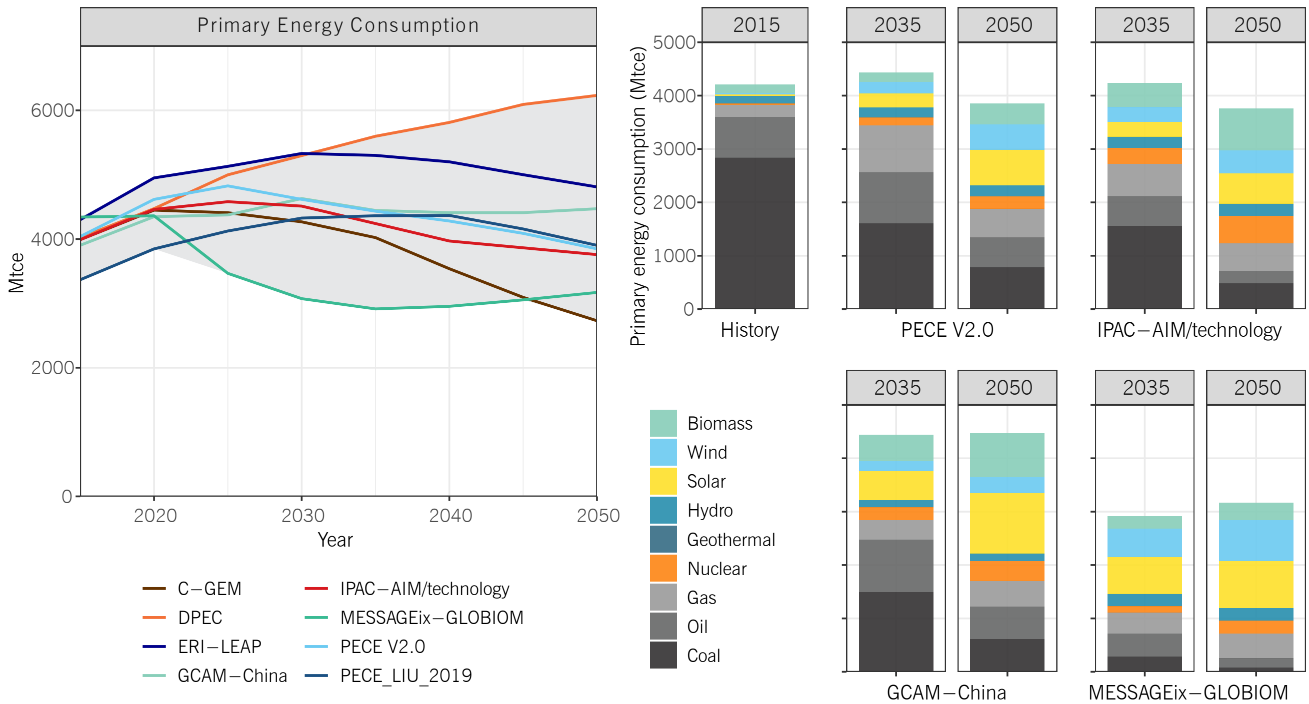
Note that not all models include CO_2 emissions from agriculture, forestry, and other land use.



Reaching carbon neutrality before 2060 implies a rapid and extensive scale-up of low-carbon energy at the same time that China's overall energy consumption is initially growing. While the overall trajectory of China's energy evolution is uncertain and dependent on a broad range of socioeconomic and technological drivers, the scenarios synthesized in this report generally portray a slowing of recent growth in the near-term followed by a gradual decline in overall energy production and consumption (Figure 3-4). Against this backdrop of change in the overall scale of the energy system, scenarios explored in this study include an upscaling of low-carbon sources—including fossil energy with carbon dioxide capture and storage (CCUS)—from about 6% in 2015, to about 30-65% and 70-85% of total primary energy use by 2035 and 2050, respectively (Figure 3-4A). These shares are broadly consistent with similar numbers identified in the IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018) at the global scale. The non-fossil share in primary energy use would correspondingly increase from 6% in 2015 to 20-60% and almost 50-75% by 2035 and 2050, respectively.

FIGURE 3-4A. PRIMARY ENERGY IN 1.5°C SCENARIOS SYNTHESIZED IN THIS REPORT.

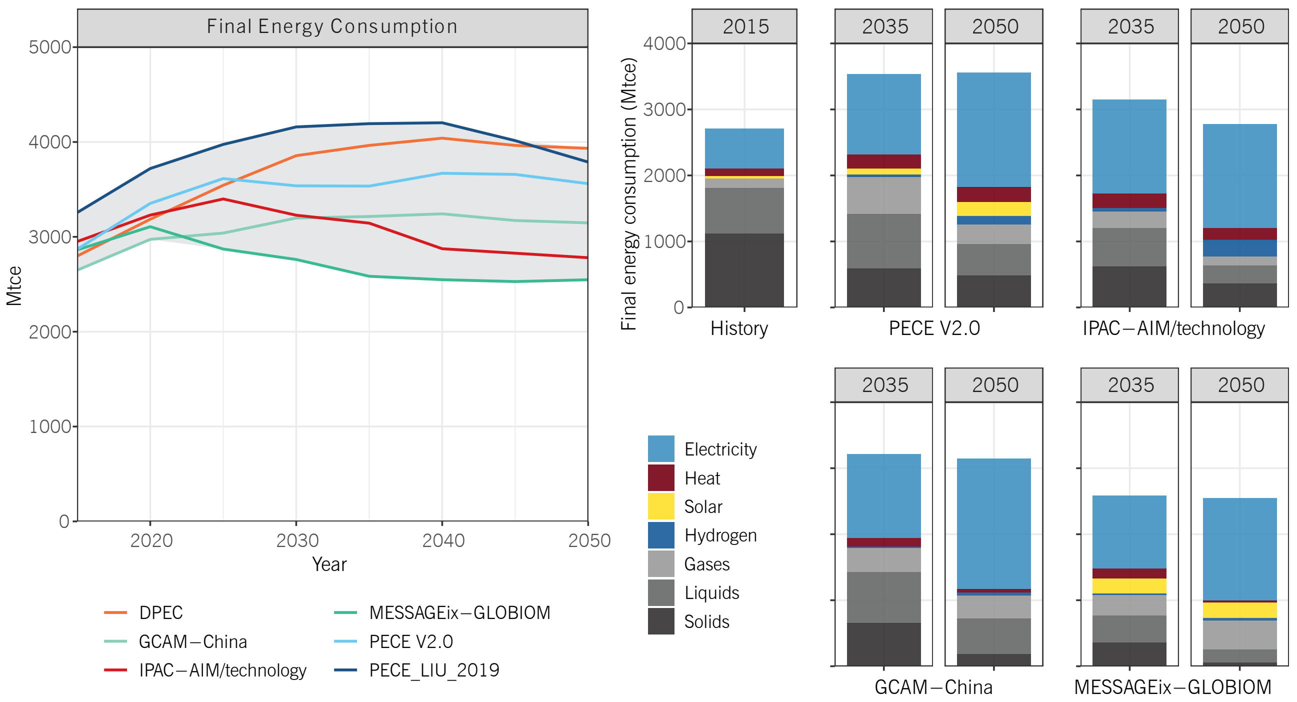
Left panel shows total primary energy in selected scenarios. Right panel shows primary energy for four illustrative scenarios. Differences in base-year numbers arise due to differences in inventories, different ways of calculating primary energy, and different projections, as 2015 is a projection year in some models.Primary energy in this report is estimated based on the direct equivalent method, different from the method used in Chinese statistics.



Implementation of these strategies will also lead to a change in energy carriers used in building, industry, and transportation. Most notably, it is anticipated that electricity will play a far greater role in China's future energy system than it does today. Much of this electrification will occur in the transportation sector, which uses very little electricity today. Challenges of pervasive electrification remain high in the industry sector with alternative fuels such as hydrogen and (sustainable) bioenergy potentially serving as options in the longer-term when emissions will need to be driven out of the hard-to-decarbonize sectors. Electrification offers the opportunity to curb and eventually reduce final energy consumption due to significantly higher efficiencies in many applications, for example in transportation, where electric drive trains have substantially higher tank-to-wheel efficiencies than internal combustion drive trains.

FIGURE 3-4B. FINAL ENERGY IN 1.5°C SCENARIOS SYNTHESIZED IN THIS REPORT.

Left panel shows total final energy in selected scenarios. Right panel shows final energy for four illustrative scenarios. Differences in base-year numbers arise due to differences in inventories and different projections, as 2015 is a projection year in some models.



Several cross-cutting strategies emerge from both the economy-wide scenarios synthesized here and other studies of deep decarbonization. Different sectors will put different emphases on these cross-cutting strategies (Figure 3-5). In order to limit warming to 1.5°C or 2°C, these decarbonization strategies will need to be complemented by comparable actions to reduce non-CO_2 emissions. Cross-cutting decarbonization strategies include:

- **Promoting sustainable demand** in all end-use sectors while maintaining high living standards through more efficient use of energy, structural change, urban planning, and lifestyle changes.
- **Decarbonizing electricity generation** by phasing out coal power generation without CCUS and rapidly increasing generation from a diverse portfolio of technologies dominated by renewables and supplemented by nuclear, and fossil or bioenergy with CCUS.
- **Electrifying end-use sectors** by increasing electric vehicles, using electricity for low-temperature heat in industrial applications, and transitioning to electric space and water heating in buildings (e.g., heat pumps).
- **Switching to low-carbon fuels** like hydrogen and biomass in industry (as fuel or feedstock) and transportation (e.g., long-haul trucking, shipping, and aviation) when electrification is not feasible or economically viable.
- **Sequestering carbon** in natural systems (e.g., forest and soil) or through CO_2 removal technologies to facilitate carbon neutrality even if emissions do not reach zero in some hard-to-decarbonize applications, such as air travel or high temperature process heat.

FIGURE 3-5. CROSS-CUTTING MITIGATION STRATEGIES AND THEIR APPLICATION IN DIFFERENT SECTORS.

MITIGATION MEASURES

Sector	Sustainable Demand	Low-carbon Generation	Electrification	Fuel Switching	Carbon Sequestration
Electricity		✓			✓
Buildings	✓	✓	✓	✓	
Industry	✓	✓	✓	✓	✓
Transportation	✓		✓	✓	
Agriculture, Forestry, and Land Use	✓				✓

Fundamental to all of these strategies is the need to phase out the use of coal without CCUS across all sectors (See Box 3-2). All mitigation studies agree on a more or less rapid phase-out of the use of coal without CCUS across the entire economy under stringent climate goals. This affects, foremost, the electricity and industry sectors where coal at present constitutes a large fraction of fuel input. The speed of this transition can be moderated by deploying CCUS technologies (e.g., in power plants, hydrogen and ammonia production, and primary steel and cement production) that capture the majority of CO_2 from fuel combustion and industrial processes and either reuse it or store it underground. CCUS deployment can help reduce the pace at which coal mines need to close down and coal-based industries need to restructure with possibly positive benefits for labor market disruptions (see Chapter 5). CCUS will not, however, obviate the need to rapidly transition away from coal as a primary fuel source.

BOX 3-2. PHASING OUT COAL IN THE ENERGY SYSTEM

Phasing out coal power in China's energy system is one of the most beneficial and technologically easiest near-term steps toward China's new growth pathway, as well as a complicated challenge that requires careful planning and implementation to ensure continued prosperity, employment, and economic growth. As the world's largest coal consumer and producer, coal is deeply embedded in China's energy system and its economy. Coal contributed 58% of China's total primary energy consumption in 2019 (NBS, 2020). It is widely used in electricity generation, steel and cement production, building materials, chemicals, and buildings. Due to progress made during 12th and 13th five-year plans (2011-2020), China's total coal consumption declined after 2013, but it has increased again in recent years, approaching its 2013 peak in 2019.

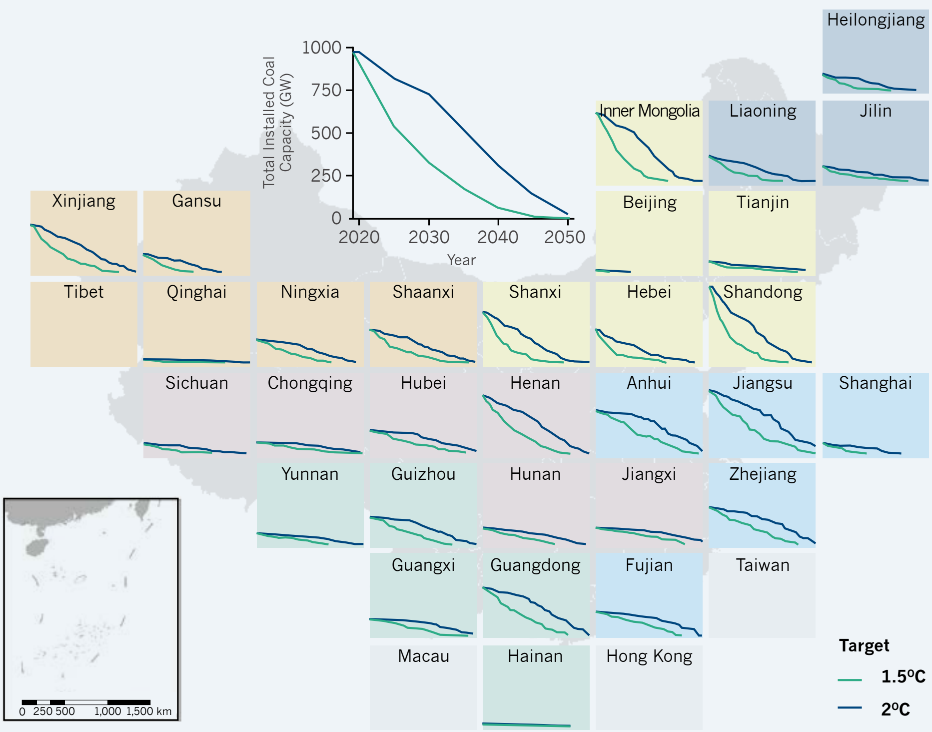
A rapid shift away from coal to non-emitting energy sources will be important for delivering on a wide number of the priorities associated with China's growth and development agenda. And it will be essential for reaching carbon neutrality before 2060. Accordingly, China needs to enter a new phase, turning quickly from controlling coal growth to accelerating a phaseout of coal without CCUS in all sectors.

Coal phaseout across different sectors. The phaseout timeline will vary across sectors based on different technical and institutional challenges as well as near-term benefits brought by early actions. Scattered coal combustion for industrial small furnaces and boilers and residential heating and cooking in rural areas can be eliminated first and within the 14th Five-Year plan (2021-2025). Within the power sector, coal power generation should be eliminated by around 2040 to 2045 to limit warming to 1.5°C. Coal consumption without CCUS in industrial sectors that are difficult to electrify (e.g., as a feedstock in steel production) should be eliminated around 2055-2060.

- **Residential and industrial scattered coal.** Significant progress has been made in reducing scattered coal use during the past decade, especially in the Beijing-Tianjin-Hebei region. The progress has been achieved by shutting down inefficient and polluting small furnaces and boilers in the industrial sector, and through wide implementation of coal-to-gas and coal-to-electricity switching in rural residential heating supported by public subsidies. These actions can feasibly be replicated rapidly across the country in combination with increasing use of renewable energy technologies, such as roof-top PV and biomass in the residential sector. In addition, phasing out scattered coal is one of the most effective near-term approaches to reduce local air pollutant emissions and generate human health benefits. It should be a priority during the 14th FYP.
- **Coal-fired power generation.** Phasing out coal is particularly important in the electricity sector, which accounts for 54% of China's total coal consumption (EPPEI, 2019). Through an immediate halt of new construction of coal-fired power plants, rapid retirement of a small portion of old, dirty, inefficient coal plants in the near term, and gradually reduced utilization of the remaining majority of operating plants, China can phase out coal power generation without CCUS by around 2040-2045 (Cui et al., 2020). Several provinces have specific near-term opportunities. Shandong, Inner Mongolia, and Shanxi are the top three coal consuming provinces. Shandong has the highest installed coal power capacity, and its share of small, old, and inefficient coal plants is larger than other provinces. Moreover, over a third of the total capacity in Shandong are industrial self-use plants not connected to the grid. They often have higher environmental impacts due to challenges in enforcing regulations and policies. Coal retirements could be implemented more rapidly in Shandong due to these less favorable technical attributes of its coal plants. In doing so, Shandong would be able to increase overall demand for green energy (likely imported initially from neighboring provinces) and accelerate the restructuring of its economy from heavy to service industries.
- **Industry coal use.** Coal consumption in iron and steel production, building materials, the coal chemical industry, and cement together account for over 40% of China's total coal consumption (EPPEI, 2019). Phasing out coal without CCUS in these sectors requires a combination of strategies, including efficiency improvements, electrification, low-carbon fuel switching (i.e., to zero-carbon hydrogen or modern biomass), and demand reductions through economic and industrial structural changes. Some of the approaches can be implemented immediately (i.e., energy efficiency), while others may take longer and depend on technological and institutional changes.

FIGURE 1. NATIONAL AND PROVINCIAL COAL POWER PHASEOUT PATHWAYS IN 1.5°C AND 2°C SCENARIOS.

(Source: Cui et al., 2020)



Societal benefits and challenges beyond climate mitigation. Phasing out China's reliance on coal will bring considerable benefits beyond climate mitigation, including continuous improvements in air quality and human health, enhanced energy independence and energy access through low-cost renewables, and the creation of new jobs and growth opportunities in a green economy.

- **Air quality and human health.** In the past decade, air quality and health benefits have increased dramatically from shutting down obsolete coal fleets and eliminating scattered coal use in China. With recent policy efforts, air quality has largely improved in the Beijing-Tianjin-Hebei area. However, major cities in the large coal-consuming provinces, such as Shandong, Henan, and Shanxi, still face severe air pollution problems, and often rank at the bottom in terms of local air quality across the country. For these regions, lowering PM2.5 concentrations is a central motivation for eliminating scattered coal consumption in residential and industrial uses. Phasing out coal in the energy system will not only deliver significant, immediate, and broadly shared health benefits, it will also provide a necessary path towards long-term improvements in air quality to the highest standards (Tong et al., 2020).
- **Restructuring of local economies.** Phasing out coal will also bring opportunities to the major coal producing and exporting provinces, including Inner Mongolia, Shanxi, and Shaanxi. With an increasing reliance on coal to support their economies, they are increasingly vulnerable to the well-known "resource curse" of overdependence on low-value and volatile resource extractive industries. Both Shanxi and Inner Mongolia have experienced difficult economic conditions due to volatility in coal markets. With abundant renewable resources, these provinces have the opportunity to diversify their energy portfolios and their economic systems to find a new impetus for long-term growth. With the inevitability of a transition away from fossil fuels, it is important to begin now and ease the transition instead of continuing on the current course and facing a crisis with little time to react.
- **Employment.** Phasing out coal will reduce the number of older jobs across the entire coal supply chain from mining to fuel processing, conversion, and end-use. Given the fundamental role of coal in the Chinese economy at present, employment in the coal industry will, in the short term, be heavily affected by the low-carbon transition (Huang et al., 2018, 2019, 2020; Shi et al., 2018). Due to the combination of stagnating coal consumption and increasing labor productivity as a result of continued mechanization, the number of workers in coal mining and washing has already

decreased by over 40%, from 5.3 million in 2013 to 3.2 million in 2018 (He et al., 2020b). These changes are inevitable even without enhanced climate mitigation (Shi et al., 2018), but will be further accelerated on a pathway towards carbon neutrality before 2060. Moreover, employment and economic impacts tend to have different distributional effects within the provinces. Specific communities that have traditionally centered around a coal economy are expected to be hit the hardest. About 25% of China's total coal employment is in Shanxi province, followed by Shandong, Henan, Anhui, and Heilongjiang. These regions have experienced different levels of challenges in managing the coal job losses in the past five to seven years and will need to continue to find solutions to carefully manage the social implications of these losses along with those that will occur from an accelerated coal phaseout (China Coal Cap Project, 2019).

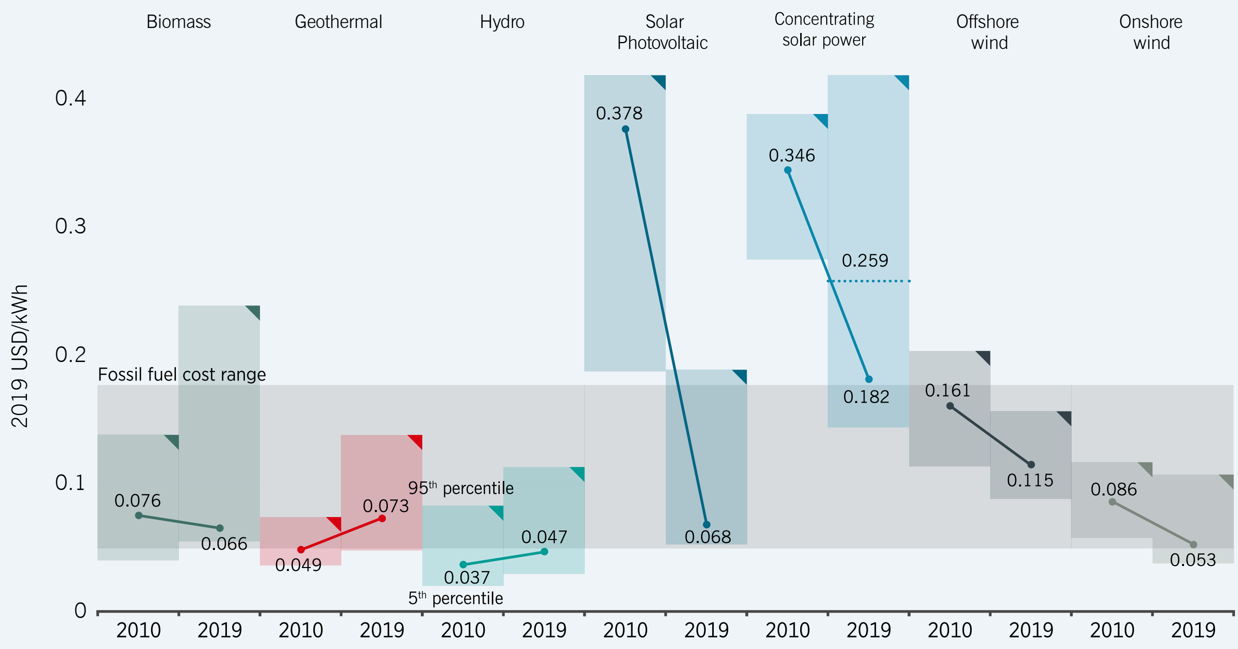
Achieving a high-ambition coal transition in China in a just and equitable way must be a policy priority. Possible approaches include carefully designing and implementing a comprehensive policy package that includes resettlement and retirement policies for older workers, retraining and education programs for younger workers, fiscal policies to provide compensation and financial support to both individuals and companies, and economic incentives to create new businesses and development opportunities for the local economy. Coal mining is a tough job with high health impacts and security concerns. A coal phaseout with effective transition management can help provide a better quality of life for millions of coal workers and for China's future energy workforce.

BOX 3-3. INNOVATION AND THE RAPID PACE OF CHANGE IN ENERGY TECHNOLOGIES

Technology is at the heart of climate mitigation. Without technology options that can compete with fossil fuels and that can support broader priorities such as clean air, it will be difficult to limit temperature change to 2°C or 1.5°C. A number of technologies—PV cells, batteries, digitalization—are changing the mitigation landscape and providing cost-effective options for near-term decarbonization. But they may not be enough in the long run. More innovation is needed.

FIGURE 1. GLOBAL WEIGHTED AVERAGE LEVELIZED COST OF ELECTRICITY (LCOE) FROM UTILITY-SCALE RENEWABLE POWER GENERATION TECHNOLOGIES, 2010 AND 2019.

(Source: IRENA, 2020)



Note: For CSP, the dashed bar in 2019 shows the weighted average value including projects in Israel.

China's long-term strategy needs to emphasize innovation and technology leadership. The emerging low-carbon economy will be powered by those countries that can take technological leadership. Those countries that are not able to take leadership will be followers, buying technology from those that have supported robust national, low-carbon innovation systems. As China looks forward to mid-century and its near-term planning, it needs to invest in innovation, focusing on those technologies that are most strategic both for its own mitigation efforts and for global leadership in the low-carbon economy.

Several promising technologies need further development or demonstration. Promising technologies that need further development and demonstration include hydrogen, biofuels, CCUS, nuclear power, and energy storage. Hydrogen and biofuels can be variously used in applications that are not amenable to electrification, such as long-distance transport, air transport, chemicals, and high temperature heat. Hydrogen can also be used to manage the grid and provide storage capacity. Despite promising recent advances, efforts are needed to improve all elements of the hydrogen fuel cycle, from the generation of hydrogen, to storage, to fuel cells. Bioenergy energy from cellulosic feedstocks holds the promise of directly replacing liquid fossil fuels, but current technology is not competitive, and a range of broader concerns about impacts on agriculture and land use remain. China has a large underground storage capacity to potentially support CCUS deployment, which would allow China to continue using fossil fuels in electricity generation and industrial applications. The use of bioenergy coupled with carbon dioxide capture and storage (BECCS) could deliver negative emissions – that is, sequester CO_2 from the atmosphere – and offset CO_2 emissions in hard-to-decarbonize sectors. Nuclear power remains a viable option for baseload electricity generation with current technologies, and advanced reactor designs and emerging technologies, such as small modular reactors, hold promise for a greater role in future electricity grids. Advances in energy storage would support enhanced grid flexibility, which will be particularly valuable in grids with high penetration of wind and solar power.

The era of Energy Internet (E-Energy) is providing opportunities in digitalization and electrification. Energy Internet—the fusion of information and communication technologies and energy systems—is reshaping energy systems towards more flexible, smart, and efficient systems. Digitalization and electrification will serve as foundations for the energy systems of the future. The Energy Internet holds the promise of successfully integrating diverse elements of future electricity systems – variable renewable energy technologies, hydrogen, electric vehicles, and energy demand systems in buildings and other end uses – to create more efficient and resilient systems.

Broad investments in science, technology, and innovation across the economy will support both decarbonization and broader technology leadership. Innovation and technology are crucial not only for China's low-carbon transition. They are a foundation for long-term economic prosperity. Beyond the direct innovative opportunities in low-carbon technologies, a pathway towards science, technology, and innovation across the spectrum of key strategic areas of science and industries will accelerate China's low-carbon transition. The Chinese government has been active in identifying priority areas, concentrating on high-tech fields as strategic pillar industries that promote an industrial transformation. A broad investment in science, technology, and innovation can deliver a win-win solution, supporting both the low-carbon transition and broader economic growth.


Central Conservatory of Music

4. SECTORAL STRATEGIES AND OPPORTUNITIES

Achieving China's carbon neutrality goal will require a comprehensive, economy-wide agenda for action. This will include efforts across key sectors, including electricity generation, buildings, industry, transportation, and the confluence of agriculture, forestry, and other land use (AFOLU). Each of these sectors presents its own challenges; each is associated with its own long-term requirements to support carbon neutrality; and actions today in each sector will be among the first essential steps toward meeting these requirements. Sectoral strategies can serve as an organizing framework for guiding action on mitigation.

A cross-cutting approach will be necessary to support successful mitigation. Many technologies will be implemented across sectors, and improvements to technology in one sector will support mitigation in others. For example, solar PV will be used in centralized electricity generation applications as well as in the buildings sector as distributed electricity generation. Batteries will support electrification of transport while simultaneously supporting electricity system operations and the integration of renewable electricity, and they may prove valuable for building energy management. Foundational technology areas such as digitalization will have implications across the energy system.

Mitigation will also involve interactions between sectors. For example, using hydrogen in industry for high-temperature heat requires a transformation in hydrogen production, switching from natural gas to renewable sources as the primary input. Using biomass in industry or electric power will have implications for agriculture and land use, because of the interaction and potential competition between biomass production, agriculture, and afforestation or deforestation. Increased reliance on wind and solar power will lead to higher demand for industrial materials such as cement, steel, and glass, and will call for accelerated decarbonization of industry.

Increased use of electricity will also strengthen inter-sectoral linkages. Increased electrification in buildings, industry, and transport will accelerate the need for new electric power capacity. For example, electrifying transport can reduce tank-to-wheel vehicle emissions, but decarbonization of electric power will need to be tackled simultaneously with reductions in production and end-of-life vehicle emissions to achieve net system-wide emission reductions. Meanwhile, the electricity system, with increasing shares of variable renewable energy, will need more flexibility and will require responsiveness in the end-use sectors.

Improving the coherence of policies and programs across ministries and sectors will be critical for China's low-carbon transition. A successful transition will require a more mutually supportive policy mix within the energy system, as well as across energy, environmental, and agricultural sectors. It will require significant improvements in both vertical (national, provincial, and local) and horizontal (cross-ministerial) policy coordination. Cross-cutting policies such as carbon pricing may prove valuable as part of a policy portfolio. Similarly, technology is fundamental to the transformation that lies ahead and to China's economic leadership in the new, green economy. Investments in technology innovation will therefore be an essential part of a strategy that can support action across sectors.

Cross-sectoral, cross-institutional coordination should go beyond the energy and environmental systems. Coordination needs to extend to fiscal and financial policies (see Chapter 5). China's low-carbon transition requires a significant increase in investment in low-carbon technologies and an immediate shift away from fossil energy investment to low-carbon investment. This changing investment landscape will require coordination between energy and financial policies, along with changes in fiscal policies, to align public investment with more ambitious climate targets.

BOX 4-1. USING SCENARIOS TO EXPLORE SECTORAL TRANSITIONS

While a broad set of scenarios were collected from modeling teams for this report, only subsets of those models are included in the various figures and numerical results describing the sectoral transitions in this section. Exploring sectoral transitions requires models with sufficient granularity to produce scenarios of key characteristics such as total energy, fuel mix, and sectoral CO_2 emissions. Not all scenarios assessed in this report included sufficient granularity, and some scenarios are therefore excluded from comparisons. In addition, some scenarios did not provide sufficient data and some scenarios included insufficient sectoral coverage to be included in comparisons (e.g., representing only the residential component of the building sector). Finally, in some cases, scenario results were considered to be preliminary and not viable for comparison. The models that are assessed and described in each of the sectors varies based on these different factors.

4.1 ELECTRICITY SECTOR TRANSITIONS

Current Status and Trends

China has the largest electricity sector in the world, with an installed capacity of 1900 GW and a total generation of around 7000 TWh (He et al., 2020a; CEC, 2019). China's electricity demand has grown from 1,250 TWh in 2000 to 6,830 TWh in 2018 (IEA, 2020b). Energy-intensive industries, such as steel, chemicals, and aluminum, have been the main driving force behind China's rapid increase in electricity demand. However, the ongoing economic transition and structural shift towards service-based industries may make the role of service industries, residential consumption, and potentially transportation electricity consumption more prominent in the future (IEA, 2019a; Lin et al., 2020).

Along with the rapid growth in electricity demand and production, China's CO_2 emissions from electricity generation tripled between 2000 and 2017. Electricity production currently accounts for about 50% of energy-related CO_2 emissions in China. China's coal-based power generation system is particularly carbon intensive, with a carbon intensity of 610g CO_2/kWh, compared to 410g CO_2/kWh in the U.S. and 270g CO_2/kWh in the European Union (IEA, 2020c).

China's electricity generation is dominated by coal (Figure 4-1). More than 1,000 operating coal-fired power plants, a total of about 1,000 GW, provided 64% of China's electric power production in 2018 (CEC, 2019). The majority of existing plants were installed after 2005 and therefore have a remaining design lifetime of decades. Early retirement of the large coal-based infrastructure would therefore create high risks of stranded assets. Meanwhile, the coal power industry is already facing financial challenges, largely from overcapacity and competition from increasingly competitive renewable generation. Installed coal capacity has been growing at a faster pace than coal power generation, meaning that coal plants are not being fully utilized. The average utilization of coal plants has dropped to below 50% (CEC, 2020), and, consequently, half of the existing plants are running at a financial loss.

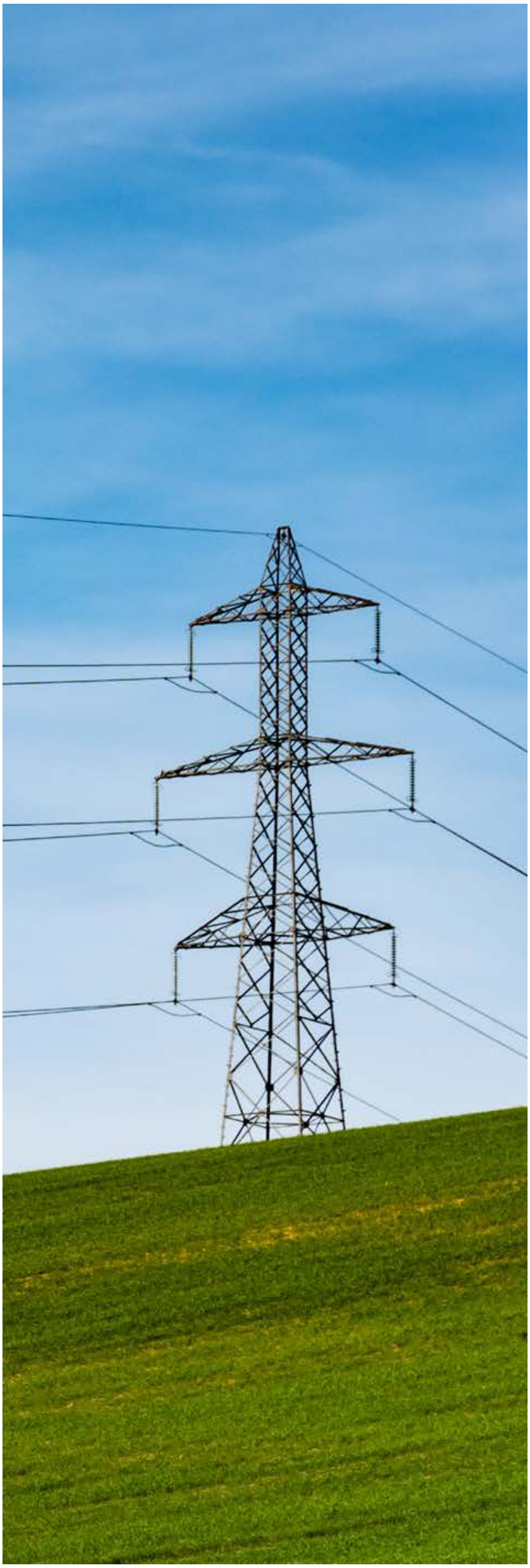
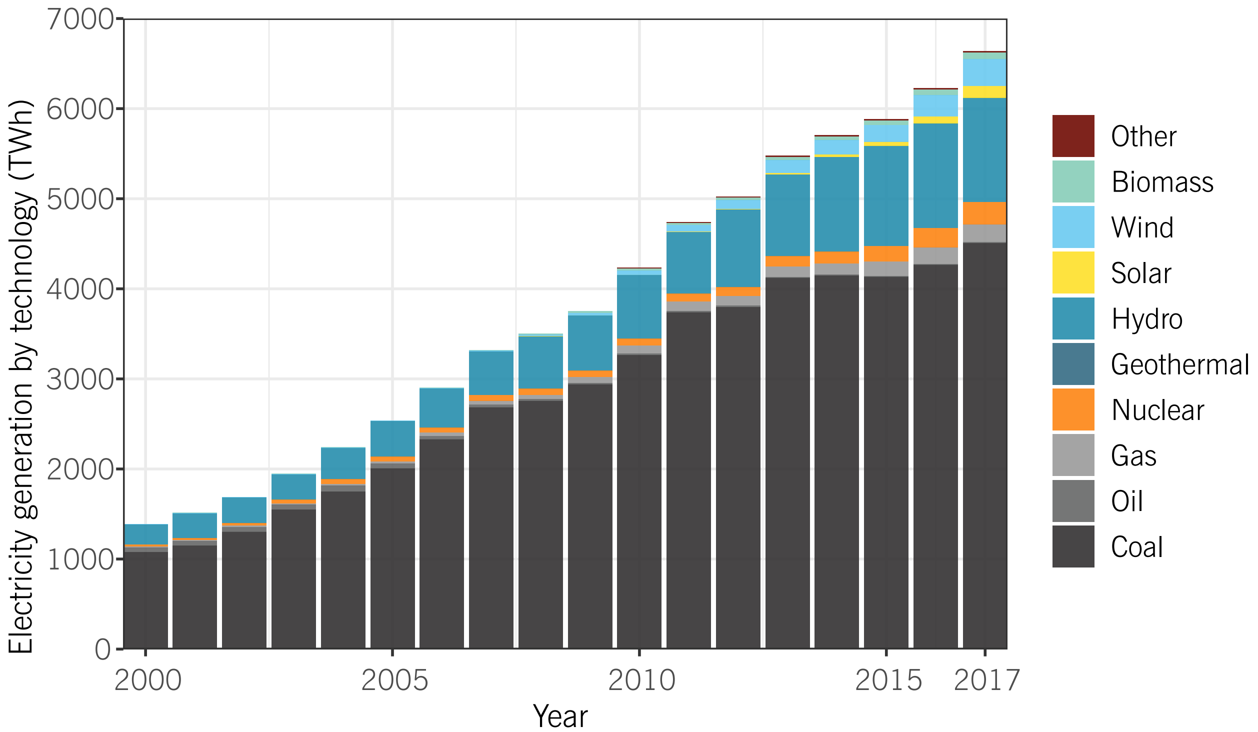


FIGURE 4-1. ELECTRICITY GENERATION BY TECHNOLOGY, 2007-2017.

(Source: IEA, 2019c)



Although non-hydro renewable energy currently makes up only a small percent of China's electricity generation, China has become a global leader in the deployment of and investment in renewable energy. The installed wind power capacity grew significantly in the past four years, from 130 GW in 2015 to 210 GW in 2019, and the installed PV capacity increased almost five times during the same period, from 42 GW to 210 GW (CEC, 2016, 2020). Currently, China's installed wind power capacity accounts for a third of the total global capacity; PV capacity accounts for a fourth of the total global capacity. China has become the world's largest investor in renewable energy* since 2013 and has contributed to around a third of the global total investment in renewable energy capacity (UNEP and BNEF, 2020).

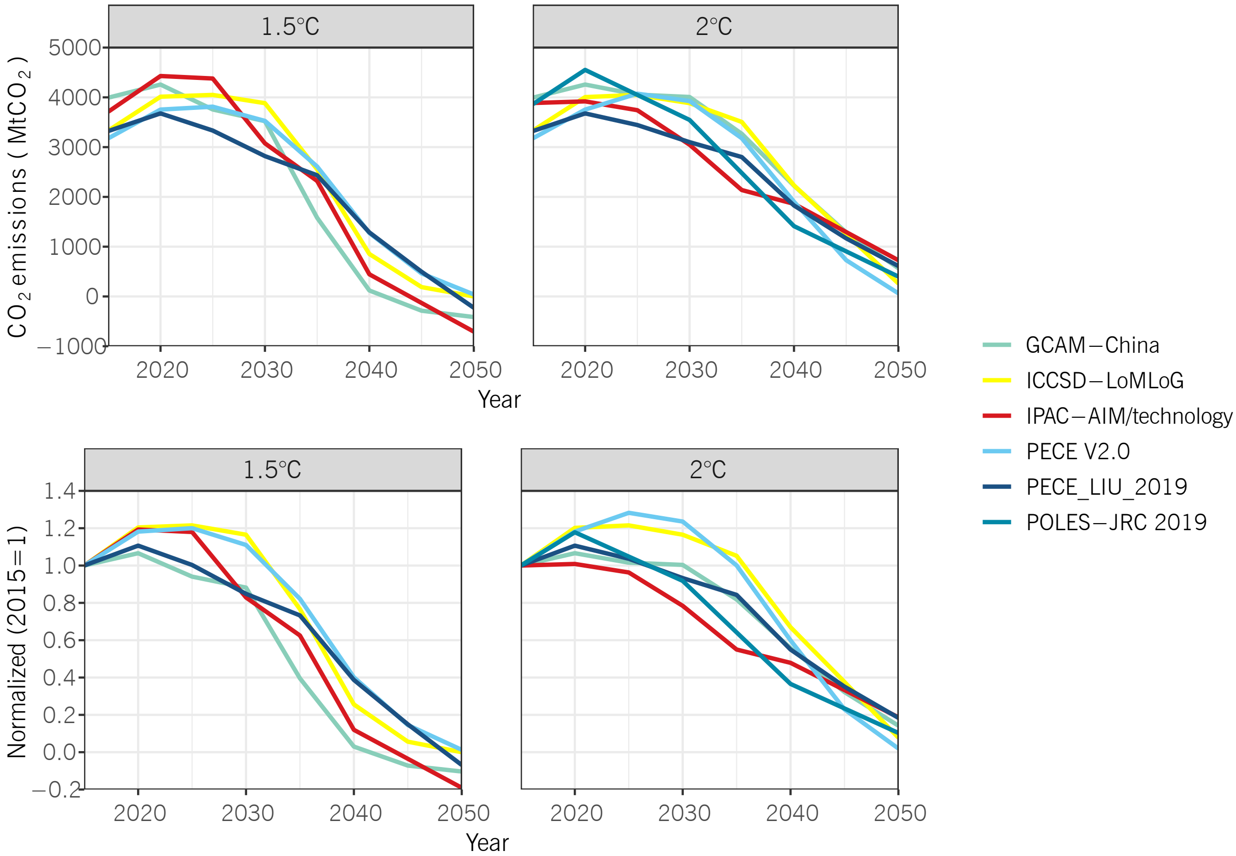
* According to UNEP and BENF (2020), renewable energy investment includes investment in the following sectors: wind, solar, biomass and waste, small hydro, geothermal, biofuels, and marine. Renewable electricity investment accounts for more than 95% of renewable energy investment.

BOX 4-2. ELECTRICITY: KEY ELEMENTS OF LONG-TERM STRATEGY FOR CARBON NEUTRALITY

- Electricity emissions need to peak and start to decline immediately; they should be zero or negative by 2050.
- Rapid electrification needs to occur in all end-use sectors; depending on the evolution of lifestyles, efficiency improvements, and technology options, electricity generation may grow by 120-160% from current levels by 2050.
- Conventional coal-fired power plants without CCUS need to be nearly phased out by 2040 or 2045.
- Renewable power generation needs to increase significantly and will become the dominant source of electricity, contributing around 70% of generation by 2050.
- CCUS and nuclear need to be retained as options to provide low-carbon electricity, with actual contributions depending largely on the degree of policy support.
- The flexibility of the power grid needs to be significantly improved through flexible generation, improved grid infrastructure, demand side response, and deployment of storage technologies to integrate high shares of variable renewable energy.

Electricity emissions need to peak and start to decline immediately; they should be zero or negative by 2050 to limit warming to 1.5°C. Rapid and deep decarbonization of the electricity sector has consistently been identified by research studies as a key strategy for limiting warming to 1.5°C. In the scenarios synthesized here, the electricity sector will need to be largely decarbonized by 2050 to limit warming to below 1.5°C; whereas in 2°C consistent pathways, electricity sector CO_2 emissions need to be reduced by around 80-100% in 2050 (Figure 4-2).

FIGURE 4-2. ELECTRICITY SECTOR CO_2 EMISSIONS IN 1.5°C AND 2°C SCENARIOS.



Rapid electrification needs to occur in all end-use sectors. Electricity sector decarbonization will be accompanied by increasing demand for electricity driven by income growth, digitalization, and increasing use of electricity in industry, buildings, and transportation (see Box 4-3 and later chapters). Depending on the evolution of lifestyles, efficiency improvements, and technology options, electricity demand may vary to a great extent by 2050. In the scenarios synthesized here, electricity generation grows by 120-160% from current levels by 2050, reaching 15,000-18,000 TWh (Figure 4-4A).

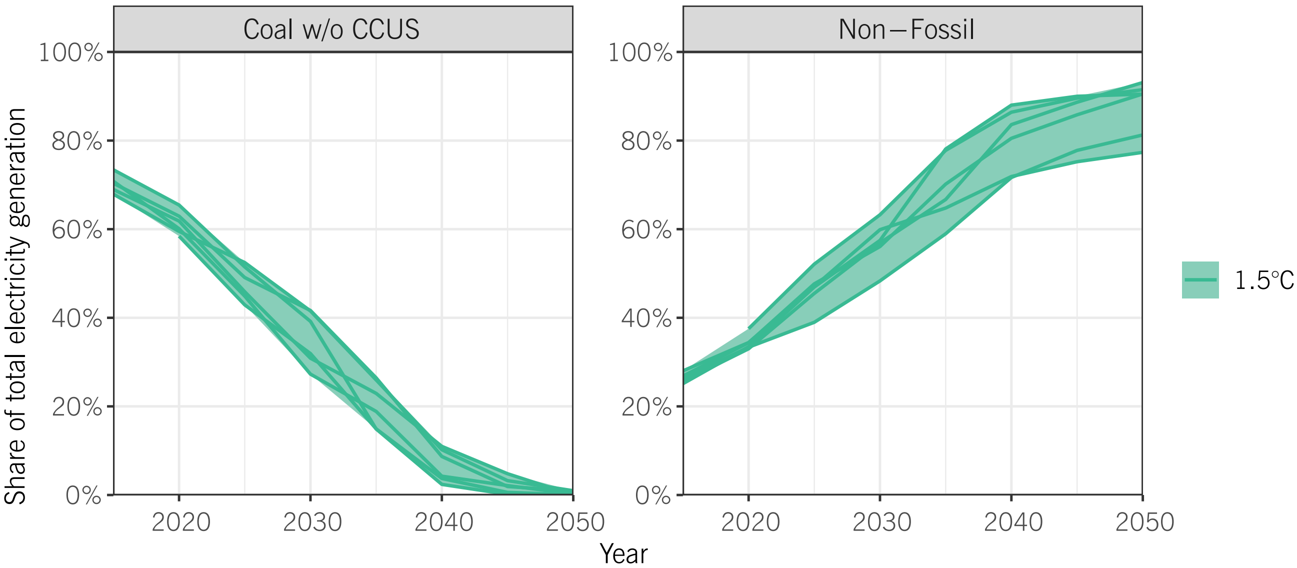
BOX 4-3. THE IMPORTANCE OF ELECTRIFICATION IN LONG-TERM STRATEGY

Across research on deep decarbonization, electrification combined with decarbonization of the electricity sector has been identified as a key element of long-term strategy. Limiting warming to 1.5°C or 2.0°C implies that electricity may become the dominant fuel in final energy consumption by 2050. Taking advantage of the most viable opportunities, the share of electricity in total final energy in China could increase from 22% in 2015 to 35-45% (1.5°C) and 35-40% (2°C) in 2035 and 55-65% (1.5°C) and 45-55% (2°C) in 2050. Electrification will be driven by increasing energy services and shifting from fossil energy to electricity in all end-use sectors. In the industrial sector, industry processes that require low temperature heat can be electrified without fundamental changes to the system. In the buildings sector, increasing digitization and switching from fossil fuels-based to electric equipment will lead to gradual transitions. A transition to electric vehicles is a key strategy for the transportation sector, particularly in passenger road and rail transportation. Taking advantage of these opportunities, there could be around 50 million electric vehicles in China in 2030, providing a storage capacity of 3 billion kWh and a flexible load of nearly 500 million kW. Total electricity demand might reach 15,000-18,000 TWh (1.5°C) and 12,000-16,000 (2°C) by 2050, depending on lifestyle and technology choices (Figure 4-4A).

Rapid decarbonization and electrification have several implications for long-term electricity sector strategies. First, **coal-fired power plants without CCUS need to be phased out before 2050 to limit warming to 1.5°C.** In the scenarios synthesized here, conventional coal-fired power generation not equipped with CCUS needs to be phased out by 2040-2045 to reach the 1.5°C goal and 2050-2055 for the 2.0°C goal (Figure 4-3). This phaseout can be achieved by halting construction of new coal-fired power plants without CCUS; rapidly retiring a small portion of old, dirty, inefficient plants; gradually reducing utilization of the majority of remaining plants; and implementing CCUS technology on viable existing and all new plants. Both the "no new coal" strategy and the rapid shutdown of "low-hanging fruit" plants are near-term actions that can deliver immediate economic and social benefits (see Box 3-2 in Chapter 3).

FIGURE 4-3. SHARE OF CONVENTIONAL COAL GENERATION (PANEL A) AND NON-FOSSIL GENERATION (PANEL B) IN CHINA'S POWER GENERATION IN 1.5°C SCENARIOS FROM SELECTED SCENARIOS.

Note that Conventional coal only includes coal without CCUS. Non-fossil energy includes solar, wind, geothermal, hydro, nuclear, and biomass.



In the long run, to phase out China's large and relatively young coal fleets, a viable path is needed to allow the majority of existing plants to operate over a minimum guaranteed lifetime but with gradually reduced utilization. This would reduce early retirements and, in doing so, reduce the risks of stranded assets. With decreased utilization, coal plants will transition from base load to peaking generation. Cui et al. (2020) finds that using this strategy, for 1.5°C pathways, the minimum guaranteed lifetime would need to be shortened to 20 years, and average utilization would need to be reduced from today's 4,350 hours to 2,640 hours in 2030, 1,680 hours in 2040, and zero hours 2045. For 2.0°C pathways, the majority of existing coal plants can operate over a minimum of 30 years, while the average operating hours would need to be reduced to 3,750 hours in 2030, 2,500 hours in 2040, and below 1,000 hours in 2050.

The phaseout of conventional coal power generation will happen at different speeds in different provinces. Several provinces have specific near-term opportunities. Taking into account multiple technical, economic and environmental criteria, coal retirement can be implemented more rapidly in Shandong, Shanxi, and Inner Mongolia due to less favorable attributes of their coal plants (see Box 3-2).

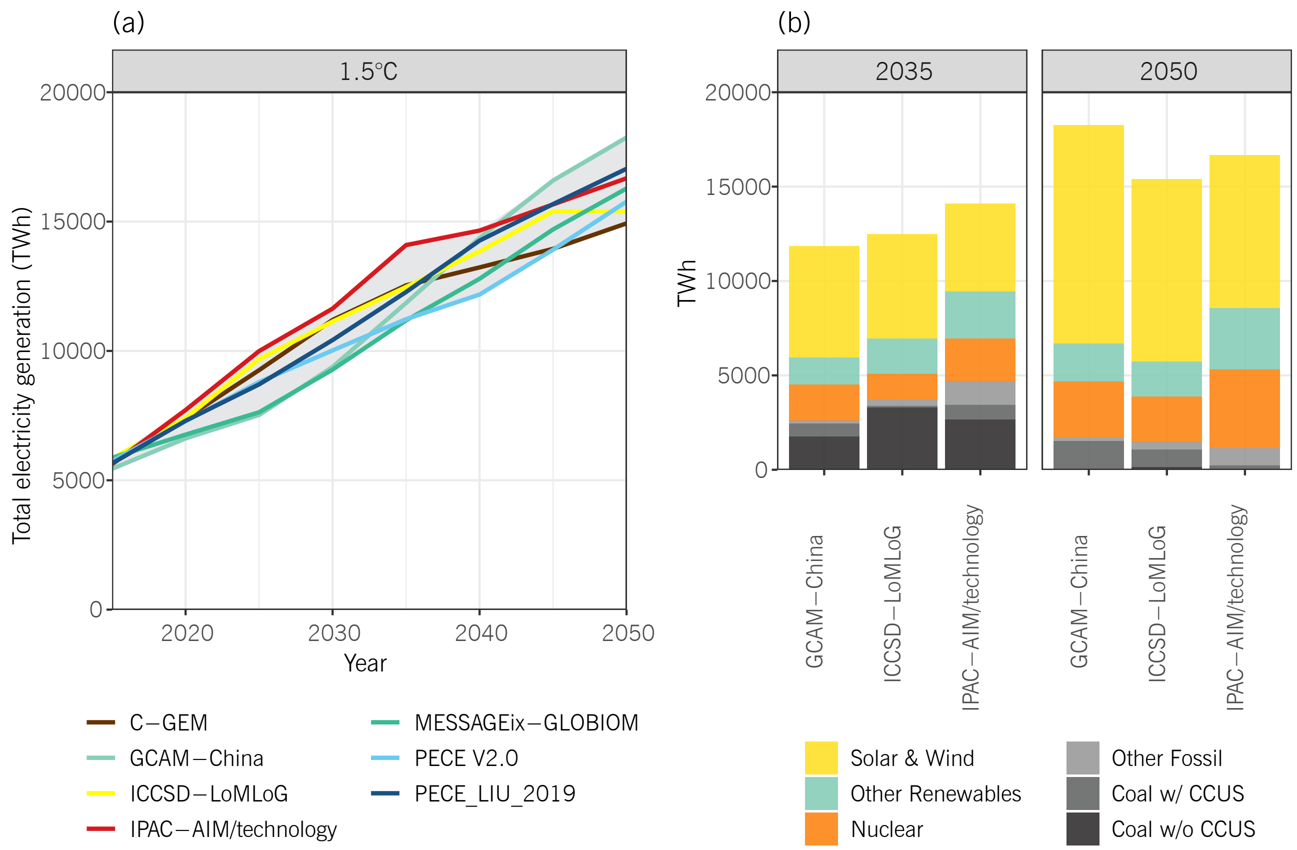
As coal is being phased out, new investments will be needed in no-emissions generation technologies, with the non-fossil share reaching 80% or more of generation (Figure 4-3B). There are multiple zero-emissions options, including wind power, solar power, nuclear power, fossil power with CCUS, and bioenergy with CCUS. Studies both on China and other countries do not provide a consensus on which approach might be best (Figure 4-4B), because of different perspectives on future costs and the viability of technologies, such as nuclear and fossil or bioenergy with CCUS, as well as perspectives about the ability to integrate high shares of wind and solar into the electric grid.

Nonetheless, studies do generally agree that **renewable power generation needs to increase significantly and will become the dominant source of electricity, contributing around 70% of electricity by 2050.** In the 1.5°C scenarios synthesized here, renewable generation contributes 65% to 75% of generation by 2050. In addition to climate and other environmental benefits, renewable energy uses domestic resources and therefore provides important energy security benefits. Solar and wind generation in total in 2035 reach 4,000-5,900 TWh/year in the 1.5°C scenarios synthesized here, and they reach 2,500-4,200 TWh/year in the 2°C scenarios. In terms of geographical distribution, He et al. (2020a) estimated that solar generation would be concentrated in northwestern provinces—Inner Mongolia, Qinghai, and Shaanxi—with more than 100 GW installed capacity in each by 2030, while wind capacities would be more evenly distributed, spreading across northwestern, northeastern, and coastal regions. By 2050, solar and wind generation provide 45-65% of total electricity generation in the 1.5°C scenarios synthesized here, and they provide 30-60% of electricity generation in 2°C scenarios.

CCUS and nuclear need to be retained as options to provide low-carbon electricity, with actual contributions depending largely on the degree of policy support. Both nuclear power and fossil energy with CCUS can prove valuable complements to variable renewable power. The role of nuclear power will depend on factors such as infrastructure development, policy and public support, and institutional barriers to nuclear deployment (Yu et al., 2020a). In the 1.5°C scenarios synthesized here, nuclear electricity generation in 2050 ranges from less than 2,000 TWh to over 4,000 TWh, and the fraction of nuclear electricity in total electricity generation in 2050 varies between 10% and 25% (Figure 4-4B).

FIGURE 4-4. TOTAL ELECTRICITY GENERATION (PANEL A) AND FRACTION OF DIFFERENT TECHNOLOGIES IN TOTAL ELECTRICITY GENERATION IN 1.5°C SCENARIOS (PANEL B).

Electricity generation by technology includes results from a subset of models that demonstrate how different generation technologies can be used to achieve high growth in electricity generation in 1.5°C consistent scenarios.

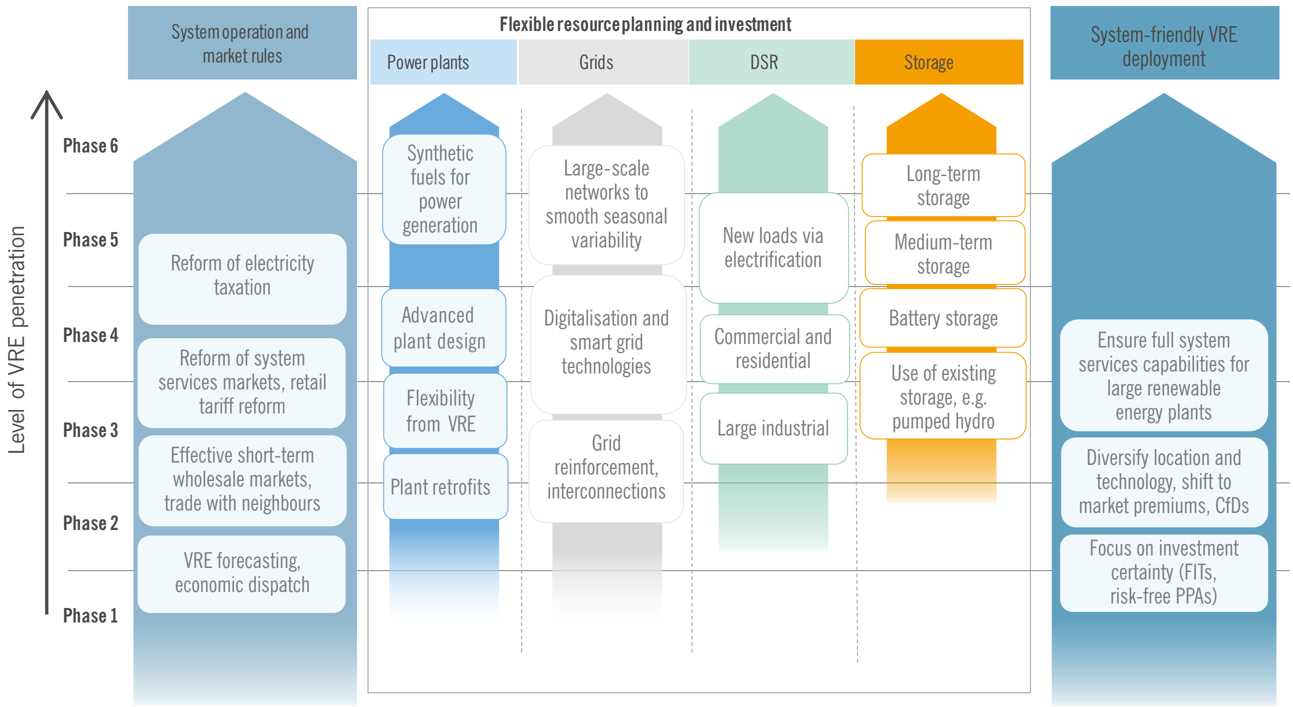


CCUS is widely recognized as an important option for decarbonizing China's electricity system because of China's potentially large CO_2 storage capability and its reliance on fossil generation (Yu et al., 2019). The availability of CCUS technologies carries important implications for energy transitions, particularly for the continued use of fossil fuels and slowing down coal retirements by at least a decade, which could alleviate stranded assets and a sudden transition of coal jobs.

The flexibility of the power grid needs to be significantly improved through flexible generation, improved grid infrastructure, demand side response, and deployment of storage technologies to integrate high shares of variable renewable energy. Although the power system always had some ability to accommodate changes in supply and demand, power system flexibility is a much broader concept (Figure 4-5). It includes changes in grid infrastructure, demand-side response, electricity storage, and flexible operation of power plants. A well-functioning electricity market is also essential to managing contingencies and supporting grid flexibility.

FIGURE 4-5. SOURCES OF POWER SYSTEM FLEXIBILITY.

(Source: IEA, 2019a)



Notes: CfD = contract for difference; DSR = demand-side response; FIT = feed-in tariff; PPA = power purchase agreement.

Different levels of renewable integration require an evolving approach to improving power system flexibility. IEA has developed a phase categorization to capture changing impacts on the power system and resulting integration issues. At the national level, China is currently in Phase 2, while some provinces, such as Xinjiang, Ningxia, Gansu, and Qinghai are considered to be in Phase 3 (IEA, 2019a).

BOX 4-4. THE IMPORTANCE OF AN EFFECTIVE ELECTRICITY MARKET IN ACHIEVING GRID FLEXIBILITY

Reforming the electricity market and setting correct price signals are crucial for flexibility. An efficient market setup will significantly lower costs and optimize system efficiency, provide economic incentives for flexible demand and storage options, and ensure efficient integration of seasonable hydro and variable renewable energy. A recent IEA study has shown that implementing market-based dispatch and expanding regional transmission interconnectivity in China could reduce annual operational costs by 15% or $63 billion and decrease power sector CO_2 emissions up to 750 Mt in 2035 (IEA, 2019a).

Quick ramping electricity generation can add flexibility to the grid. Coal-fired power plants, when retrofitted, can provide flexible output. Hydroelectric plants and combined-cycle natural gas plants can also provide a significant degree of flexibility, but their roles might be limited. Meanwhile, encouraging power plants to operate as balancing load rather than baseload would require carefully designed transition mechanisms, as these power plants would face higher costs and lower revenues.

Improved transmission and distribution infrastructure can also increase grid flexibility. Increasing regional interconnectivity, such as building ultra-high-voltage transmission lines, allows electricity to be transported within a larger balancing area, not only providing better balance variability but also allowing for more efficient generation. Creating a networked distribution grid also increases the value of distributed renewable energy (Aggarwal and Orvis, 2016). Studies estimated that the interregional transmission capacity could be expanded to around 300 GW by 2030 and 500 GW by 2050 (Li et al., 2016; SGERI, 2018), and this might be further increased with higher variable renewable energy in 1.5°C and 2°C consistent pathways. Moreover, several studies noted that transmission lines connecting Northwest and Central grid regions and lines connecting Northwest and East grid regions have the highest transmission capacities, and the Northwest region emerges as a national supplier of low-carbon electricity (Li et al., 2016; SGERI, 2018; He et al., 2020a).

Digitalization opens up new options to balance electricity supply and demand, and demand response becomes a powerful approach for increasing grid flexibility. The availability of real-time monitoring systems with bidirectional communication across grids, loads, and generation is critical and could be enabled by improved digitalization and connectivity in end-use sectors. For example, dynamic electric vehicle charging adapts the charging cycle to both the conditions of the power system and the needs of users and optimizes the charging process according to distribution grid constraints, availability of local energy resources, and users' preferences (IRENA, 2019a). Smart thermostats, appliances, and controls in buildings are also useful demand response tools. An important element of demand response is an effective market design, which allows demand response to participate in all wholesale markets (see the discussion on electricity market reform below).

Energy storage can also provide flexibility on the grid. Grid-scale batteries can support short-term contingencies, while pumped hydro and compressed air systems provide long-term storage options. Use of synthetic fuels and hydrogen is also a viable option for seasonal storage when there are high shares of variable renewable energy in electricity generation.

The power system transition and grid flexibility require coordination not only within the power system, but also across different systems. With high shares of renewables, there is an increasing need to improve coordination between generation, transmission, and distribution planning processes. Increased grid flexibility also encourages broader energy system integration and opens synergies with developments in the end-use sectors (e.g. the deployment of electric vehicles and smart building technologies).

BOX 4-5. DECARBONIZING POWER, ENERGY SECURITY, EMPLOYMENT, AND ECONOMIC GROWTH

The benefits of decarbonizing the power sector extend well beyond climate mitigation. Growth in low-cost solar and wind energy resources, along with electrification of the energy system, will increase energy independence, reduce long-term exposure to fuel price volatility, and improve access and affordability to electricity. Moreover, renewable energy generation is more resilient to changes in market conditions. Coal power generation was hit most significantly during the COVID-19 crisis in almost all world regions (IEA, 2020b; EIA, 2020). In China, while the total power generation in the first quarter of 2020 dropped 6.8% from a year earlier, thermal power generation dropped by 8.2% (Xu and Singh, 2020).

New employment opportunities from a decarbonizing power sector can boost local economies. These clean-energy jobs are higher quality compared to coal jobs and often in less developed areas and rural communities, creating new opportunities for underserved communities (Muro et al., 2019).

At the same time, it is also true that decarbonization of the power system will significantly reduce coal-related jobs in China. Coal mining and washing accounted for around 3.2 million jobs in 2018 and some regions with high concentrations of coal-related jobs, such as Shanxi Province, will be disproportionately affected (He et al., 2020b). Measures have been taken by other countries, including setting a transition timeline to help local industries plan early, establishing just transition funds to finance the transition, creating employee transfer programs with on-the-job retraining, enhancing local infrastructure investment, and developing social programs that provide assistance with education and relocation (Bridle et al., 2017; Sartor, 2018).

The transition from coal generation to renewable generation could also lend impetus to China's economic growth. China is a global leader in manufacturing, as well as in innovation and deployment of renewable energy technologies, placing it at the forefront of the global energy transition. It accounted for around 30% ($83.4 billion) of the global renewable energy investment in 2019 (UNEP and BNEF, 2020). China is also leading in renewable energy patents, with 29% of the global total in 2016, followed by the U.S., EU, and Japan (IRENA, 2019b). Low-carbon transition in the power sector could help maintain China's global leadership in clean energy.

Near-Term Challenges, Opportunities, and Actions

BOX 4-6. ELECTRICITY: NEAR-TERM ACTIONS TO SUPPORT A LONG-TERM TRANSITION

- Stop new construction of coal-fired power plants without CCUS.
- Identify and quickly close a small fraction of the existing coal plants that are old, dirty and inefficient.
- Continue to increase the share of non-fossil generation (around 45% by 2025).
- Establish electricity spot markets.
- Increase interprovincial trade on green electricity through power market reform.
- Enhance CCUS policies to promote CCUS-ready in new fossil fuel plants and/or CCUS retrofit in existing facilities

Stop new construction of coal-fired power plants without CCUS. The coal power industry has been financially troubled in recent years. Due to overcapacity and competition from renewables, coal plants in China on average were running at 4,290 hours (below 50% of their full capacity) in 2019 (CEC, 2020), and over half are operating at a loss (Bodnar et al., 2020). At the same time, the current project pipeline includes about 100 GW of new projects under construction and another 50 GW permitted (Global Energy Monitor, 2020), indicating that China's total installed coal capacity is likely to continue to grow during the 14th Five-Year Plan.

Continued coal builds will only exacerbate the financial strain within the industry. New builds will further lower the utilization of all coal plants and undermine their financial viability. Moreover, continuing to install new coal-fired power plants while simultaneously attempting to meet the long-term carbon neutrality goal will result in premature retirement of these newly added plants, accelerate the phaseout of existing plants, lock in energy infrastructure, and substantially increase stranded assets and the costs of achieving the long-term carbon neutrality goal. Taking immediate actions to stop new construction of coal plants is an effective and beneficial near-term approach that should be considered during the 14th Five-Year Plan.

Identify and quickly close a small fraction of the existing coal plants that are old, dirty and inefficient. A total of 38 GW of small, old, inefficient plants were shut down during 2015-2018 (CEC, 2016, 2017, 2018, 2019) to combat local air pollution and address overcapacity. Specific targets and action plans are being made across individual provinces to continue retiring obsolete plants through the end of 2020. Such a process should continue in the 14th Five-Year Plan to identify low-hanging fruit plants based on technical, economic and environmental criteria and develop retirement targets and plans. Rapidly shutting down these small, old, dirty, and inefficient plants is not only an essential part of a well-structured coal transition plan, it has the potential to deliver co-benefits on air quality, public health, and other societal objectives in the near-term.

Continue to increase the share of non-fossil generation. With no new coal plant construction and a rapid shutdown of inefficient coal plants, the share of non-fossil fuels in electricity generation needs to rapidly increase in the near term. About 33% of total electricity currently comes from non-fossil energy sources. In the 1.5°C scenarios synthesized here, this share increases to 40-50% by 2025, to 50-60% by 2030, and to 60%-80% by 2035 (Figure 4-3B).

The integration of non-fossil generation will require efforts to improve the integration of renewables into the grid. In particular, market-based dispatch and inter-provincial transmission can help prioritize low-cost renewable electricity generation, increase clean energy supply from renewable rich regions, and incentivize investments in renewable capacity. Instead of building new fossil (gas or coal) plants for quick ramping generation, retrofitting existing coal plants with improved flexibility can potentially help support renewable integration in the near term. A total of 220 GW coal plants were planned to be retrofitted with improved flexibility during the 13th Five-Year Plan; however, only a quarter of the target has been reached by 2020 (Yuan et al., 2020).

Establish electricity spot markets. Creating an effective electricity market is critical to high penetration of variable renewable energy and grid flexibility. Establishing electricity spot markets is one of the major components needed to improve market rules and system operation. International experience has shown that a well-functioning, short-term electricity market is essential to drive power system transformation (IEA, 2019a). It reveals real electricity prices at different times and locations, which can inform long-term electricity pricing, guide investment in new generation capacity, and help with the establishment of financial markets for electricity. A liquid spot market with well-designed rules also allows for market entry of new actors, such as storage and demand aggregators, which are critical to demand side response and grid flexibility.

China is trying to move from an equal allocation dispatch system to a market-based dispatch system. Currently, there are eight provincial-level electricity spot market pilots underway, which can help regulators understand the impact of different market designs responding to different regional challenges and resources mix. The design of spot markets needs to address several challenges, including potential resistance from generators, local governments, and other stakeholders, appropriate rules to reward right behaviors and penalize noncompliance, and revenue changes of existing generators.

Increase interprovincial trade on green electricity through power market reform. Combining well-designed spot markets with better utilization of interconnections and improved grid investment can significantly improve power system efficiency and flexibility and allow for high shares of variable renewable energy from wind and solar power. Although China currently has inter-regional mid- and long-term trading, this practice is not fully adopted. Significant efforts are needed to harmonize various markets, improve market coordination, and encourage broad participation by both state-owned and private generators (IEA, 2019a).

Enhance CCUS policies to promote CCUS-ready in new fossil fuel plants and/or CCUS retrofit in existing facilities. Although there are uncertainties around wide deployment of CCUS, CCUS remains an important option for net zero emission systems. Given China's coal-based energy system, CCUS retrofits could help lower the risks of stranded assets by reducing premature retirements of existing fossil plants. When combined with bioenergy, CCUS can generate negative emissions, offsetting emissions that are difficult to mitigate, such as from air travel or high-temperature heat. Although a broad range of issues and challenges surround the use of bioenergy with CCUS, many of which are associated with the production of bioenergy crops, it is important to maintain multiple options for decarbonizing electricity and potentially creating net-negative emissions. Despite the potential for CCUS in the Chinese power sector, investments in CCUS are unlikely to happen without explicit policy support. R&D and pilot projects are needed to move forward on pilot projects to advance the technology and create the option to apply CCUS more broadly. In addition, near-term CCUS policies can focus on promoting CCUS-ready in all new fossil fuel plants and identifying the appropriate features for existing plants' CCUS retrofit.

The electricity sector transition will require coordinated efforts across the entire value chain of electricity production and consumption. It will improve coordination between electricity sector policies and policies for buildings, transportation, and industry. Rapid electrification in end-use sectors not only drives electricity demand, it also provides opportunities for better demand side response and a more flexible power system.

4.2 BUILDINGS SECTOR TRANSITIONS

Current Status and Trends

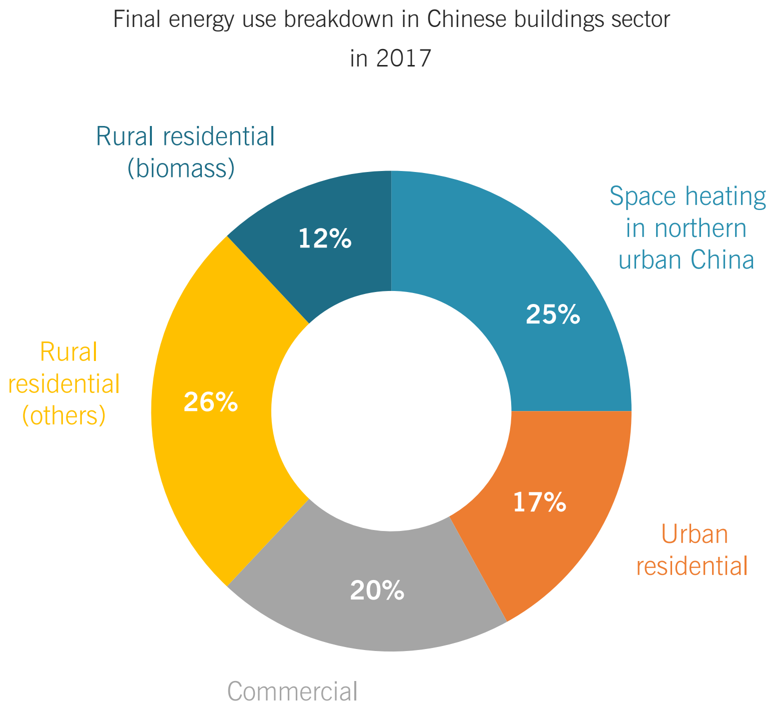
Energy use in buildings includes both operational energy use—the energy used to operate the building—as well as embodied energy—the energy consumed for manufacturing building materials such as cement and steel. Building operational energy consumption—final energy consumption—has been growing rapidly in the past decade. Final energy use in Chinese buildings grew 2.3% annually between 2005 and 2018. Total final energy use was 630 Mtce in 2018, larger than the total energy consumption of all end-use sectors in Japan and the UK combined in that year (IEA, 2020d). Embodied energy use in buildings is about half as large as operational energy use in terms of primary energy, using the substitution accounting method (THUBERC, 2019).

Urban residential, rural residential, commercial, and space heating in northern urban China respectively account for 17%, 38%, 20% and 25% of the total operational energy of all buildings in China in 2017 (Figure 4-6). Electrification is about 47% for urban residentials, 59% for commercials, 9.7% for rural residentials, and 3.3% for space heating in northern urban China respectively. Self-collected biomass constitutes 30% of energy use in rural buildings. District space heating dominates space heating in northern urban China, providing heat for 85% of total floor space in this region—that is about 15 billion m^2—in 2018. The current heat source mix in this region is about 50% by coal combined-heat-power (CHP) plants, 3% by gas CHP plants, 35% by coal heat plants, and 12% by gas heat plants (in terms of heated floor space) (THUBERC, 2019). Around one-third of district space heating in China is based on coal heat plants.

From 2008-2017, energy intensity (operational only) increased 28% (from 214 to 273 MJ/m^2) for urban buildings excluding district space heating, 5.0% (from 346 to 363 MJ/m^2) for rural buildings, and 20% (from 586 to 703 MJ/m^2) for commercial buildings excluding district space heating. The only application in which energy intensity decreased was space heating in northern urban China, where energy intensity decreased 17% (from about 527 to 440 MJ/m^2). This decrease of energy intensity was primarily due to better building envelopes and the deployment of more efficient district heating plants in the past years (THUBERC, 2019).

FIGURE 4-6. FINAL ("OPERATIONAL") ENERGY USE IN THE BUILDINGS SECTOR.

Final energy use for urban residential and commercial buildings excludes the energy use for space heating in northern urban China. (Source: THUBERC, 2019)



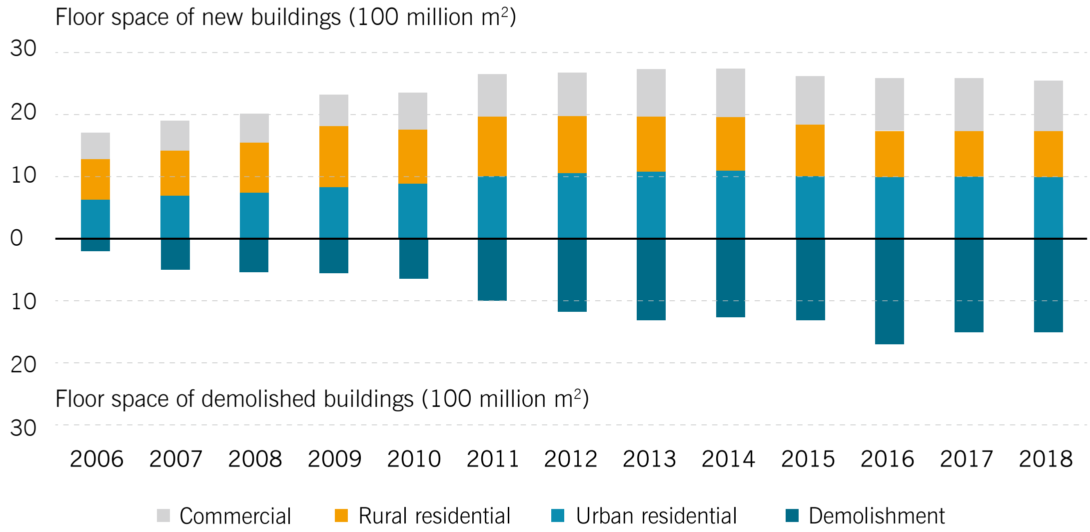
Energy consumption in China's building sector has been driven by continued urbanization, economic growth, increasing digitalization, and a transition towards a service-based economy. Income growth and a rising middle class resulting from robust economic growth have led to improved standards of living and increased service demands in buildings. Increasing digitalization is also reshaping energy use in buildings. People are staying longer at home because of convenient online shopping, and more people are working from home. Online retail sales in China increased by about 16.5% in 2019 (NBS, 2020). Moreover, China's ongoing transition to a service-based economy requires the construction of more complex and large-scale commercial buildings, which has driven the fast growth in energy use in commercial buildings in the past decade.

The total buildings stock in China was 60 billion m^2 in 2018, comprised of 24 billion m^2 of urban residential buildings, 23 billion m^2 of rural residential buildings, and 13 billion m^2 of commercial buildings (THUBERC, 2020). Urbanization is a continuing dynamic in China that will have important implications for building sector decarbonization strategies. According to the UNDESA (2019), China is expected to experience rapid urbanization, from 61% of the population currently to 80% in 2050. Continued urbanization will close the gap in service demands between rural and urban households and potentially lead to higher energy consumption in buildings. Currently, there is a significant ownership gap in certain energy intensive household appliances between urban and rural China. For example, the number of air-conditioning units and water heaters per 100 households are 53 and 63 in rural areas, respectively, while they are 129 and 91 units in urban areas (NBS, 2019).

There are two significant features relating to China's building stock dynamics during the past several years (Figure 4-7). First, the Chinese building stock has grown dramatically in recent years. The construction boom has led to around 2.5 billion m^2 of new floorspace per year, on average, since 2011, resulting in a 17% increase in the total stock. This is equivalent to constructing Japan's total building floorspace every three to four years (Yashiro, 2009). The construction boom has roots in the Chinese government's long-held preference for viewing real estate development as one of the main drivers of economic growth. Second, in addition to construction, China continues to demolish a substantial fraction of the existing building stock every year. China demolished around 1.5 billion m^2 in 2018, or 2.5% of the total stock at that time. As a result, the average lifetime of Chinese buildings is only about 25-30 years, much less than that in most developed countries (usually more than 50 years).

FIGURE 4-7. BUILDING STOCK DYNAMICS FROM 2006-2018.

(Source: THUBERC, 2020)



Even with the dramatic growth in China's building stock, China's per capita floor space significantly lags behind that of developed countries. In 2017, the average per capita floor space in China was around 34 m^2 for residential buildings (about 31 m^2 in urban and 38 m^2 in rural), and 9 m^2 for commercial buildings (Wang, 2018). China's residential floorspace was about 85% of that in Japan and about 60% of that in the United States; China's commercial floorspace was about 65% of that in Japan and about 35% of that in the United States. Were China to maintain its current pace of construction and demolition—about 1.1 m^2/capita of floorspace growth annually on balance, two-thirds in residential buildings and the remainder in commercial buildings—it is estimated that China's per capita floor space would reach Japan's current level by 2035 and the current U.S. level by 2055 or 2060.

BOX 4-7. BUILDINGS: KEY ELEMENTS OF A LONG-TERM STRATEGY FOR CARBON NEUTRALITY

- Emissions need to peak immediately and should be reduced by about 90% in 2050 relative to 2015.
- Around 75% of buildings energy use should be supplied by electricity by 2050.
- Most district heating systems in northern urban China need to be decarbonized by 2050.
- Reduce embodied energy in buildings by extending building lifetimes through retrofits and/or using higher-quality building materials.
- Control the overall scale of building stock while continuing to improve living standards.

Emissions need to peak immediately and should be reduced by about 90% by 2050 relative to 2015. In most of the scenarios synthesized here that limit warming to 1.5°C, direct emissions of CO_2 from the Chinese buildings peak immediately and decline. For these scenarios, emissions decline 50%-95% by 2050 relative to 2015 levels (Figure 4-8). Associated with these emissions reductions, China will need to constrain its energy demand growth. In most of the 1.5°C scenarios synthesized here, building final energy consumption in 2050 is either near today's levels or well above today's levels. This range of future outcomes represents different perspectives on the countervailing forces of improved efficiency, on the one hand, and, on the other hand, increased urbanization and demands for building energy services in an increasingly affluent society (Figure 4-9).

FIGURE 4-8. BUILDINGS SECTOR DIRECT CO_2 EMISSIONS IN 1.5°C AND 2°C SCENARIOS.

This chart does not include scenarios that do not reach 50% CO_2 reductions by 2050 in 1.5°C. CBEM was excluded from this chart due to different accounting on CO_2 emissions. There is no 1.5°C scenario from the POLES-JRC model.

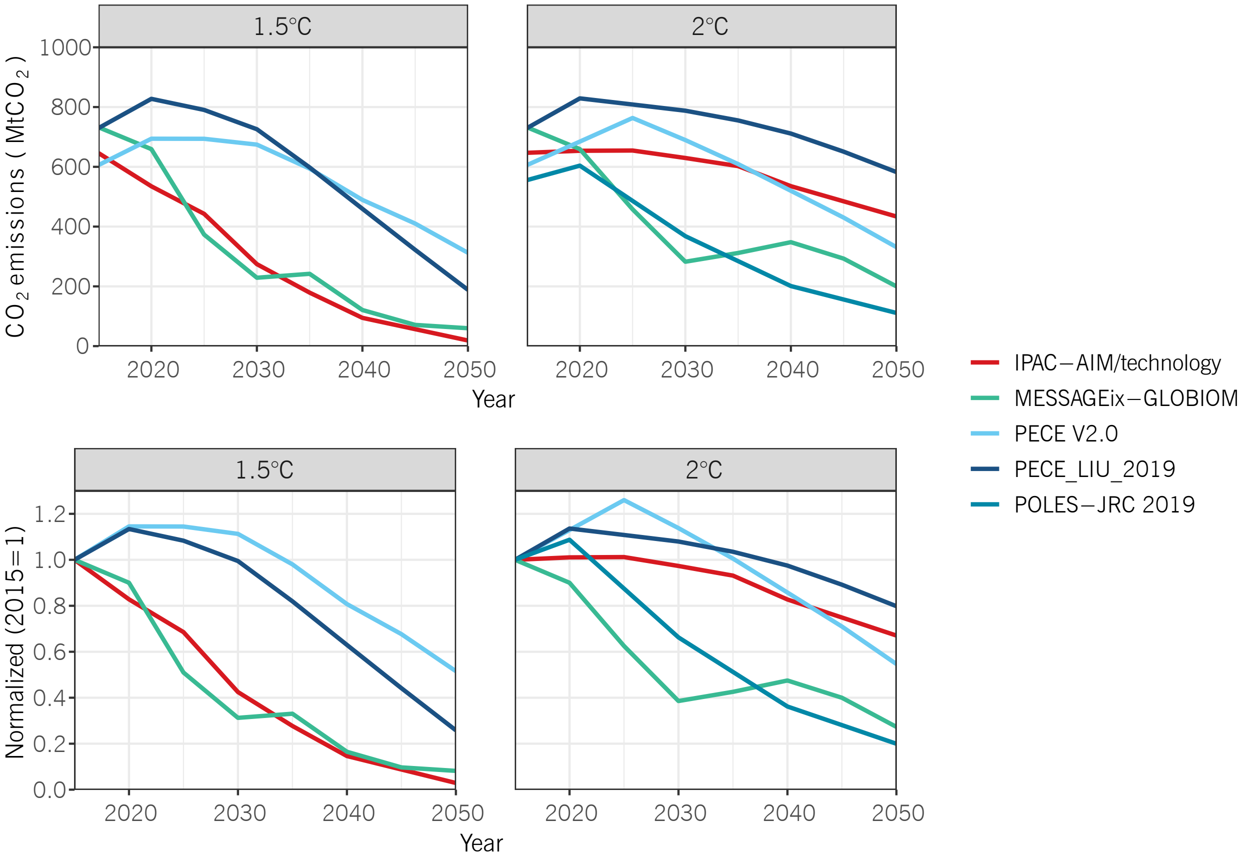


FIGURE 4-9. FINAL ENERGY USE IN CHINESE BUILDINGS IN 1.5°C SCENARIOS.

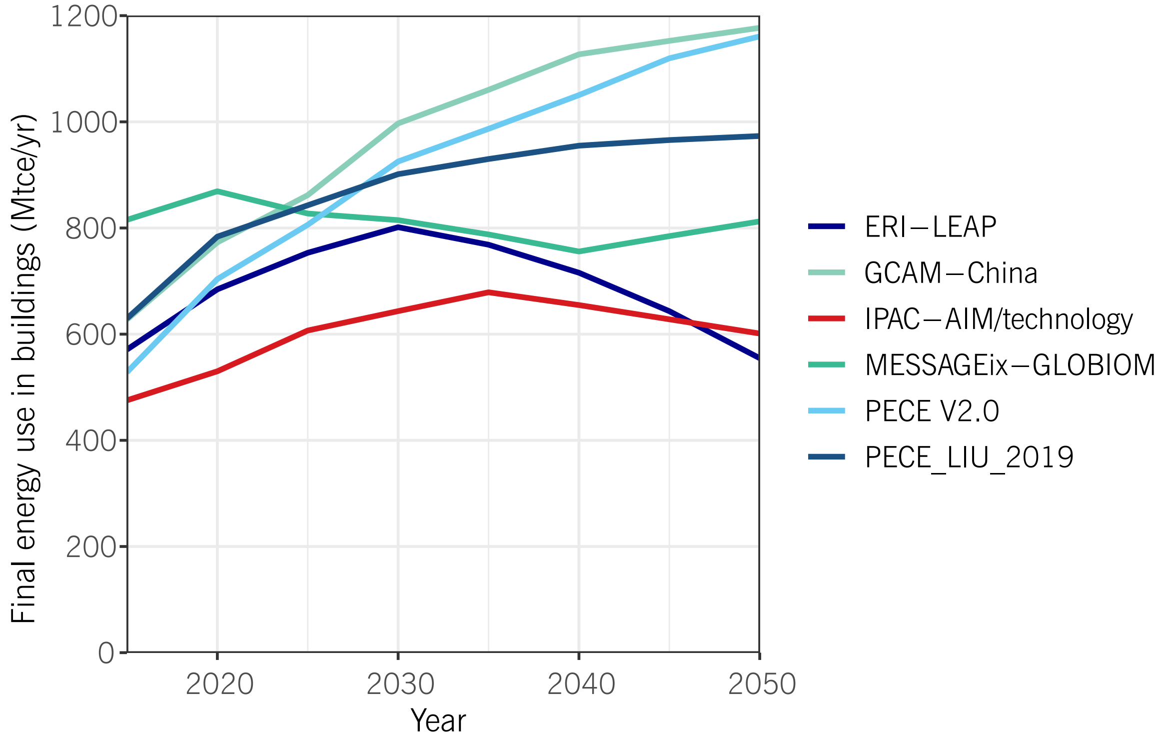
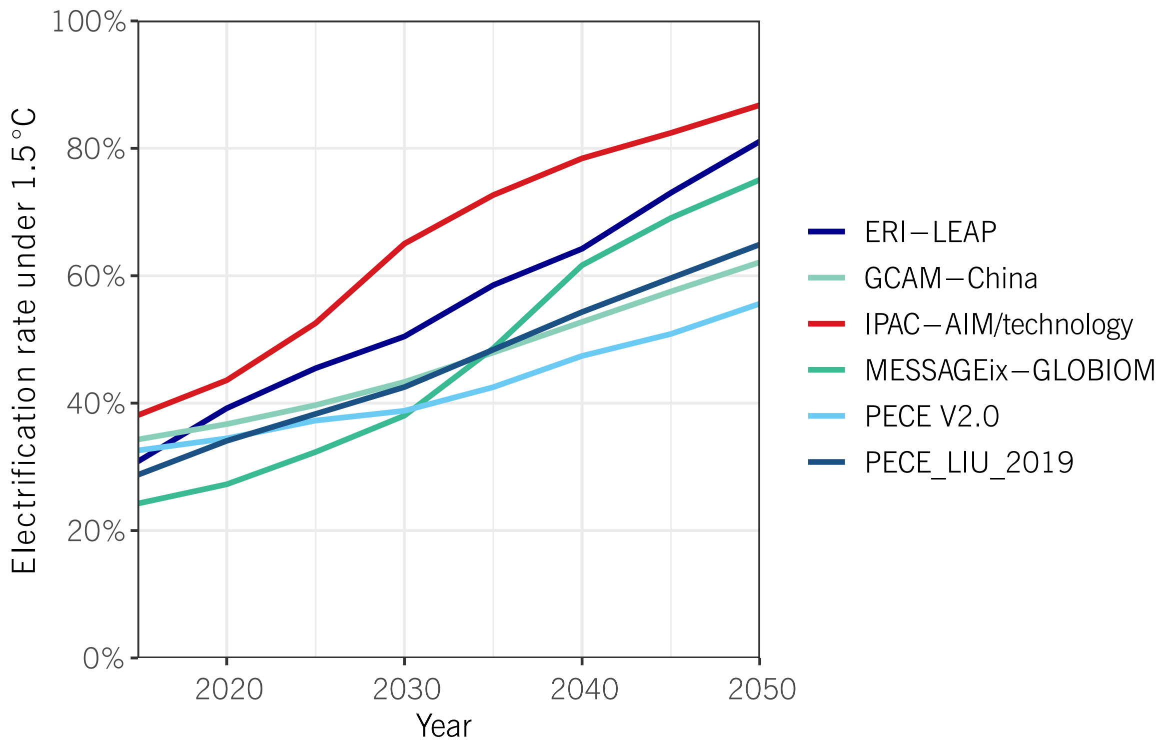


FIGURE 4-10. BUILDINGS SECTOR'S ELECTRIFICATION IN 1.5°C SCENARIOS.



Around 75% of buildings energy use should be supplied by electricity by 2050. The 1.5°C scenarios synthesized here articulate two levels of electrification. At the high end, scenarios include 75-85% electricity in final energy; at the low end, scenarios include 55-65% electricity in final energy (Figure 4-10). The main difference between these two perspectives lies in the projected amount of use of heat and gas in the future. The "low electrification" scenarios suggest that heat and gas will account for about 30% of the final energy use in the buildings sector; the "high electrification" scenarios suggest heat and gas will account for only around 15%. Achieving higher electrification implies using electricity for space heating, cooking and water heating in buildings. In the "high electricity" scenarios, electricity use in Chinese buildings increases from 1,450 TWh in 2015 to about 3,650-5,000 TWh in 2050 in 1.5°C scenarios, implying an annual increase of 2.7% to 3.6%.

Most district heating systems in northern urban China need to be decarbonized by 2050. District space heating can be viewed as involving four components: the source of the heat, the pipeline network, the heating system within buildings using the heat, and the envelope of buildings and their thermal characteristics. Opportunities for saving energy from the latter three have been well-studied. They include, for example, improved insulation of pipelines, appropriately sizing water pumps, improved system operation and adjustment to avoid an uneven distribution of heat across the system (leading to overheating in some parts of the system), and higher energy performance of building envelopes. Long-term strategy needs to focus on decarbonizing heat sources for district heating in northern urban China. There are two main options to decarbonize heat sources in district heating: using electric heat pumps for space heating, which would also increase electrification of the building sector, and adopting waste heat from industrial factories and coal or nuclear power plants in regions where this opportunity is available. Of the two options, adopting waste heat is more economical and should be given a higher priority. China has rich waste heat resources from industrial processing facilities and from thermal power plants. In 2018, the total floor space with district space heating in urban areas in northern China was about 12 billion m^2, and district space heating consumed about 5 billion GJ of heat. It has been estimated that low-temperature waste heat from industrial facilities, coal power plants, and nuclear power plants in northern China are about 0.8, 7.8 and 2.6 billion GJ/year, respectively. Studies show that the feasible utilization rate of such waste heat may be around 20-40% (THUBERC, 2019). If only 15% of the waste heat could be used, it would provide about 1.7 billion GJ/year, which would reduce space heating energy consumption in northern urban China by about one-third.

Reduce embodied energy in buildings by extending building lifetimes through retrofits and/or using higher-quality building materials. Retrofitting buildings consumes much less energy than constructing new ones. In addition, the use of high-quality building materials (e.g., high-quality cement) can avoid early demolition. The demolition rate in China is currently about 2.5%. In contrast, the U.S. rate is about 0.3% to 0.5% for residential buildings (EIA, 2018). If the annual demolition rate in China could be reduced to 1% (implying reducing 0.9 billion m^2 new buildings per year), overall buildings sector CO_2 emissions (including the indirect CO_2 emissions from embodied energy consumption) could be reduced by about 11%. Decarbonizing building material manufacturing processes (e.g., using more renewable electricity and hydrogen as heat source) will also help to reduce CO_2 emissions related to embodied energy consumption (See Chapter 4.3).

Control the overall scale of building stock while continuing to improve living standards. In addition to extending building lifetimes, controlling the overall scale of China's building stock is essential, in the long run, for decarbonizing the sector's embodied and operational energy use. As noted above, per capita floor space in China may reach the level of developed countries within the next two to three decades (e.g., Japan, Europe, US). Given China's population, an increase in per capita floor space to the U.S. level may significantly impede China's pursuit of sustainable development, particularly in terms of energy consumption and land use. Therefore, planning a reasonable long-term building stock development pathway (i.e., setting up a stock cap) may be essential for China to achieve climate neutrality before 2060. However, controlling the total building stock should not hinder housing affordability for low-income families. Governments need to consider developing social housing for certain affected social groups if the "stock cap" policy is implemented.

Building strategies will need to be coordinated with those of other sectors. Electrification in the buildings sector is supported by decarbonization of the power sector. In order for buildings to function as soft load takers of grid electricity, it will be necessary to integrate smart building-integrated PV (BIVP) systems and electric vehicle charging stations into building energy systems. This requires holistic policy design between the power, transportation, and building sectors. Additionally, changes in building lifetimes and the total building stock, as well as building materials and construction practices, could affect the demands and production processes of industrial products, particularly products such as cement and glass. These linkages emphasize the need for cross-sectoral policies and strategies.

Near-Term Challenges, Opportunities, and Actions

BOX 4-8. BUILDINGS: NEAR-TERM ACTIONS TO SUPPORT A LONG-TERM TRANSITION

- Continue to enhance building design standards for energy efficiency by improving requirements, including electrification, and renewable energy integration.
- Continue to improve Energy Efficiency Standards and Labeling schemes of appliances to incorporate smart-enabling technologies and address system energy savings opportunities.
- Phase out coal use in rural residential buildings by promoting onsite PV and efficient biomass use.
- Encourage the use of passive technologies, such as natural ventilation and lighting, by developing small-sized commercial buildings and reducing the focus on large-size commercial buildings.
- Deploy smart technologies in order to improve demand side response and grid flexibility.

Continue to enhance building design standards for energy efficiency by improving requirements, including electrification, and renewable energy integration. Currently, China has five sets of national building design standards for energy efficiency (also called building energy codes), three for the residential buildings in different climate zones (i.e., JGJ 26, JGJ 75 and JGJ 134), one for rural residential buildings (i.e., GB/T 50824) and one for commercial buildings (i.e., GB 50189). These codes are tightened from time to time to reflect the advance of relevant technologies, particularly on the adoption of better wall insulation, higher energy performance windows and more efficient district space heating systems. In the future, the stringency of these codes needs to be improved, and the coverage of these codes also needs to be broadened to facilitate electrification and renewable integration.

Continue to improve Energy Efficiency Standards and Labeling schemes of appliances to incorporate smart-enabling technologies and address system energy savings opportunities. The existing energy efficiency standards and labeling (EES&L) schemes have covered many key energy use appliances in buildings, including air-conditioner, TVs, washing machines, lamps, chillers, copy machines, fans, printers, water heaters, range hood, and electromagnetic stoves. These regulatory EES&L schemes need to be further improved to address more system energy savings opportunities by incorporating smart-enabling technologies, such as information feedback function of appliances, optimal stand-by modes of appliances, and improved efficiency under non-full load.

Phase out coal use in rural residential buildings by promoting onsite PV and efficient biomass use. The short-term decarbonization strategies for the rural residential buildings in China lie in improving the onsite renewable energy use, such as PV and biomass, and using them in place of coal. The main energy carriers for rural households are coal, biomass, and electricity. Coal and biomass are used for cooking, space heating, and water heating. Rural households in China currently consume about 90 Mtce of self-collected biomass every year (about 30% of the energy use in rural households). In order to decarbonize rural residential energy use, three key measures need to be taken: developing onsite PV on the substantial roof and courtyard floor space in rural China; processing self-collected biomass into compacted shapes or converting them into biogas in order to improve the energy efficiency of biomass use; and replacing on-site coal use by electricity, biogas, or compacted shape biomass. It is estimated that the available floor space in rural China for installing PV is about 15 billion m^2 (THUBERC, 2019). This area could host about 1500 GW of PV and provide at least 2,000 TWh of electricity. In 2017, the final energy use in Chinese rural residential buildings was about 2,400 TWh (including 0.262 billion tce of heat and 229 TWh of electricity). That is to say, the electricity generated from potential onsite PV in rural China could meet about 80% of the energy needs of Chinese rural households.

Encourage the use of passive technologies, such as natural ventilation and lighting, by developing small-sized commercial buildings and reducing the focus on large-size commercial buildings. The high overall energy intensity of China's commercial buildings is due in large part to the proportion of large-size buildings in the commercial building stock. The energy intensity of large-size commercial buildings (e.g., larger than 40 thousand m^2 in terms of floorspace) is typically 30-100% higher than that of small-size ones, due to factors such as the need for more artificial lighting, mechanical ventilation, large pumps, and extensive use of elevators (THUBERC, 2019). Small-size commercial buildings have lower internal heat gains, therefore requiring less space cooling, and they use natural lighting and ventilation more effectively. In this sense, they can provide a healthier built environment. It is therefore important to consider regulatory or economic policies to encourage the development of small-size commercial buildings rather than large-size ones, particularly in the non-first-tier cities.

Deploy smart technologies in order to improve demand side response and grid flexibility Continuing advances in efficient, smart technologies and onsite renewables are changing how electricity is supplied to and used in buildings. Buildings not only act as shock absorbers for the grid, but they also provide new services. Innovative policies are needed to tap these opportunities (see Box 4-9). Accelerating the deployment of technologies such as smart sensors, meters, appliances, and distributed generation will make it easier to balance electricity demand in a seamless, automated fashion. Moreover, to fully realize this potential, market reforms are needed to allow building owners and operators to access the electricity market and obtain economic gains from energy savings and electricity trades.

BOX 4-9. BUILDINGS AS GRID SHOCK ABSORBERS

To further improve the energy efficiency of high-power and low-power appliances/equipment in buildings (e.g., elevators, pumps, fans, air-conditioners, and refrigerators), an emerging trend is to adopt DC motors instead of AC motors, to realize convenient speed control. Other appliances, such as LED lamps, PCs, and displayers, already use DC power. It is feasible and beneficial to adopt DC type micro-grids within buildings by converting grid electricity from AC to DC to supply electricity for buildings. Such a shift could make buildings good shock absorbers when combined with building integrated PV (BIPV) and smart electric vehicle charging stations. Developing BIPV could largely facilitate the onsite use of PV in urban China, where low-rise and high-rise buildings dominate. Additionally, the stock of electric vehicles in China is increasing rapidly, so there is a growing demand for electric vehicle charging stations. The combination of these three "blocks" could allow buildings to act as soft load takers for the electric grid, and even act as additional electricity providers in certain periods. A pilot project is now being implemented in the city of Shenzhen, China.

BOX 4-10. MITIGATING HOUSEHOLD AIR POLLUTION BY REPLACING SOLID FUELS FOR COOKING AND SPACE HEATING IN RURAL CHINA

Solid fuels like coal and raw biomass still account for about 80% of energy use in rural China, mainly for cooking and space heating (THUBERC, 2016). These solid fuels are not burned efficiently due to the use of inefficient space heating appliances and cooking stoves. Consumption of these fuels results in significant indoor air pollution. It has been reported that the household air pollution from space heating has caused about 0.67 million premature deaths and 14.0 million disability-adjusted life years in rural China (Chen et al., 2018a). Replacing solid fuels with electricity (e.g., onsite PV or wind turbines) and gas (e.g., biogas) for cooking and space heating in Chinese rural residential buildings, particularly in provinces in western, central and northeastern China, could not only help reduce CO_2 emissions, but also reduce the significant negative health effects on occupants, mostly the elderly, women, and children.

BOX 4-11. REDUCING NON-CO_2 EMISSIONS FROM BUILDINGS THROUGH LOW-GWP REFRIGERANTS

China's GHG emissions from the HFCs are expected to increase substantially, driven by increasing demands for cooling services and the phase-out of CFCs and HCFCs. HFCs emissions (R410a) from room air-conditioners in China increased from 9.2 tonnes in 2006 to 12,000 tonnes in 2017 (SN-CMA, 2020). Even with full compliance with the Kigali Amendment, it is estimated that the cumulative HFCs emission from room air conditioners in China from 2018 to 2050 will still be about 1.6 million tonnes, or the equivalent of around 3.2 Gt CO_2 (SN-CMA, 2020). Low Global Warming Potential (GWP) refrigerants, particularly refrigerants such as propane (R-290) for air conditioners and isobutene (R-600a) for domestic refrigeration, could substantially reduce GHG emissions. The use of these refrigerants can also save electricity. It has been estimated that switching to R-290 can save about 1.6% of electricity used for space cooling compared to the current popular refrigerant R-410A (Purohit et al., 2018).

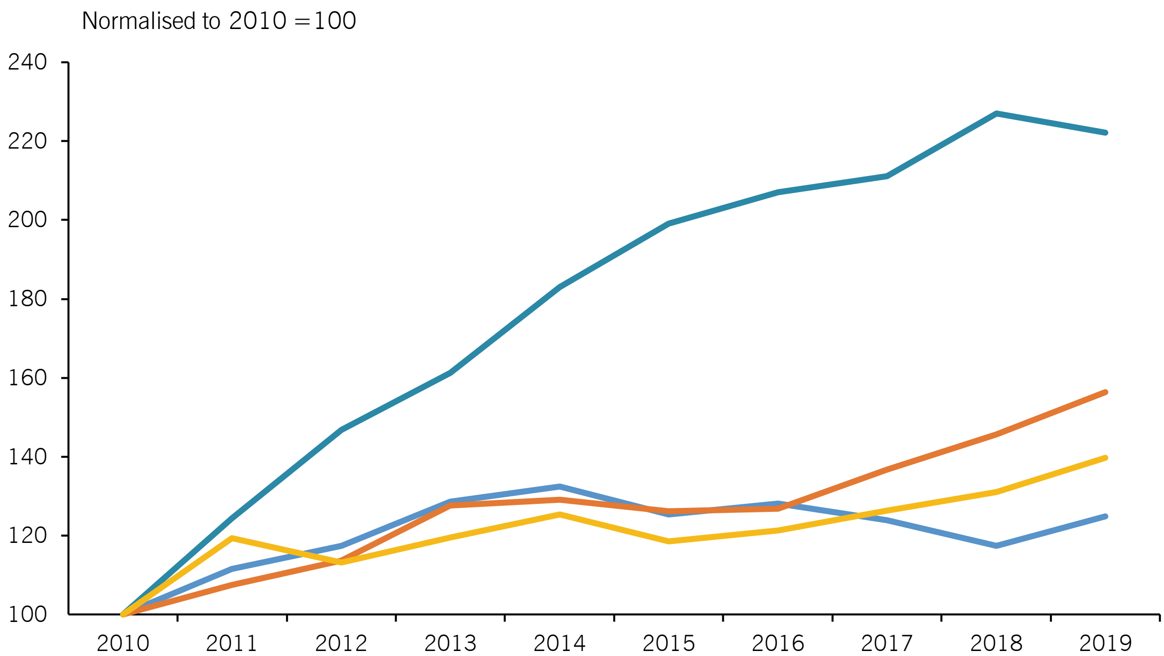
4.3 INDUSTRIAL SECTOR

Current Status and Trends

Over the past decade, China's output of major industrial products has continued to grow rapidly. Electrolytic aluminum production more than doubled and crude steel production grew nearly 60%. China produced more than half of global cement (57%), crude steel (51%), electrolytic aluminum (56%) and a significant share of other industrial products (e.g., more than a third of global ammonia) in 2018. China's industrial sector contributed 41% of China's total GDP in 2017, but it consumed 65% of the country's total final energy (NBS, 2019) and was responsible for 68% of energy-related CO_2 emissions (IEA, 2019b).

FIGURE 4-11. CHANGES IN CHINA'S OUTPUT OF MAJOR INDUSTRIAL PRODUCTS AND ITS SHARE IN WORLD PRODUCTION.

(Sources: NBS, 2019; Wang, 2020a)



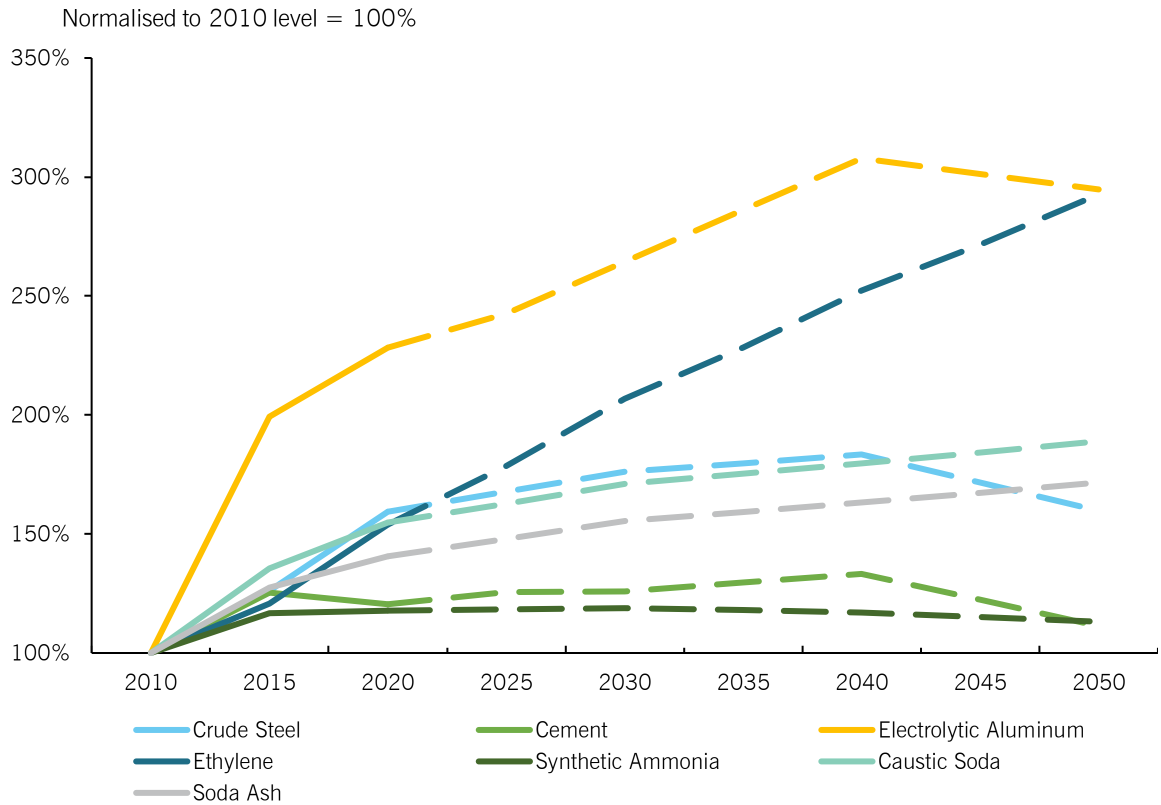
	Cement	Crude Steel	Electrolytic Aluminum	Plain Glass
Production in 2018	2208 Mt	928.0 Mt	35.8 Mt	868.64 Million weight cases
Share of global production	57%	51.3%	55.6%	50%

Sustainable development of China's industry faces many challenges. China's industrial output growth remains overly dependent on resource and energy inputs. Its energy consumption per unit of industrial value-added is 5 to 8 times higher than that of developed countries (ERI, 2020). China has become the world's largest importer and consumer of bulk products such as iron ore, crude oil, bauxite and even coal (BP, 2020). China is increasingly dependent on external input sources, and associated economic security risks are rising. Excess capacity is another major challenge. Low utilization of its production capacity could affect investment returns and capital gains, which in turn could lead to systemic financial risks. As the largest source of air pollutants such as sulphur dioxide (90%), nitrogen oxides (69%), and dust (78%), industry is facing great pressure to control air pollution (MEE, 2018). China's industry is deeply integrated into global supply chains, and the 2020 pandemic could reduce globalization and reshape these global supply chains. With China already accounting for a substantial share of global industrial products, a post-pandemic economic recovery plan without well-designed policy and well-guided investment has the potential to exacerbate China's excess industrial capacity, exacerbate the structural problems it faces, lock the industrial sector into inefficient and outdated production, and increase the difficulty of a long-term transition consistent with China's vision of growth and development.

Domestically, the demand for China's major industrial products is expected to continue to grow in the near term and remain robust well into the future, in order to meet continuing infrastructure construction needs associated with China's comprehensive modernization targets (Figure 4-12). China's continued urbanization implies a significant requirement for new and upgraded infrastructure and that demand for basic industrial products will remain high for several decades. In order to achieve China's 2050 comprehensive modernization targets, China's industrial value added needs to quadruple by 2050. Following a traditional growth model, industrial output, energy consumption, and carbon emissions will nearly double. The precise character of China's future industrial development cannot be known with certainty, due to uncertain changes in the future demand structure. Yet several robust insights do emerge from the studies. Demand for crude steel and cement are expected to remain stable after relatively quickly reaching a peak, while demand for the main petrochemical products and electrolytic aluminum will continue to increase.

FIGURE 4-12. CHINA'S FUTURE DEMAND FOR MAJOR INDUSTRIAL PRODUCTS THROUGH 2050.

Due to different definitions, the assumptions of the different scenarios regarding China's demand for industrial goods in 2050 vary considerably. The PECE_LIU_2019 scenario, cited here, depicts a continued rise in China's industrial goods, after which they stabilize and then ultimately begin to decline. (Source: Liu et al., 2019c)



Elements of Long-Term Strategy

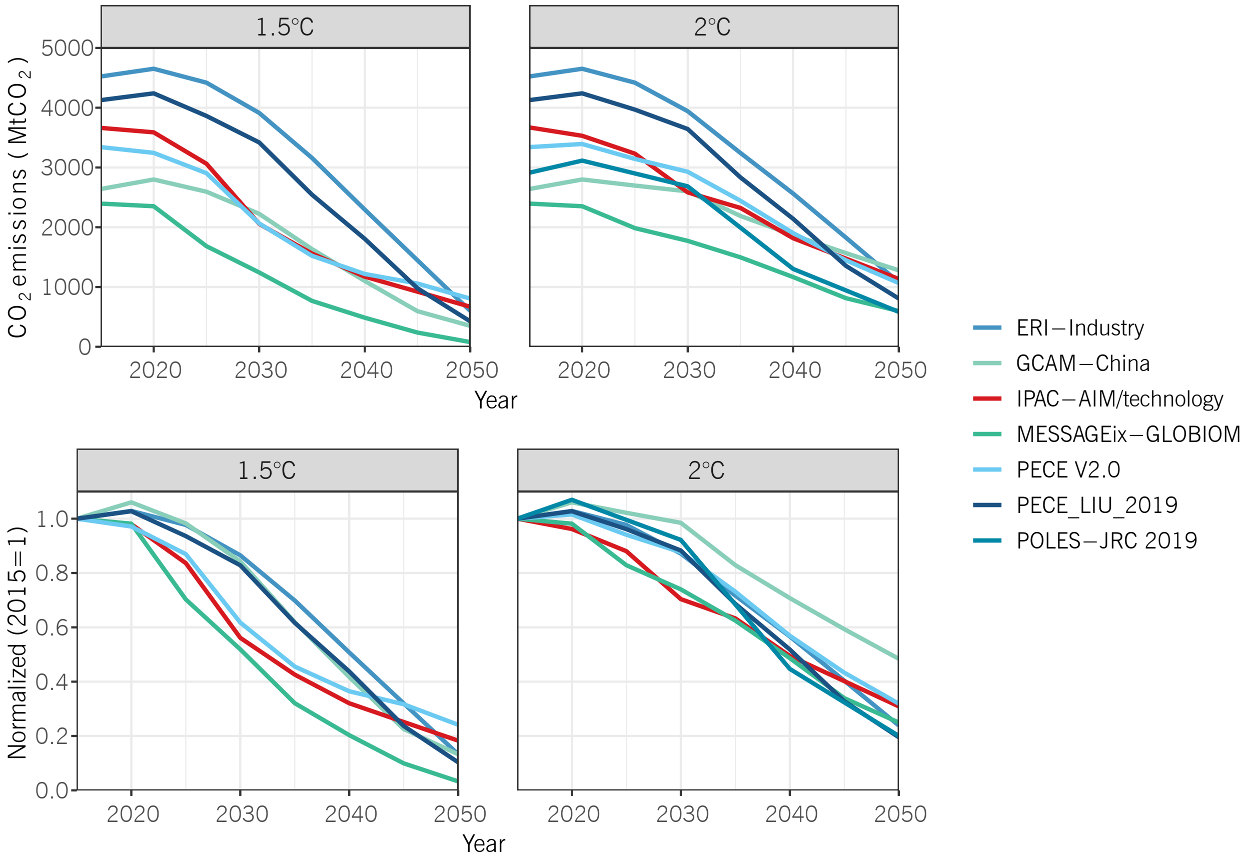
BOX 4-12. KEY ELEMENTS OF A LONG-TERM STRATEGY FOR CARBON NEUTRALITY

- CO_2 emissions peak immediately and decline by around 90% relative to 2015 levels by 2050.
- Building a modernized industrial sector will accelerate industrial digitalization and restructure manufacturing sectors, constraining the overall scale of industrial energy demands and reducing carbon intensity.
- Energy efficiency improvements, material substitution, and circular economy will lead to reduced energy demand.
- Industry electrification continues to increase due digital transformation and switching from fossil fuels to electricity for low temperature heat.
- Switching fossil fuels to zero-carbon hydrogen or biomass in industrial processes and high-temperature heat production.
- Applying CCUS to exhaust gases in applications with high CO_2 concentrations.

CO_2 emissions need to peak immediately and decline by around 90% relative to 2015 levels by 2050. A low-carbon transformation of China's industrial sector is essential to promote China's high-quality economic development, maintain economic, financial and energy security, protect the environment and control carbon emissions. In addition, due to its share of global production, energy consumption, and emissions, as well as its position in the global industrial chain, the low-carbon transition of China's industry will reshape the global supply chain. Industrial sector CO_2 emissions must decline rapidly to reach carbon neutrality before 2060. An immediate peak in emissions will lay the foundation for a national peak well before 2030 and for limiting cumulative CO_2 emissions (Lugovoy et al., 2018; Zhou et al., 2018; Liu et al., 2019b). In the 1.5°C scenarios synthesized in this report, industrial CO_2 emissions peak immediately and decline at an average annual rate of between about 2.5% and 3.2%. In contrast, in 2°C scenarios, they decrease at an average annual rate of between about 1.8% and 2.7%. By 2050, industrial CO_2 emissions are 75% to 95% lower than 2015 levels in 1.5°C scenarios.

FIGURE 4-13. INDUSTRIAL SECTOR CO_2 EMISSIONS IN 1.5°C AND 2°C SCENARIOS.

Because models have different definitions of what falls within the industrial sector, base-year numbers vary substantially between models, as shown in the left panel. For consistent comparison of trends, relative changes across models can be used, as shown in the bottom two panels.



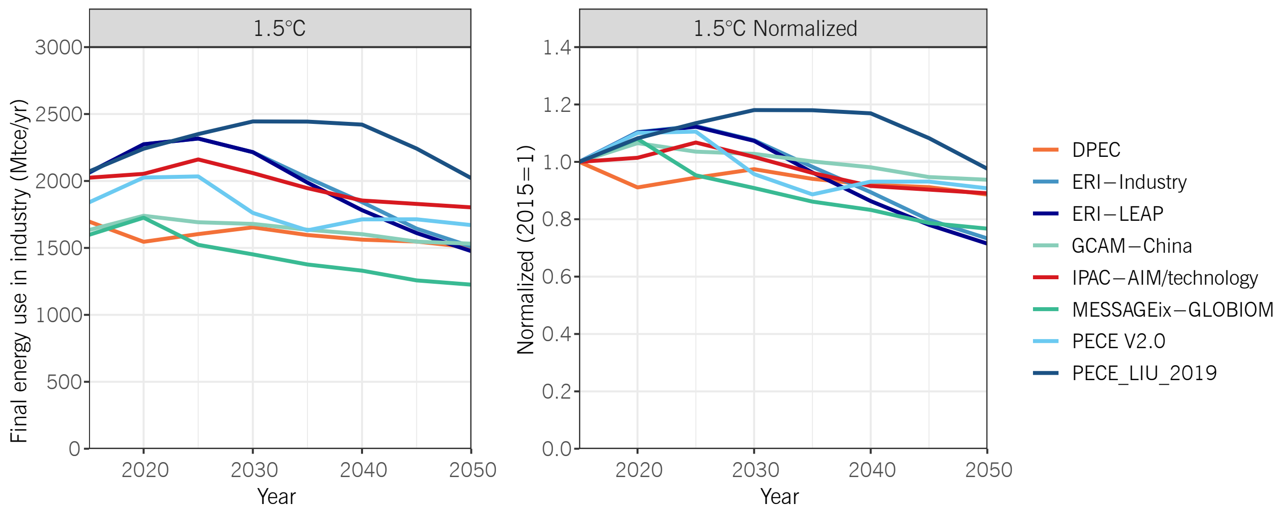
Building a modernized industrial sector will accelerate industrial digitalization and restructure manufacturing sectors, constraining the overall scale of industrial energy demands and reducing carbon intensity. The future scale and character of China's industrial energy demands will depend on modernization of China's industrial sector. A transition toward high value-added industries and shift from manufacturing-based to service-based industries will lower energy intensity and help to constrain energy demands. Through the development of producer services, the construction of a service-oriented manufacturing industry, the optimization and upgrading of industrial internal structure, and the promotion of service industries, the total added value per industry output can be increased substantially, leading to a rapid decline in carbon intensity. A new round of industrial revolution is also characterized by intelligence, digitalization and networking. Accelerating the deep integration of informatization and industrialization, deploying new-generation information technologies such as cloud computing, big data, blockchain, Internet of Things (IOT), 5G, and other new technologies in the industrial sector can improve productivity from a systems perspective and bring additional energy efficiency benefits.

Energy efficiency improvements, material substitution, and circular economy will lead to reduced energy demand. A broad range of technology options to improve energy efficiency can be found across the industrial sector, from more efficient motors to more efficient means of generating process heat. More broadly, a transition to a circular economy, focused on reducing, reusing and recycling materials, will interact with industry modernization and lead to different means of production and material substitution, both of which raise opportunities for increased efficiency.

Reflecting the broad possibilities for industrial sector evolution, scenarios articulate a wide range of different levels of future energy demands. All the 1.5°C scenarios synthesized in this study lead to decreased energy demands by 2050, yet the pathways are different and the overall level of reduction is different. In some of the scenarios synthesized in this study, industrial final energy consumption decreases by 2% to 11% in 2050 relative to 2015; while other scenarios indicate the possibility of reducing industrial final energy consumption by almost 30% (27% to 28%) compared to 2015. The timing of when industrial energy demand will peak also varies across models, from immediately in some models to as late as 2030 in one model.

FIGURE 4-14. INDUSTRIAL FINAL ENERGY CONSUMPTION IN 1.5°C SCENARIOS

Because models have different definitions of what falls within the industrial sector, the base-year numbers vary substantially between models, as shown in the left panel. For consistent comparison of trends, relative changes across models can be used, as shown on the right.

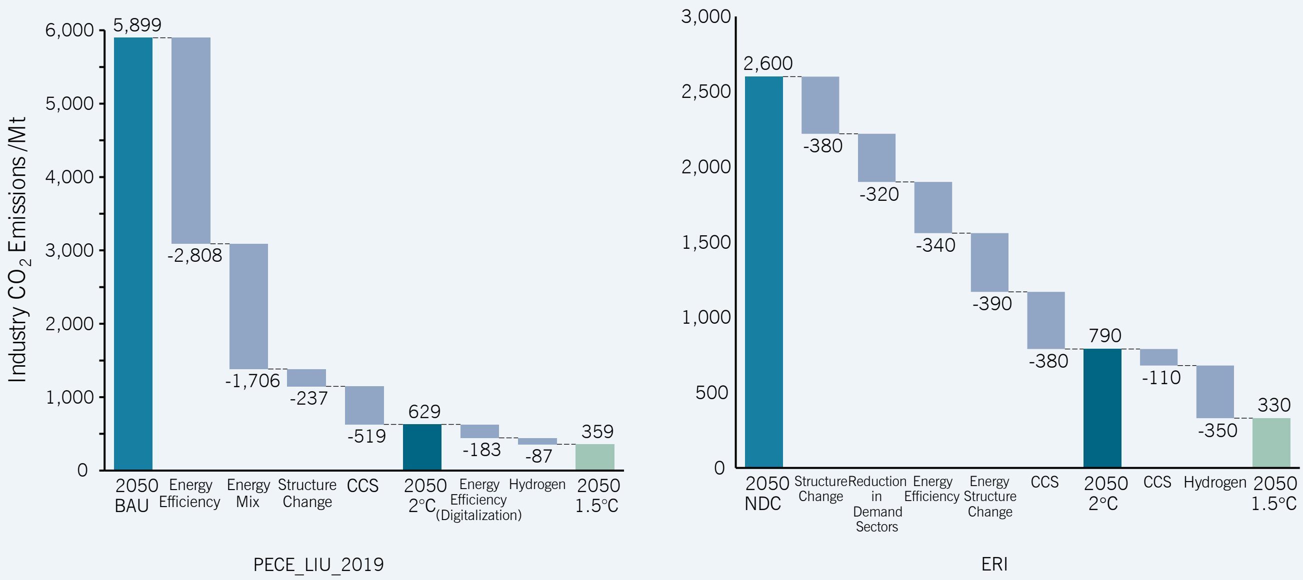


BOX 4-13. SCENARIOS OF DEEP DECARBONIZATION IN CHINA'S INDUSTRIAL SECTOR

The traditional development model for China's industry is not supported by the potential for continued growth in global markets, materials and resources availability, or carbon neutrality goals. In order to address these multiple limits on China's traditional development model, China's industrial sector must follow a low-carbon transition by improving energy efficiency, optimizing energy structure, increasing recycled materials use, and applying CCUS, hydrogen, and other new technologies on the premise of maintaining a large scale of products and value-added. Given the many uncertainties that surround future industrial development and future markets for industrial products, multiple industrial decarbonization pathways are possible, and different scenarios illustrate these different pathways.

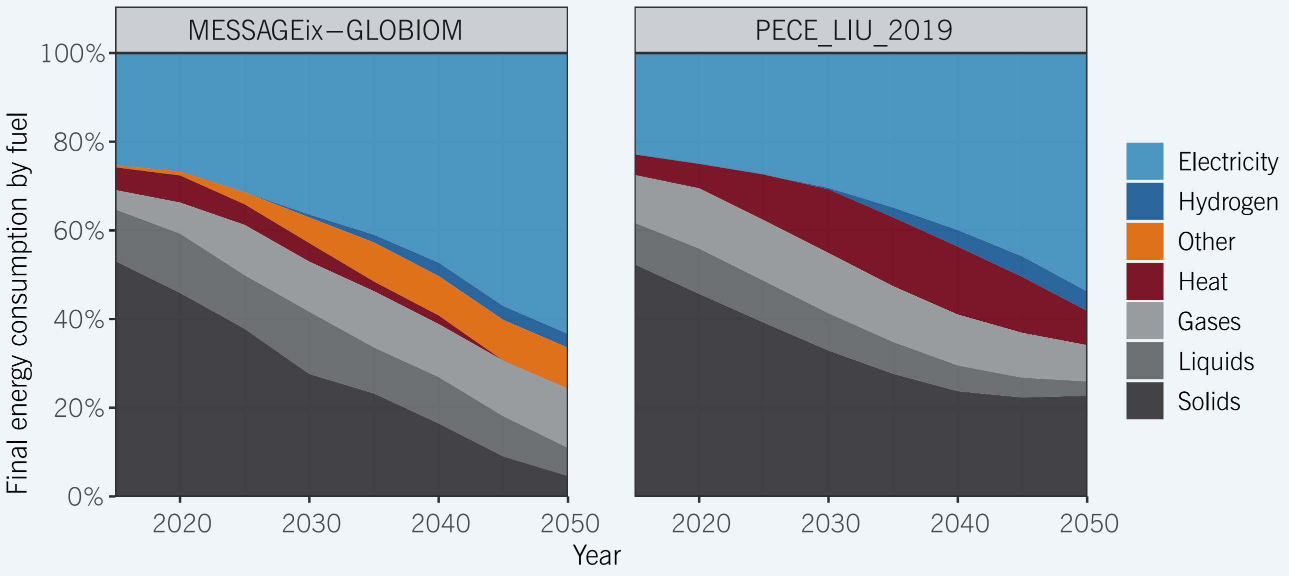
Scenarios from the PECE_LIU_2019 model and the ERI-Industry model demonstrate the relative contributions to decarbonization that could be expected from different measures. In the PECE_LIU_2019 model, from a business-as-usual scenario—a scenario assuming no explicit efforts to reduce emissions—to the 2°C scenario, 53% of the decarbonization comes from energy efficiency improvement, 32% from changes in the energy mix, 4% from the adjustment of industrial structure, and 10% from the application of CCUS. Additional emission reductions to limit warming to 1.5°C mainly come from continued improvements in energy efficiency and substitution toward hydrogen. Hydrogen contributes 33% of the additional decarbonization. The ERI-Industry scenario explores decarbonization starting from China's NDC. From the NDC scenario to the 2°C scenario, emissions reductions similarly come from industrial structure, energy efficiency, energy structure, end-demand management and CCUS applications. From 2°C to 1.5°C, 24% of the additional emission reduction comes from the further application of CCUS, and 76% comes from substituting to hydrogen. Both scenarios show that low-carbon technologies such as CCUS and hydrogen will be crucial for decarbonization of the industrial sector, but that different combinations are possible.

FIGURE 1. MITIGATION CONTRIBUTIONS BY MEASURES IN 2050 IN TWO ILLUSTRATIVE 1.5°C AND 2°C SCENARIOS.



Decarbonization of the industrial sector will alter the composition of the fuels that the industrial sector consumes. Different scenarios also demonstrate significant differences in the final energy structure of the industrial sector in 2050, when limiting temperature change to 1.5°C. For example, the industrial sector in PECE_LIU_2019 is more dependent on accelerated electrification to replace fossil energy. In contrast, in the scenario from MESSAGEix-GLOBIOM, alternative substitutes for fossil energy such as bioenergy, play a larger role.

FIGURE 2. INDUSTRIAL FINAL ENERGY STRUCTURE FROM TWO ILLUSTRATIVE 1.5°C SCENARIOS.

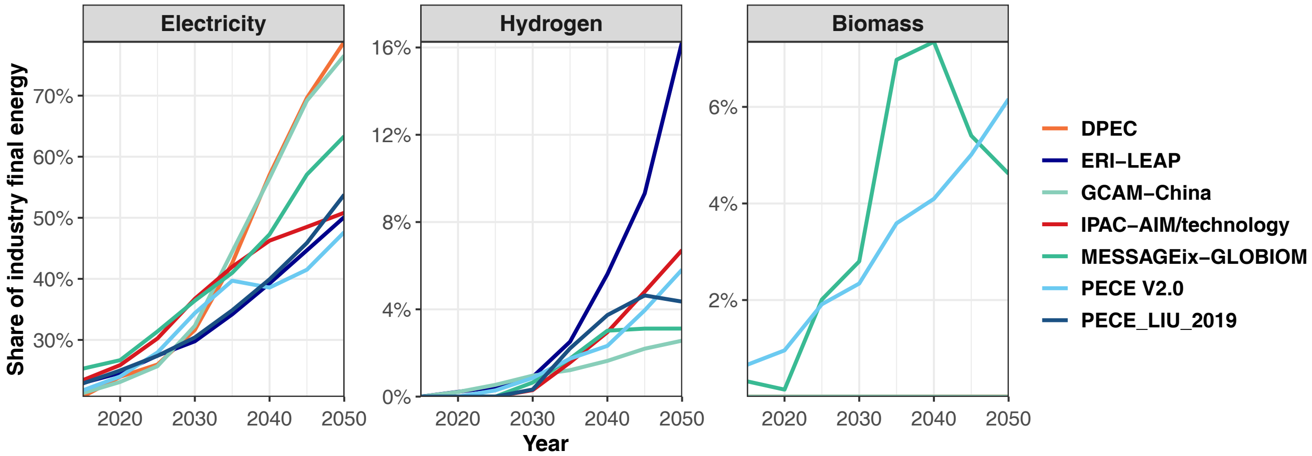


Industry electrification continues to increase, due to digital transformation and switching from fossil fuels to electricity for low temperature heat. In the 1.5°C scenario synthesized in this study, the industrial electrification rate rises from 23% in 2015 to anywhere from 45% to 80% in 2050. Examples of opportunities for electrification in the industrial sector include switching from blast furnaces to electric arc furnaces in steel production and using electricity for low temperature heat in most manufacturing sectors.

Switching from fossil fuels to zero-carbon hydrogen or biomass in industrial processes and high-temperature heat production. Accelerating green hydrogen (produced from zero-carbon electricity) and sustainable biomass deployment as new energy carriers and feedstock will play a crucial role in reducing emissions in applications where it will be difficult to use electricity. Hydrogen has the potential to serve as an efficient, clean, and flexible secondary energy source, and will play an important role in the deep decarbonization of the industrial sector. In the 1.5°C scenarios synthesized here, hydrogen accounts for 3% to 18% of final energy in 2050, and biomass accounts for around 5%. It is therefore important to develop demonstration projects of green hydrogen production and sustainable biomass production, and integration with industries such as petrochemicals and iron and steel to promote the necessary RD&D and reduce long-term costs.

FIGURE 4-15. ELECTRICITY, HYDROGEN, AND BIOMASS PERCENTAGES IN INDUSTRIAL FINAL ENERGY CONSUMPTION IN 1.5°C SCENARIOS.

Only two scenarios included biomass results up through 2050. For PECE V2.0, distributed solar are treated separately from final electricity that would impact the share of electricity in final energy.



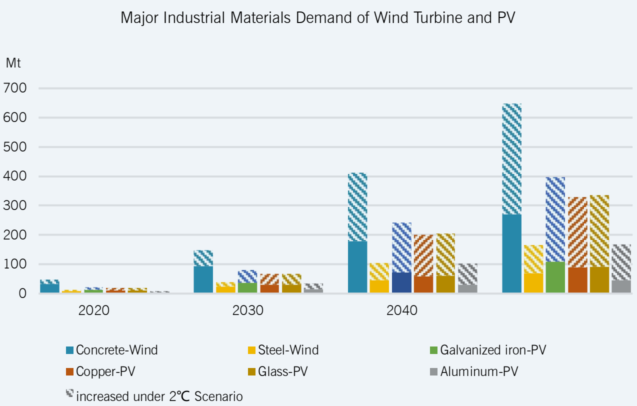
Applying CCUS to exhaust gases in applications with high CO_2 concentrations. China is endowed with a relatively large underground storage capability. CCUS could be applied both in electricity generation and in industrial applications with high CO_2 concentrations, such as iron and steel, cement, and chemicals. The use of CCUS would allow the industrial sector to retain a certain amount of fossil energy consumption to meet the demand for high-grade heat sources for specific processes without increasing CO_2 emissions. CCUS could also be used in production of hydrogen produced from bioenergy, which would result in negative emissions.

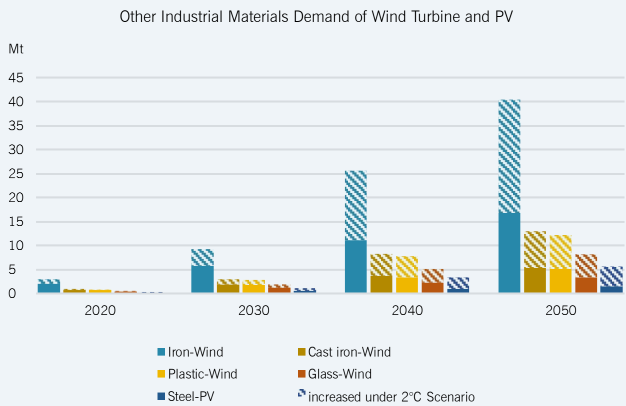
BOX 4-14. WHY DO WE NEED INTEGRATED, CROSS-SECTORAL MITIGATION STRATEGIES AND ACTIONS? IMPACT OF RENEWABLE ENERGY GENERATION ON INDUSTRIAL MATERIALS AND CARBON EMISSIONS IN CHINA

Renewable power is expected to be a cornerstone of China's decarbonization strategy, as it is throughout much of the world. The construction, installation, and maintenance of wind and solar power, however, consume large quantities of industrial materials. The main industrial materials consumed in wind turbine construction are concrete, steel, and iron. PV modules require galvanized iron, glass, copper, and aluminum. One study (Wang et al., 2020b) suggests that, to limit warming to 2°C, production of wind turbines in China in the next 30 years could consume 650 million tons of concrete, 170 million tons of steel, and 40 million tons of iron during 2020-2050. PV production in China could consume 400 million tons of galvanized iron, 340 million tons of glass, 330 million tons of copper and 170 million tons of aluminum over this same time period.

FIGURE 1. INCREASE IN MAJOR INDUSTRIAL MATERIALS DUE TO THE DEPLOYMENT OF RENEWABLE ENERGY IN A 2°C SCENARIO (WANG ET AL., 2020B).

The "BAU" scenario assumes no additional mitigation actions are taken and that industry follows recent trends. In the "Under 2°C scenario", wind power and PV electricity generation expand substantially consistent with limiting warming to 2°C. The "2°C plus scenario" assumes additional technological innovation of the industrial sector while still limiting warming to 2°C: the industrial sector reduces the material demand and associated carbon emissions in the construction of wind and PV through energy-saving technologies.

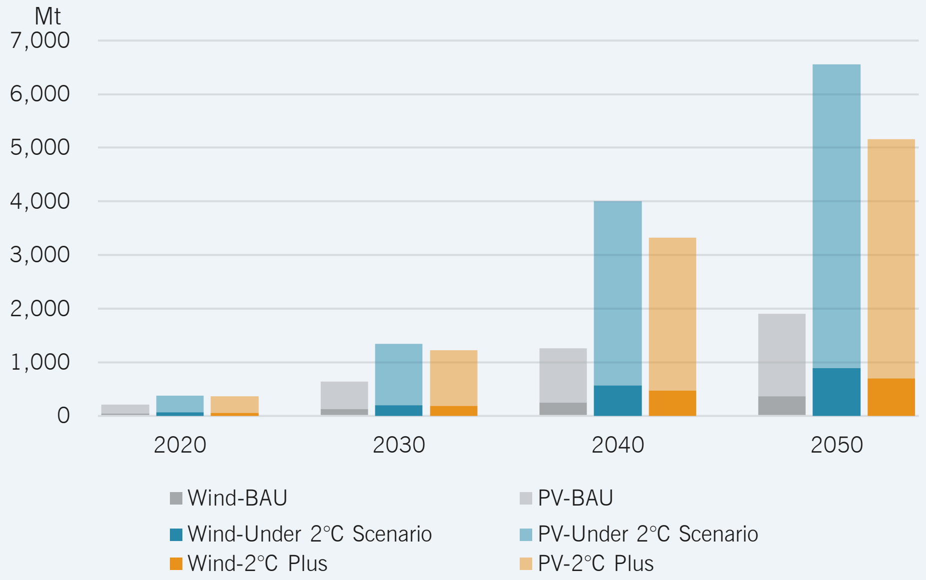




These increased materials demands will call for associated industrial sector mitigation. Under the same 2°C scenario, the demand for industrial materials brought by increased deployment of wind and solar power will cumulatively generate 6.6 billion tons of CO_2 by 2050, increasing industrial emissions by 11% over the same period. If the industrial sector's own technological progress is considered (2°C plus scenario in Figure 2), the cumulative emissions from the above-mentioned industrial materials may be reduced to 5.2 billion tons. The study finds that these increases in the demand for industrial materials for wind and solar deployment will not impact the feasibility of limiting warming to 2°C, but they could prove more challenging for limiting warming to 1.5°C.

FIGURE 2. CO_2 EMISSIONS EMBODIED IN INDUSTRIAL MATERIALS DUE TO THE DEPLOYMENT OF RENEWABLE ENERGY IN A 2°C SCENARIO.

(Wang et al., 2020b) The "BAU" scenario assumes no additional mitigation actions are taken and that industry follows recent trends. In the "Under 2ºC scenario", wind power and PV electricity generation expand substantially consistent with limiting warming to 2ºC. The "2ºC plus scenario" assumes additional technological innovation of the industrial sector while still limiting warming to 2ºC: the industrial sector reduces the material demand and associated carbon emissions in the construction of wind and PV through energy-saving technologies.



Near-Term Challenges, Opportunities, and Actions

BOX 4-15. INDUSTRY: NEAR-TERM ACTIONS TO SUPPORT A LONG-TERM TRANSITION

- Further remove excess capacity, increase concentration, and optimize industry structure in order to improve efficiency and increase innovation.
- Improve the relevant processes and standards of environmental impact assessment and energy technology assessment to guide investment and to control capacity expansion in high energy consuming industries.
- Implement demand management measures to control the output of industrial products and lower total energy demand.
- Prioritize energy efficient technology deployment to control total energy demand.
- Increase electrification, particularly to replace coal consumption.

During the 14th Five-Year Plan period, the industrial sector will face challenges associated with the impulse to expand, low industrial concentration, excess capacity, a high proportion of energy-consuming products, low value-added of products, low energy efficiency, and uneven regional distribution. The 14th Five-Year Plan will be a period of significant changes in China's economic structure, especially its demand structure. When adapting to changes in the overall economic situation and responding to these challenges, China's industrial sector will also be presented with significant opportunities to upgrade and transform. A low-carbon transition in China's industrial sector will comprehensively increase industrial total factor productivity (TFP), change production methods, cultivate new business models, achieve structural optimization, and lay a solid foundation for long-term high-quality development.

Further remove excess capacity, increase concentration, and optimize industrial structure in order to improve efficiency and increase innovation. Excess capacity is one of the biggest challenges to a near-term industrial transition. In order to effectively remove excess capacity, it will be necessary to change the government's approach to engaging in the market and to promote the establishment of a market-based mechanism. A market mechanism could determine the price and allocation of factors of production based on corporate competitiveness, thereby eliminating backward production capacity. A "green yardstick" should also be established for "removing excess capacity", taking energy efficiency, environmental protection, safety, quality, and other factors into consideration, and combining them with industry development. Through all of these measures, the goal is to achieve an increase in the rate of overall capacity utilization of more than 5% in the major industrial sectors during the 14th Five-Year Plan period.

Improve the relevant systems and standards of environmental impact assessment and energy technology assessment to guide investment and to strictly control capacity expansion in high energy-consuming industries. China is a vast country, with different levels of economic development in the east, middle and west regions, and different industrial structures, layouts and technology levels. High energy-consuming industries are still attractive to the central and western regions. It is important to improve the relevant systems and standards of environmental impact assessment and energy technology assessment currently implemented in China in order to guide the investment and control the expansion of high energy consuming industries across regions. When formulating the post-pandemic stimulus plan, it will also be necessary to control the further expansion of industrial production capacity. To address the issue of excess capacity, the goal is that the total capacity of major industrial sectors will no longer increase during the 14th Five-Year Plan period.

Implement demand management measures to control the output of industrial products and lower total energy demand. Measures to avoid demolition and reconstruction, prolong the current lifetime of infrastructure to 50 to 100 years, plan for reasonable levels of total building floor space, and develop a circular economy to increase the recycling and reuse of resources could reduce the demand for materials significantly without sacrificing people's consumption. Limiting the export of energy intensive products will also lower the demand for industrial output. Through demand management measures, the goal is that the output of industrial products such as crude steel and cement will peak before 2025, and the growth of the output of industrial products such as chemicals and electrolytic aluminum will be effectively controlled. During the 14th Five-Year Plan period, it is recommended to set a cap on CO_2 emissions in the iron and steel and cement sectors which can be effectively included in the national carbon market of China.

Prioritize energy efficient technology deployment to control total energy demand in the industrial sector. While China is at the cutting-edge of efficiency in some energy-intensive industries, such as aluminum, in others, such as steel, cement, ethylene, flat glass, and caustic soda, the energy consumption per unit of output product of the more advanced producers internationally is 10% to 30% lower than that of China (CCEEE, 2019). Utilizing the energy saving potential of existing technologies is the most cost-effective way to reduce emissions. There are still many opportunities to improve energy efficiency in a cost-effective way by utilizing current existing technologies during the 14th Five-Year Plan period. To maximize near-term energy savings potential, it is therefore important to highlight the importance, overcome the difficulties and challenges, and accelerate the application of mature technologies and equipment in key energy-consuming enterprises. First, improve the energy efficiency of key enterprises and products, and promote energy conservation from partial and individual energy conservation to process- and system-wide energy conservation. Second, promote green upgrades and energy efficiency improvements of key energy-consuming equipment such as boilers, motors, and transformers. Finally, accelerate the application of digitalization and information technology in the field of energy conservation. The goal is to improve overall industrial energy efficiency by more than 15%, and to have most industrial energy efficiency indicators reach the international advanced level during the 14th Five-Year Plan period.

Increase electrification, particularly to replace coal consumption. Increasing electrification is the intrinsic requirement for modernizing industry, and, in combination with decarbonization of the power sector, is important for the industrial sector's early peaking. There are several steps that need to be taken. Promote innovation in industrial methods and realize the synergistic advancement of industrial electrification and digitalization and intelligence. Replace traditional production processes with advanced electricity-using production processes to meet the production needs of products of higher specifications. Promote the development of electric heating so that low temperature heat can be provided by electric heat pumps. Finally, improve market mechanisms to support industrial electrification, for example, further improving peak and valley prices, differential prices, and tiered price policies according to the scale, time distribution, and electricity-consuming efficiency of industrial enterprises. The goal is to increase the overall industrial electrification rate around 5% during the 14th Five-Year Plan.

BOX 4-16. INDUSTRIAL DECARBONIZATION AND CHINA'S LONG-TERM GROWTH AND DEVELOPMENT

Integrating industrial low-carbon transformation with broader growth and development goals will help build consensus, overcome obstacles, and help China's industrial sector better position itself in the overall growth and development strategy. The low-carbon transformation of China's industry requires the deep integration of traditional industries with intelligent, digital, and network technologies to better integrate with the service sectors and give birth to new industrial sub-sectors. A future industrial sector that has achieved a low-carbon transition will better meet the needs of other economic sectors and people's desires for higher-quality industrial products, and promote **high-quality development of the overall Chinese economy.**

A low-carbon industrial sector will rely more heavily on hydrogen and biomass, reducing dependence on traditional fossil energy. The availability of higher-quality industrial products means that the demand for infrastructure in the process of urbanization will be met with higher standards, and the durability and energy efficiency of the infrastructure will also be greatly improved. All upgrades in the industrial sector will help improve overall **energy efficiency, energy security, and environmental protection**.

In addition, due to its share of global production, energy consumption, and emissions, as well as its position in the global supply chain, a low-carbon transformation of China's industry will also reshape the global supply chain, spurring **the low-carbon transformation of global industry.**

4.4 TRANSPORTATION SECTOR TRANSITIONS

Current Status and Trends

As a key enabler of economic activity and social connectivity, transportation energy consumption and CO_2 emissions have grown rapidly in China. Transportation now represents almost 12% of total Chinese final energy consumption. CO_2 emissions from the transportation sector have risen from about 400 $MtCO_2$/yr in 2005 to around 1.1 billion tons/yr in 2018 and now account for almost 11% of total China's energy-related CO_2 emissions. Road transport is the biggest emitter in the transportation sector, representing 77% of energy-related CO_2 emissions in 2018 (Figure 4-16). Transportation relies almost exclusively on liquid fossil fuels.

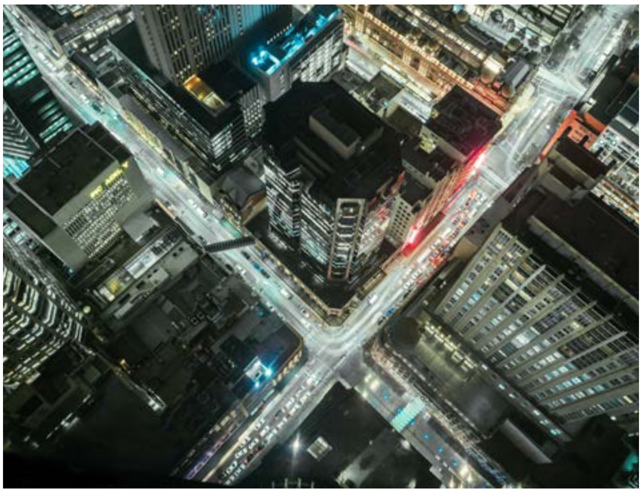
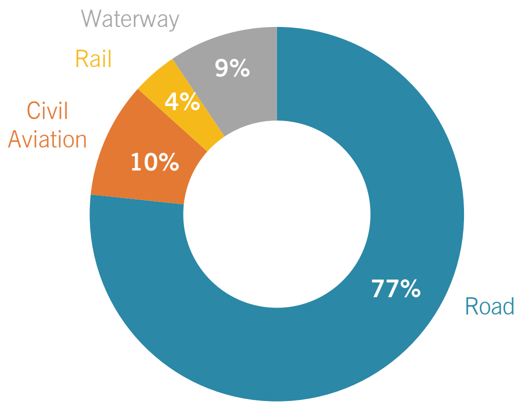
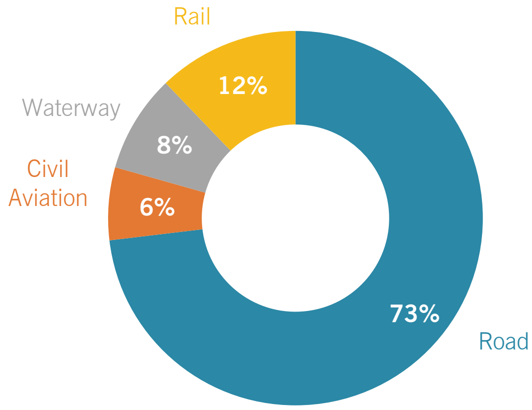


FIGURE 4-16. ENERGY-RELATED CO_2 EMISSIONS AND SHARES OF TRANSPORT ENERGY DEMAND BY MODE IN 2018.

(Source: CATS,2020)



CO_2 emissions from the transportation sector by mode in 2018 (%)



Share of transportation energy demand by mode in 2018 (%)

Driven by China's rapid urbanization and industrialization, demand for transport services has been increasing rapidly. Freight transport activity (in tonne-km) and passenger transport activity (in passenger-km) increased by 172% and 310%, respectively, between 2005 and 2019. Urban passenger transport activity increased 10 times between 2005-2019. In 2019, the share of public transport and private automobiles accounted for above 38% and 30% of urban passenger transport, respectively (CATS, 2020).

The structure of transportation and the distribution of modes play an important role in transportation energy consumption and emissions. In freight transport, China is facing the challenge of shifting from road transport to less carbon-intensive modes. The share of road transport in freight transport grew from 76% to 88% between 2005 and 2019. This was largely driven by transport of coal, iron ore, grain, and other bulk commodities.

Passenger transport activity has gradually shifted from road to rail, as a result of the rapid expansion of the high-speed railway network. Road passenger activity peaked at 1100 billion passenger-km/yr in 2014, then decreased to 880 billion passenger-km/yr in 2019. It accounted for 30% of all passenger transport in 2019. China's rail passenger transport has maintained a stable rate of increase and reached 1470 passenger-km/yr in 2019, or about 48% of passenger transport. China has the world's longest high-speed railway network and its extensive use has replaced part of the conventional rail activity. The proportion of electric rail reached 72% in 2019, increasing from 42% in 2005. China's stock of new energy vehicles, currently 3.8 million, is the world' largest, accounting for 1.5% of its total vehicles. (Chen et al., 2018b; NBS, 2019)

High-quality development and green transformation of the transportation sector has been a national strategy to strengthen the construction of an "Ecological Civilization" and "Beautiful China". The "Outline of Building China into a Powerful Transportation Country", issued by the CPC Central Committee and the State Council in September of 2019, puts forward the goal of "building a safe, convenient, efficient, green and economical modern comprehensive transportation system", and regards "green development, economical and intensive, low-carbon and environmental protection" as the strategic focus of future transportation development. Considering medium- and long-term trends, the transportation sector urgently needs to promote energy conservation and emission reduction in road freight, and to promote the electrification of and transformation to new and clean energy in urban public transport, urban logistics, and distribution vehicles.

However, China's low-carbon transformation in transportation faces a number of challenges. One challenge is poor transportation structure and low transportation efficiency. A considerable proportion of long-distance, bulk cargo transportation takes place by road, which has higher energy consumption and emissions. A second challenge is that some areas of transportation development raise ecological and environmental issues that have not been resolved. Total GHG emissions in transportation continue to rise. Finally, there is room for significant improvement in green transportation governance capabilities and monitoring and evaluation assessment systems.

Looking to the future, China's transportation system may be reshaped by emerging technologies and new modes of working and living, which may have a positive impact on transportation decarbonization. Passenger and freight transportation demands will continue to evolve in the face of emerging technologies, changes in commercial patterns, and changing human behaviors, such as remote offices, online banking, online shopping, shared cars, autonomous driving, drone technology, E-commerce, and 3D printing. Large-scale application of electric vehicles, intelligent trains, self-driving cars, and intelligent ships are likely to revolutionize transport infrastructure design and operations. The Chinese government is exploring green fuel substitution in aviation. With the application of advanced internal combustion engine technologies and new materials, energy-saving and new energy vehicles are becoming increasingly popular. In addition, urban traffic infrastructure is gradually evolving, due to strategic spatial planning featuring multi-center, small-block, and mixed-function models.

Elements of Long-Term Strategy

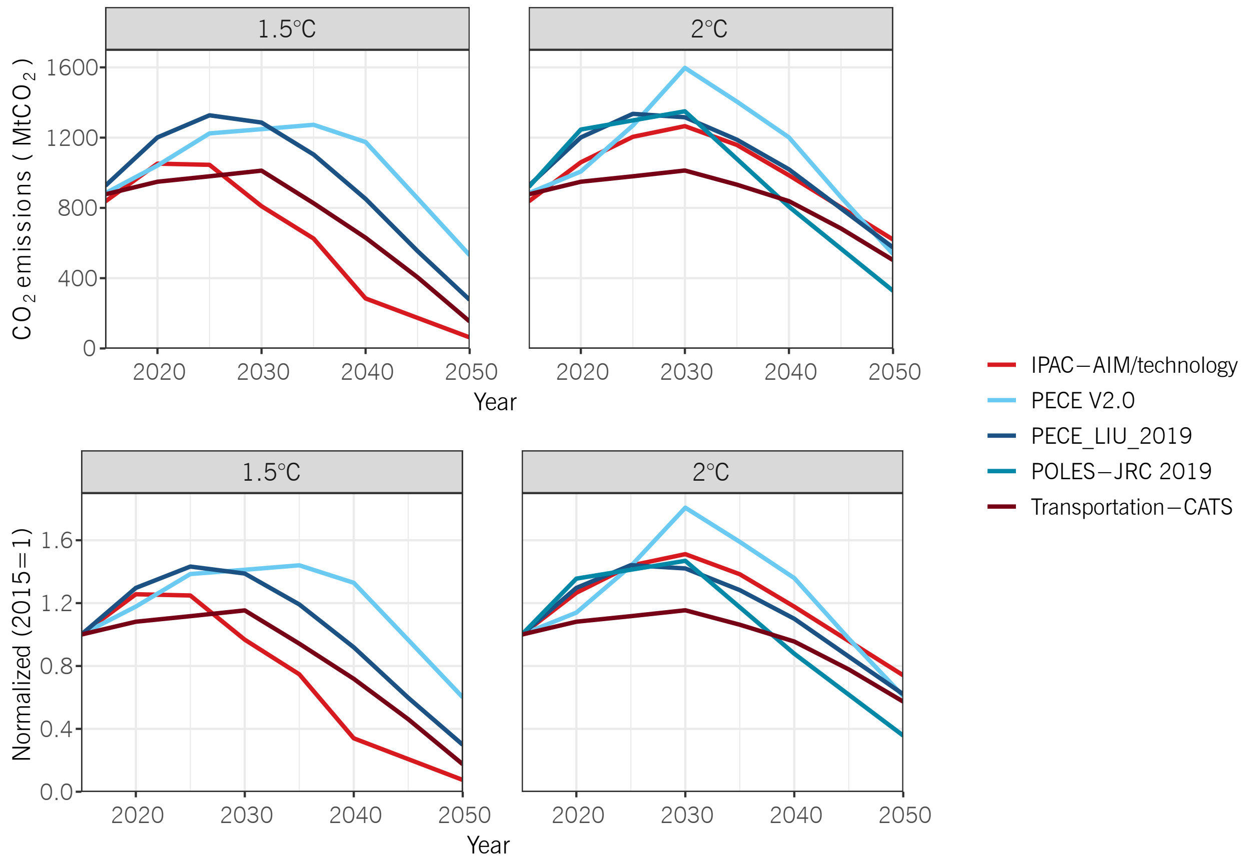
BOX 4-17. TRANSPORTATION: KEY ELEMENTS OF A LONG-TERM STRATEGY FOR CARBON NEUTRALITY

- Transportation CO_2 emissions peak between 2025 and 2035 and then decline by around 80% by 2050 relative to 2015.
- Transition to low-carbon energy sources across the transportation sector, including electricity, sustainable biofuels, and hydrogen.
- A shift to greater energy efficiency and low-carbon transport modes through comprehensive transportation planning.
- Increased integration of innovative technologies, such as big data, 5G, artificial intelligence, blockchain, supercomputers with infrastructure and vehicles to build an electrified, smart, and shared transportation system.

Transportation CO_2 emissions peak between 2025 and 2035 and then decline around 80% by 2050 relative to 2015. In 2°C scenarios, emissions peak around 2030 for most models. Emissions in 2050 are 25%-65% lower than 2015 levels (Figure 4-17). The variation between scenarios arises from different assumptions about future transport services, due, in large part, to differences in assumptions about future economic and social development, differences in options for energy efficiency, and differences in the mix of technologies that will be implemented to decarbonize the transportation sector.

FIGURE 4-17. TRANSPORTATION SECTOR CO_2 EMISSIONS IN 1.5°C AND 2°C SCENARIOS.

Differences in base-year numbers result from differences in calibration methods, scope and definition of the transportation sector, and historical data sources. For example, scenarios from models which incorporate emissions from international shipping and aviation might generally be higher than scenarios from models which exclude these emissions. For consistent comparison of trends, relative changes across models can be used, as shown in the bottom two panels. Differences in accounting methods can also have implications for future emissions due to differences in the ability to reduce emissions in particular sectors.



The future of transportation is uncertain, and different models articulate different visions of transportation sector change and potential pathways for decarbonization (Figure 4-18). For example, the scenarios from the IPAC model assume high future service demand, with 3 times growth from 2015 to 2050. The scenario from the Transportation-CATS model, in contrast, assumes a flat future service demand trend.

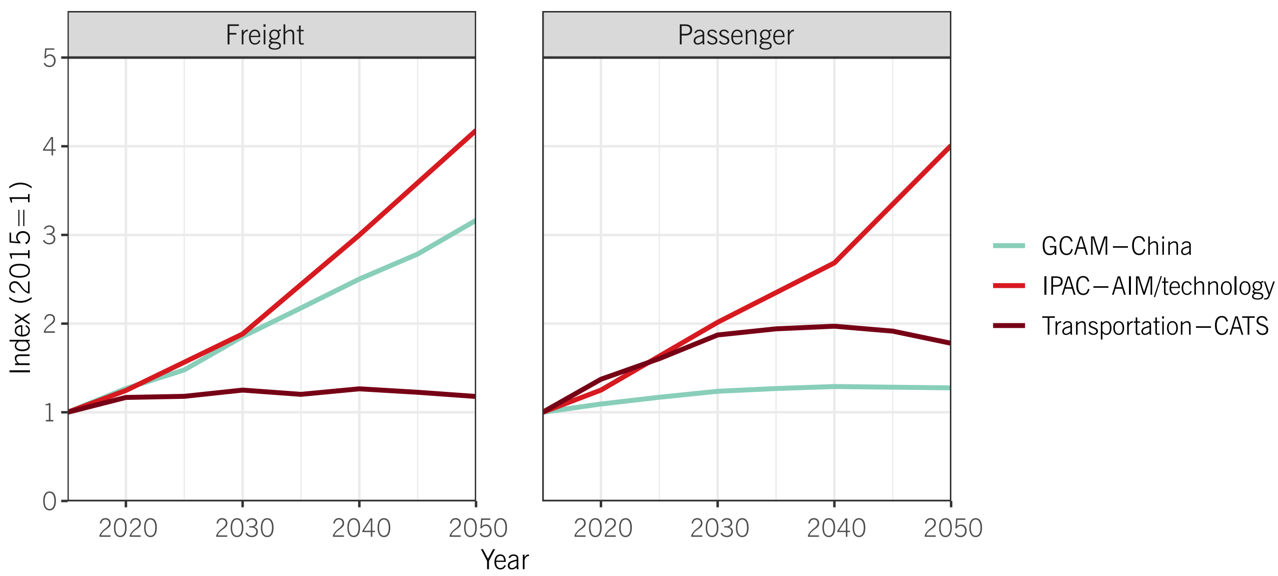
In the freight sector, the scenario from the Transportation-CATS model assumes that freight demand continues to grow slowly through 2030. From 2030 to 2040, industrial output growth slow, further reducing the growth rate in freight service demand. After 2040, freight transportation peaks and maintains a slow downward trend. The Transportation-CATS scenario assumes that China's demand for heavy and bulk freight transportation will peak before 2030. After 2030, following the completion of the urbanization process and infrastructure construction, bulk freight transportation will decline. After that, it will remain relatively stable. The scenario assumes that road transport will remain the most important mode of freight transportation. With the implementation of an ambitious low-carbon transportation policy, a portion of the demand for road freight will be transferred to railways and waterways. With the promotion of multimodal container transport, railway and waterway cargo transportation will have greater potential for growth. Freight transport in air and pipelines will increase, but will remain a relatively low proportion of overall freight transport.

It is important to note that the scope of freight transportation within models can affect the scenarios they produce. For example, GCAM-China and IPAC models both include freight from international shipping and aviation, and both models expect to see an increase in these sectors. The Transportation-CATS model, in contrast, considers only domestic shipping and aviation services.

The three scenarios illustrate three different trends in passenger transport. In the IPAC scenario, passenger transportation continues to rapidly increase, with an aggregate growth of 400% between 2015 and 2050. In the GCAM-China scenario, activity rises more slowly, at an aggregate rate of 130%. In the Transportation-CATS scenario, activity increases 4%/yr before peaking in 2040, at which point it declines at about1%/yr.

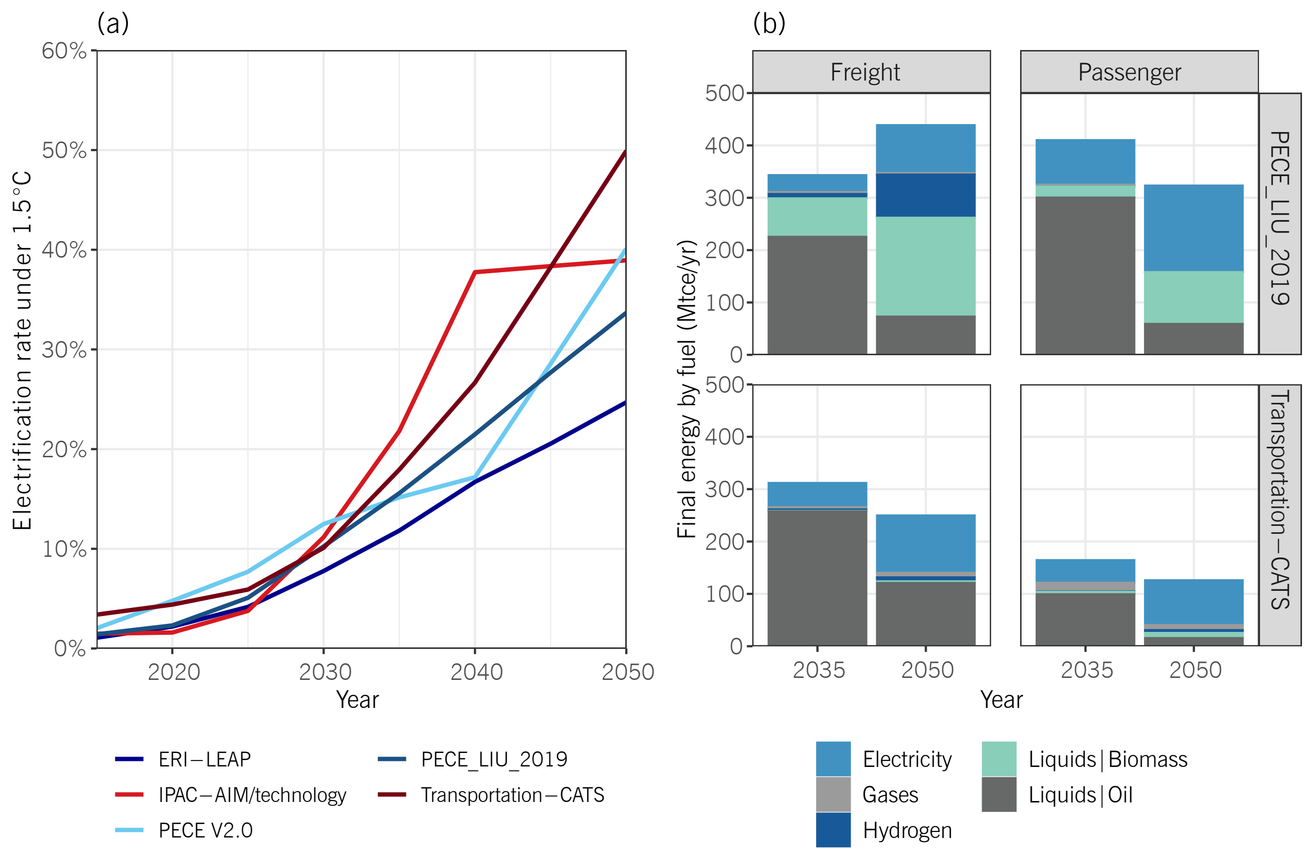
The Transportation-CATS scenario assumes that the slowdown of urbanization rate after 2030 will significantly influence passenger transport demand. It assumes that China will remain in the transition period of industrialization and urbanization until 2030 and that China's urbanization gradually matures from 2030 to 2050, leading to a slowdown in passenger transportation demand. In this scenario, civil aviation has the fastest growth rate, followed by railway transportation. In urban travel, people tend to favor private cars because they are faster, more comfortable, and more convenient, and there is more freedom to choose routes. In the future, the development of new technologies and modes such as autonomous driving and shared cars will make car travel more attractive. Different types of cities will experience different trends in public transport. Demand for public transport in urban areas with low population densities will decline further.

FIGURE 4-18. NORMALIZED PROJECTIONS OF TRANSPORTATION SECTOR ACTIVITY (IN TONNE-KM FOR FREIGHT AND IN PASSENGER-KM FOR PASSENGER) IN THREE 1.5°C SCENARIOS.



Transition to low-carbon energy sources across the transportation sector, including electricity, sustainable biofuels, and hydrogen. A primary means of reducing transportation CO_2 emissions will be to switch from liquid fossil fuels to alternative fuels with lower carbon footprints. All the 1.5°C scenarios synthesized here include transitions to electricity, hydrogen, and biofuels. Yet the mix of low-carbon fuels differs among scenarios, reflecting uncertainty about how technology will develop and which technologies will ultimately prove most effective in different applications (Figure 4-19). Across the 1.5°C scenarios synthesized here, electricity supplies 25%-50% of transportation energy by 2050. As an example, the PECE_LIU scenario has a relatively low electrification rate of 35%, but it has a higher share of biofuels and hydrogen. In this scenario the total share of electricity, hydrogen, and biofuels in 2050 accounts for above 80% of total freight energy consumption (electricity 20%, hydrogen 20%, and biofuels 40%). The share of low-carbon fuels in passenger energy consumption is also above 80% (electricity 51%, biofuels 31%). The Transportation-CATS scenario has the highest 2050 electrification rate among the scenarios (50%), with a correspondingly lower share of hydrogen and biofuels. By 2050, the share of electricity, hydrogen, and biofuels in freight transportation energy demand are 45%, 3%, and 1% respectively, and their shares in passenger transportation energy demand are 65%, 4%, and 8%. New energy vehicles account for more than 80% of all vehicles, new energy ships account for more than 50% of all ships, and biomass energy and other new energy sources are used for 90% of civil aviation.

FIGURE 4-19. ELECTRICITY PERCENTAGE IN TOTAL TRANSPORTATION ENERGY CONSUMPTION (PANEL A) AND TWO ILLUSTRATIVE SCENARIOS OF ENERGY DEMAND AND FUEL MIX IN THE TRANSPORTATION SECTOR (PANEL B).



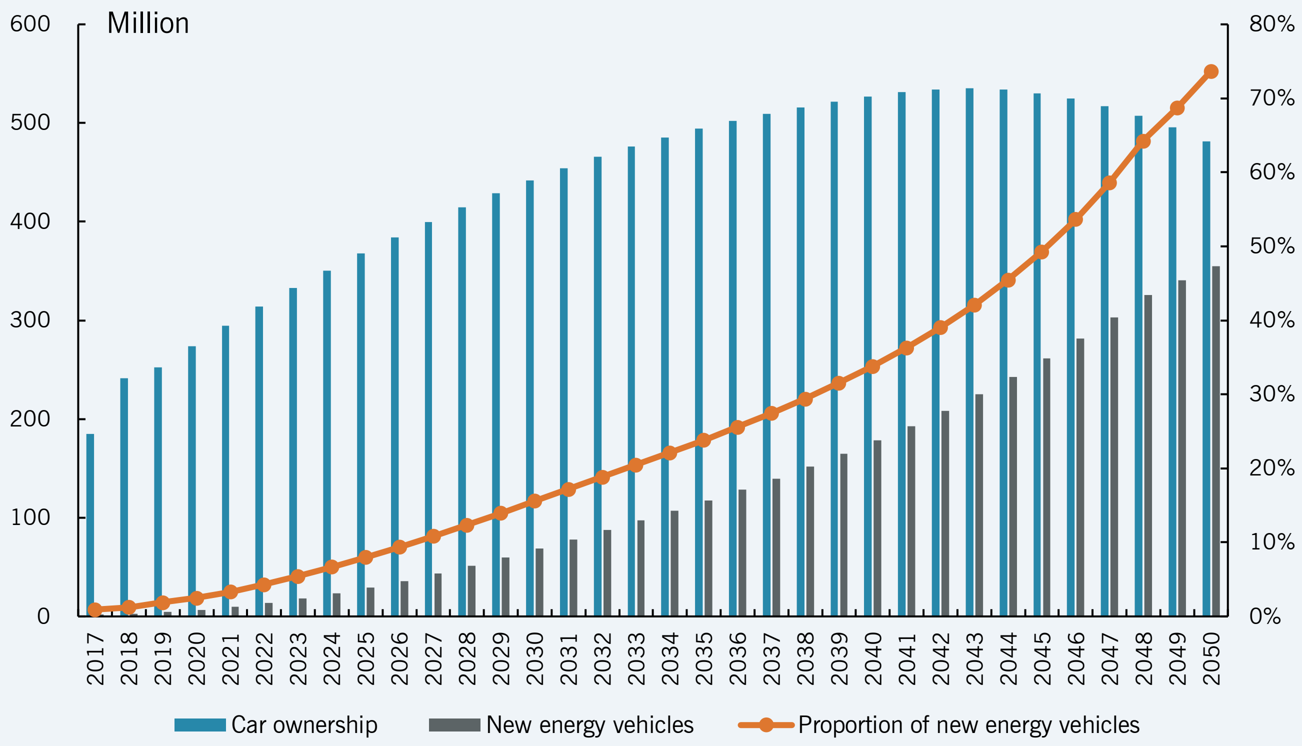
A shift to greater energy efficiency and low-carbon transport modes through comprehensive transportation planning. Accelerating the development of green transportation modes such as water transportation and railway will maximize structural emission reductions. Structural adjustments of various modes of freight transportation takes advantage of the comparative advantages of railway and waterway transportation, allowing these modes to meet an increasing proportion of the demand for freight, reduce energy demand, and reduce carbon emissions. High-speed rail can gradually support a higher proportion of inter-city travel, increasing its overall efficiency.

Increased integration of innovative technologies, such as big data, 5G, artificial intelligence, blockchain, supercomputers with infrastructure and traffic vehicles to build an electrified, smart, and shared transportation system. Broad technology trends are having effects across the Chinese economy. Future, low-carbon energy systems will integrate transportation infrastructure networks, transportation service networks, energy networks, and information networks, creating a ubiquitous and advanced transportation information infrastructure. Important transitions include: building a comprehensive transportation big data center system and deepening the development of transportation public services and e-government; applying the BeiDou satellite navigation system to transportation applications; applying driverless technology in different types of vehicles, such as buses, fire engines, logistics vehicles, taxis, smart highways, unmanned ferries in scenic spots, and cleaning vehicles; developing business models such as time-sharing leasing, network-based car rental, and comprehensive travel services for new energy vehicles to meet future personalized travel needs. As an example, in the Transportation-CATS scenario, automated driving represents more than 80% of all vehicles by 2050, and smart ships and smart docks represent more than 90% of these systems.

BOX 4-18 : HOW ELECTRIC VEHICLES WOULD RESHAPE THE LINKAGE BETWEEN THE TRANSPORTATION AND POWER SECTOR.

In 2019, the number of electric vehicles nationwide reached 3.1 million. Related supporting infrastructure has developed rapidly – 7600 charging piles had been built in 810 expressway service areas by 2019 (MOT, 2020). The popularization and application of new energy vehicles are prominent, particularly in public buses and trams. Among the 693,000 public buses in China in 2019, there were more than 410,000 new energy buses, accounting for more than 58% of all buses (MOT, 2020). In July 2018, the National Development and Reform Commission issued the "Opinions on Innovating and Perfecting the Price Mechanism for Promoting Green Development", which proposed encouraging electric vehicles in order to provide energy storage services and obtain benefits through peak-trough electricity price differences. With continuing breakthroughs in batteries, related technologies, and charging pile construction and standard setting, integrating electric vehicles into power systems is a cross cutting issue that faces both the transport sector and power sector.

FIGURE 1. CAR OWNERSHIP, NEW ENERGY VEHICLES, AND PROPORTION OF NEW ENERGY VEHICLES IN THE TRANSPORTATION-CATS 1.5°C SCENARIO.



Large-scale deployment of new energy vehicles can be synergistic with the evolution of the power grid through coordinated development of EVs and the power grid. Electric vehicles can be used for "peak-shaving", serving as a flexible load to help integrate variable renewable electricity on the grid. Large-scale, intelligent charging piles can promote the integration of electric vehicle charging systems and internal power distribution in buildings, promote car batteries to become a part of the building's flexible power consumption system, absorb the surplus power of residential buildings at night, peak shave and valley fill the power, and provide peak power consumption for office/residential buildings during daytime/peak power consumption periods.

As an example, the Transportation-CATS 1.5°C scenario estimates that the new energy vehicles will expand into urban public transportation, taxis, urban logistics and distribution vehicles, and electric trucks. Hydrogen fuel cell heavy-duty trucks in freight transportation will also increase. By 2025, new energy vehicle sales will account for 30% of total new car sales and will increase to almost all new car sales in 2050. 69 million electric vehicles in 2030 will provide a storage capacity of 3.5 TWh and a flexible load of nearly 690 GW.

These linkages highlight the need to coordinate development of an electrified transportation system and a low-carbon power sector. Important areas of coordination include: carrying out top-level design and policy mechanism research to support vehicle-to-grid systems, studying and formulating charge and discharge price policies that reflect the system values, so as to promote the connection between electric vehicles and renewable energy; guiding charging service providers to directly and deeply participate in the power market; carrying out R&D and demonstration of vehicle-to-grid and retired power battery energy storage technologies; and carrying out demonstrations of vehicle-to-grid projects to form a set of tested technical solutions, standard agreements, and market mechanisms.

Near-Term Challenges, Opportunities, and Actions

BOX 4-19. TRANSPORTATION: NEAR-TERM ACTIONS TO SUPPORT A LONG-TERM TRANSITION

- Accelerate the adjustment of long-distance freight transport by supporting the use of railways and waterways.
- Accelerate the improvement of green travel systems, focusing on "public transportation and cycling/walking".
- Improve the clean technology level, promoting the transition to new energy;
- Vigorously develop intelligent transportation.
- Significantly improve overall transportation energy efficiency.
- Strengthen the innovation in Transportation Demand Management policies.

Accelerate the adjustment of long-distance freight transport by supporting the use of railways and waterways. The "Opinions of the CPC Central Committee and the State Council on Comprehensively Strengthening Ecological Environment Protection and Resolutely Fighting Pollution Prevention and Control", the "Implementation Opinions of the Ministry of Transport on Comprehensively Strengthening Ecological Environment Protection and Resolutely Fighting Pollution Prevention and Control", and other policy documents call for reducing road freight activity and increasing railway freight activity. China needs to increase the use of railway and water transport in long-distance transportation of bulk materials, increase rail and port density of the network, and gradually reduce the proportion of heavy-duty diesel trucks for long-distance transportation of bulk cargo.

Accelerate the improvement of green travel systems, focusing on "public transportation and cycling/walking". To promote emission reduction of transportation, it is necessary to give priority to public transportation planning, land use, capital, and road rights (Jiang et al., 2019); speed up the construction of bus rapid transit, bus lanes and rail transit, as well as slow-moving systems such as bicycle lanes and pedestrian lanes; develop mass transit systems; speed up the promotion of shared transportation modes such as network car, bike-sharing and car rental; constantly improve the sharing rate of bus trips; and finally, build urban travel systems that meet diversified needs.

Promote and support the transition to new energy vehicles. With the rapid growth of China's new energy automobile industry, the sales and penetration of new energy vehicles will continue to rise. China needs to continue to accelerate the construction of charging facilities for new energy vehicles and promote a large-scale transition to new energy vehicles (Li et al., 2019). China can adopt a target to ban new sales of internal combustion engine vehicles (ICEVs) powered by gasoline, except for heavy trucks.

Vigorously develop intelligent transportation. Facilitate the research and development of applications such as the parallel technology of 5G communication technology and traditional highway communication links. Facilitate integration of 5G communication technology and vehicle-road collaboration systems (Yang et al., 2020). Through these means, pilot applications of vehicle-road collaboration could be achieved in some road sections by 2025. Through the promotion of the digitization of the full cycle of transportation infrastructure planning, design, construction, maintenance, operation, and management, large-scale and systematic big data sets and integrated transportation big data center systems of delivery vehicles and infrastructures can be established.

Significantly improve overall transportation energy efficiency. Encourage the elimination of old vehicles and vessels with high energy consumption and improve the technical level of energy conservation and environmental protection of transportation vehicles. With the technology progress in rail electrification, locomotive energy saving, and intelligent management, railway energy consumption could be reduced by 10%-15% by 2025. In road transportation, upgrading of engine and vehicle manufacturing and the application of technologies such as ecological driving could reduce road energy consumption by 15-20% by 2025 (Xie et al., 2018). Technologies such as the upsizing of ships and the standardization of ship types could increase the energy efficiency of waterway transport by 10%-20% by 2025 (Li et al., 2017). Refined flight management technology, aviation biofuel application technology, and new engine/aircraft research and development applications could increase the energy efficiency of air transport by 10%-30% by 2025 (Yu et al., 2020b).

Strengthen the innovation of Transportation Demand Management policies. Strengthen transportation demand management and make good use of economic policy levers such as green taxation and user payment to curb excessive growth and excessive use of private cars. Traffic demand management policies include, e.g., limited purchase restriction policies, differentiated parking charges, intelligent parking management, traffic congestion charges, and staggered commuting measures.

NEW TRANSPORTATION INFRASTRUCTURE, ECONOMIC GROWTH, EMPLOYMENT, AND CONSUMPTION PATTERNS

As part of its COVID-19 economic recovery efforts, China's transportation infrastructure investment is seen as a key channel not only to stimulate economic growth, but also to facilitate an economic transformation, increase employment, and upgrade consumption patterns. This new round of investment has been focused on 5G, inter-city high-speed rail systems, urban rail transit, new energy vehicles, and charging stations. These investments are conducive to a low-carbon transformation of transportation. It has been estimated that total investment in inter-city high-speed rail system and urban rail transit will reach a cumulative investment of 34,400 trillion yuan from 2020-2025 (China Merchants Securities, 2020). This new investment will drive demand for upstream metal products. The Chinese central government has recently published a series of strategic planning and supporting policies to facilitate new transportation infrastructure investment, including the "Guidance on Promoting the Construction of New Transportation Infrastructure" issued by the Ministry of transport and the "Development Plan of New Energy Vehicle Industry" approved at the executive meeting of the State Council in August and October, 2020.

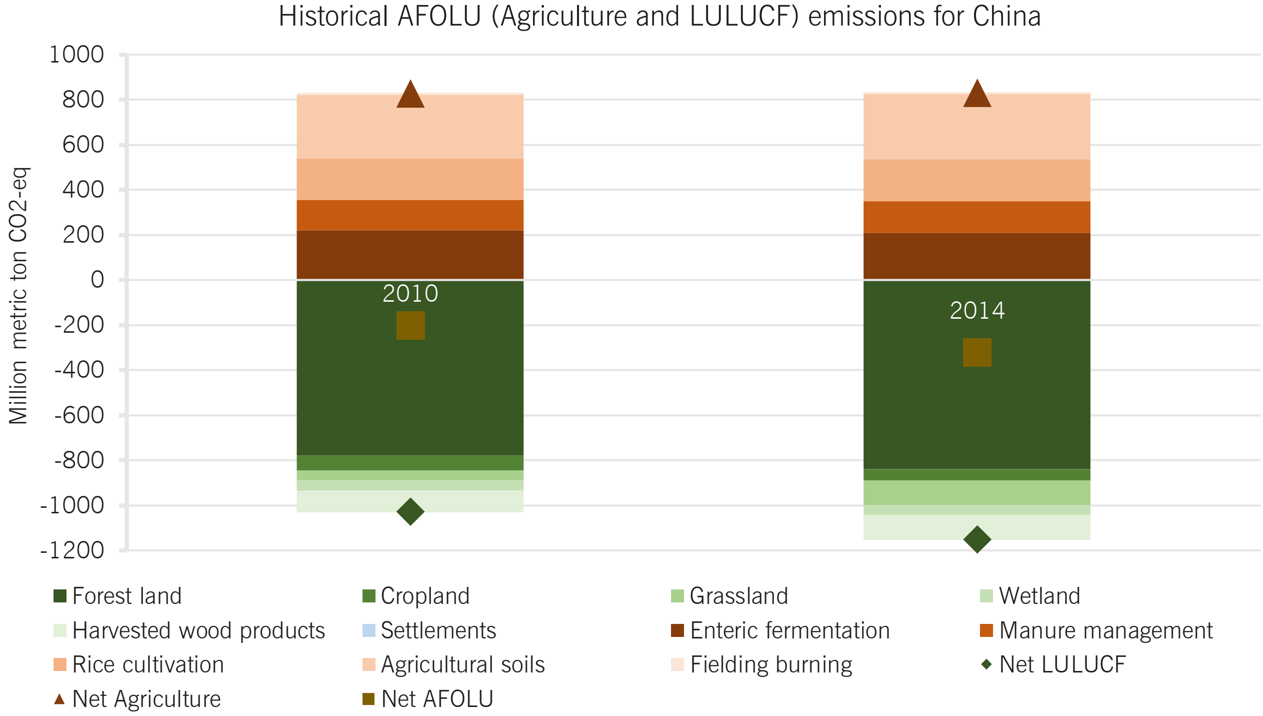
4.5 AGRICULTURE, FORESTRY, AND OTHER LAND USE

Current Status and Trends

China, a country with almost 20% of the world's population, has been struggling to feed its large population and considers food security to be a top priority in its national economic and social development. China's 135 million hectares of arable land account for just 14% of the country's total land area and about 7% of global arable land. China's agronomic achievements since 1980 are unique and unprecedented in human history, maintaining self-sufficiency in the supply of most major food crops and livestock products at more than 90% (Lal, 2018; Wilkes and Zhang, 2016). But this success has come with substantial environmental impacts (Lal, 2018). Although the Agriculture, Forestry and Other Land Use (AFOLU) sector presents a net sink of GHGs (Figure 4-20), emissions from agricultural sources increased by about 37% from 1994 to 2014 (PRC Second Biennial Update Report on Climate Change, 2018; PRC First National Communication in 2004).

FIGURE 4-20. HISTORICAL COMPOSITION OF AFOLU (AGRICULTURE AND LULUCF) GHG EMISSIONS AND REMOVALS.

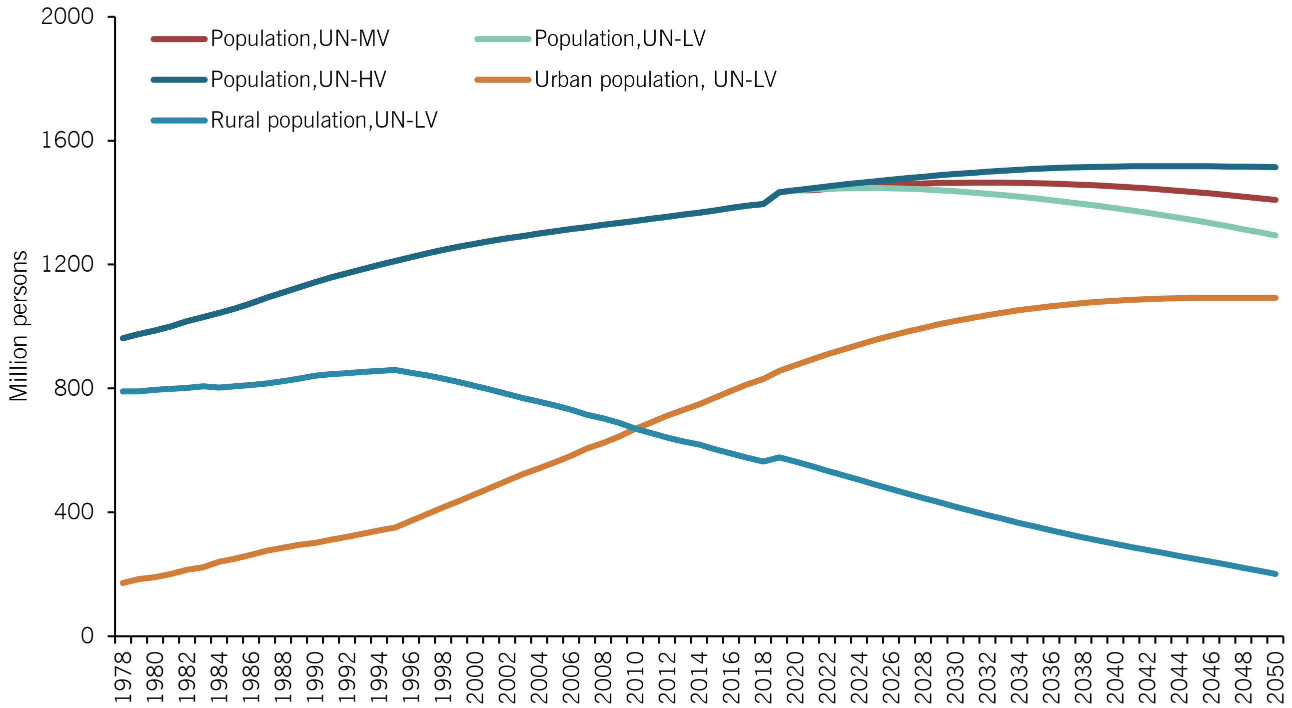
(Sources: PRC First and Second Biennial Update Report on Climate Change in 2016 and 2018; PRC first, second and third National Communication in 2004, 2012 and 2018)



Food security will remain a top priority in China's national socio-economic and agricultural strategies. Between 1978 and 2018, China's population grew from 0.96 billion to 1.39 billion (NBS, 2019). Agricultural development is therefore essential for ensuring China's long-term food security. The agriculture sector has been developing rapidly since reforms began in 1978. 2015 marked 12 consecutive annual increases of annual grain production in China, which reaching 620 million tonnes. According to the lower variant projection by the United Nations Division of Population, China's population will level off at roughly 1.45 billion in 2024 (Figure 4-21). In 2016, total food consumption was 360 kg capita^{-1} in China (Xin, 2018). As China's per capita food demand continues to rise, peaking around 2030, total food demand will peak around 2030 as well. It is projected that 720 million tons of annual grain production will be needed by 2030.

FIGURE 4-21. CHINA'S POPULATION PROJECTIONS UNDER DIFFERENT SCENARIOS.

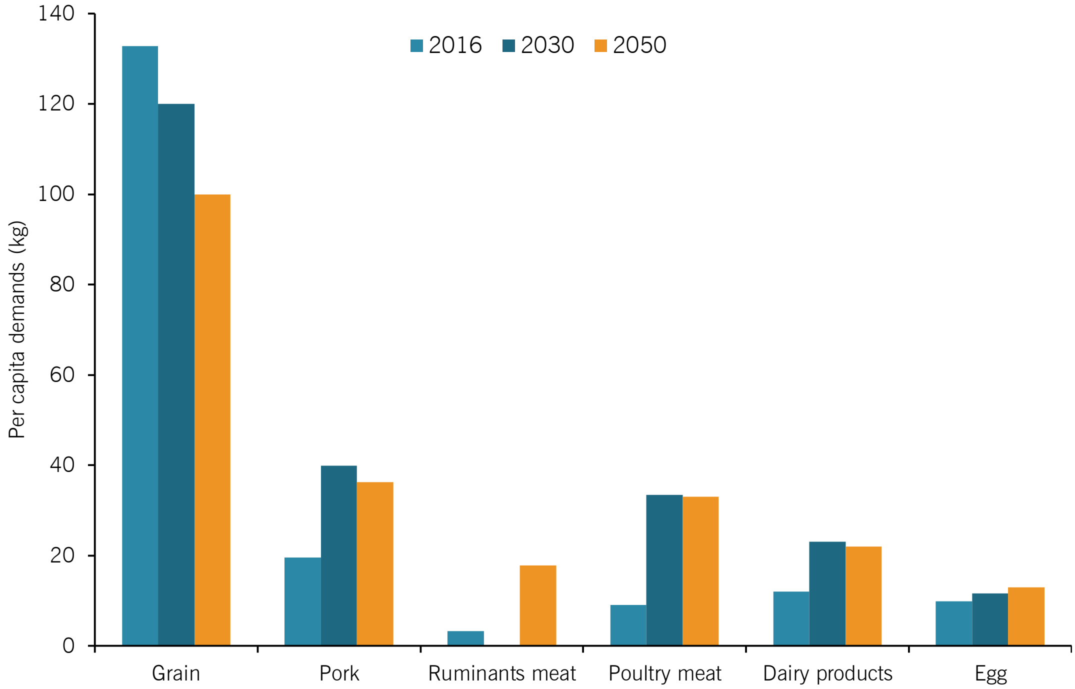
(Source: UN-DESA, 2018)



At the same time, diets in China continue to shift. With urbanization, increasing of household income and improving living quality, diets in China will continue to shift to higher intake of high-value foods, such as dairy products, beef, sheep and goat meat, fruits and vegetables, and lower intake of starchy staples (Hamshere et al., 2014). The consumption of ruminant meat increased exponentially in China from early 1990s, and dairy products from the early 2000s. China currently consumes around 50% of global pork and 23% of the global chicken, but only 14% and 7% of world ruminant meat and dairy products (Yu et al., 2016; Xin, 2018; Du et al., 2018). Without actions to alter diets, it is projected that the per capita demand for grain (excluding feed grain), pork, ruminant meat, poultry meat, dairy products, and eggs in China will reach 100kg, 36kg, 17.8kg, 33kg, 22kg and 13 kg respectively by 2050 (Figure 4-22). This is expected to lead to an increase in national emissions from the agricultural sector, thereby making it more challenging for the country to decarbonize.

FIGURE 4-22. PROJECTIONS OF CHINA'S PER CAPITA CONSUMPTION.

(Sources: Xin, 2018; Du et al., 2018)



Technology has played an important role in China's agricultural sector evolution. From 2010 to 2015, application of advanced technologies has been responsible for 56% of agricultural development (Xu et al., 2017). Integrated mechanization farming methods, including land preparation, planting and harvesting, are not used in 63% of production processes.

Since 2010, China has embraced sustainable agriculture through a variety of national strategies. These strategies will alleviate the environmental impacts of rapid agricultural development. In 2015, China released the National Sustainable Agricultural Development Plan (2015-2030), two action plans to achieve zero growth in pesticides and fertilizers, and one action plan for cultivated land quality protection, to guide sustainable agriculture development in the coming decade, including the efficient utilization of resources (e.g. land, water, energy, etc.), recycling of agricultural wastes (e.g. manure, crop residues, etc.), trapping of carbon, and alleviation of environmental impacts. These strategies will create opportunities for reducing carbon emissions from the AFOLU sector.

China has a long and successful history of reforestation. China has endeavored to restore natural forest and re-forest large areas of the country. With this aim in mind, a series of policies have been formulated (including annual harvest quotas, logging ban, etc.) and several key programs have been successfully implemented, including the Three-North Shelterbelt Program since 1978; the Grain for Green Program since 1999; and the Natural Forest Conservation Program since 2000. From the time of the first national forest resource assessment, commonly known as National Forest Inventories (NFI's), carried out in 1973-1976, to the latest 9th NFI, carried out in 2014-2018, these programs have successfully increased national forest cover from 121 million ha to 214 million ha (Zeng et al., 2015; Xu et al., 2019). At the same time, the forest growing stock volume has increased from 8.7 billion m^3 to 16.3 billion m^3.

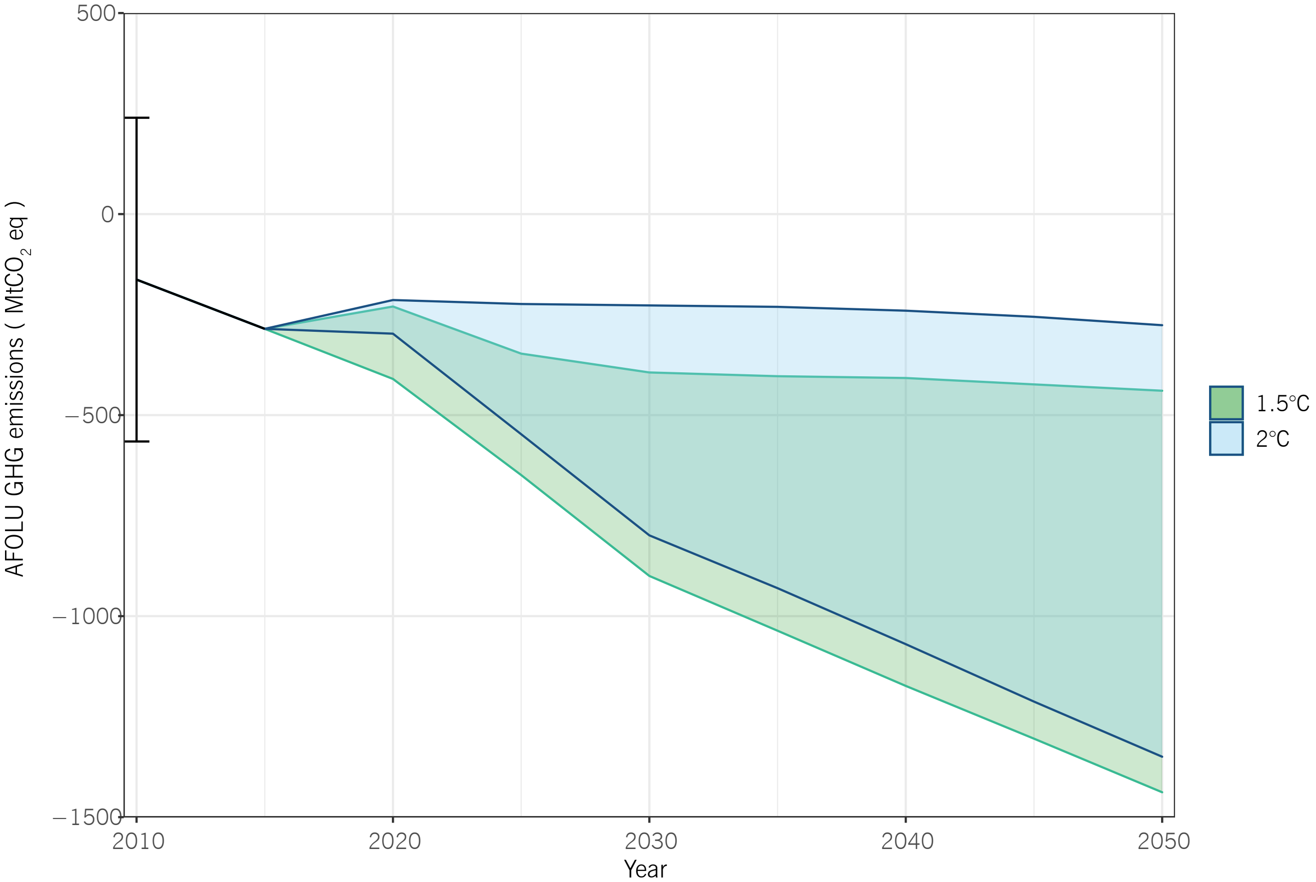
BOX 4-21. AFOLU: KEY ELEMENTS OF A LONG-TERM STRATEGY FOR CARBON NEUTRALITY

- Non-CO_2 emissions from agriculture need to dramatically decline and AFOLU sectors need to be a net carbon sink to offset emissions.
- Implement technical mitigation options (such as animal feed supplements, nitrification inhibitors or anaerobic digesters) and structural mitigation options (such as improved manure management, use of appropriate feed, crop and livestock production portfolio and shifts in international trade) within the Agricultural sector.
- Transition to a healthier and more sustainable diet with lower environmental impact.
- Sustain and enhance China's forest carbon sink through continued afforestation and reforestation efforts. Increase the forest area by 35 Million hectares in 2050 relative to 2015 levels.

Non-CO_2 emissions from agriculture need to dramatically decline and AFOLU sectors need to be a net carbon sink to offset emissions. Long-term projection shows that under current conditions (i.e. a business-as-usual scenario), emissions from the agricultural sector will continue to increase until 2050. For example, a recently released report found that emissions will reach 1100 $MtCO_2$-eq as compared to 830 $MtCO_2$-eq in 2014 (He et al., 2020c). This trend of continued increases needs to be avoided to limit temperature change to 1.5°C. In a 1.5°C (2.0°C) consistent pathway, emissions from the agricultural sector alone need to peak by 2030 and reach 628 $MtCO_2$-eq (929 $MtCO_2$-eq for 2°C scenario) by 2030 and 590 $MtCO_2$-eq (872 $MtCO_2$-eq for 2°C scenario) by 2050 (He et al., 2020c). The AFOLU sector as a whole should keep its role of net carbon sink in the baseline, to enhance carbon storage in the terrestrial biosphere and soils. In a 1.5°C consistent pathway, the net carbon sink for AFOLU sector 1020 $MtCO_2$-eq by 2050 (1030 $MtCO_2$-eq for 2°C scenario) (Figure 4-23).

FIGURE 4-23. PROJECTIONS OF TOTAL GHG EMISSIONS FOR THE AFOLU SECTOR IN 1.5°C AND 2°C SCENARIOS.

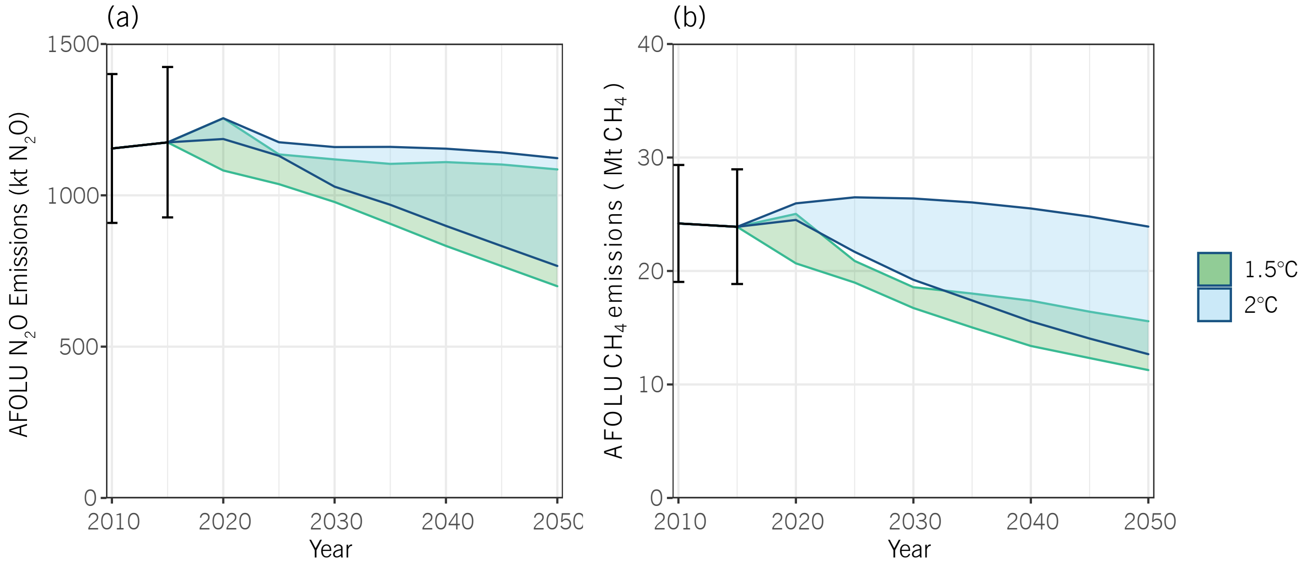
Includes scenarios from GCAM-China, MESSAGEix-GLOBIOM, AGHG-INV, and PECE. The solid black line shows the historical emissions and removals. The error bars illustrate the uncertainty of emissions and removals in the GHG inventory data as provided in the official Chinese communications to UNFCCC (Sources: PRC First and Second Biennial Update Report on Climate Change in 2016, 2019). All projections have been harmonized to the GHG Inventory estimate for 2014, using a fixed harmonization factor that stays constant over time.



Implement technical mitigation options (such as animal feed supplements, nitrification inhibitors or anaerobic digesters) and structural mitigation options (such as improved manure management, use of appropriate feed, crop and livestock production portfolio and shifts in international trade) within the Agricultural sector. Global and multi-model assessments have shown that the implementation of emission-reduction technologies and structural changes can provide significant emissions reductions in the Chinese Agriculture sector (Figure 4-24). The overall economic mitigation potential in the Chinese Agricultural sector has been estimated at 330 to 750 $MtCO_2eq/yr$ by 2050 at US$125/$tCO_2eq$. A majority of these emission reductions (30-94% of total emission reduction) would come from technical options such as animal feed supplements, nitrification inhibitors, or anaerobic digesters (Frank et al., 2016; Lin et al., 2019). Structural options can also provide large emissions reductions (17-49% of total emission reduction), mainly from shifts in management systems, crop and livestock production portfolios, and international trade. The largest cost-effective reduction potential in the agricultural sector is related to livestock management, including improved manure management and enteric fermentation through improving livestock productivity, use of appropriate feed, and the conversion of manure to compost (Lin et al., 2019). Compared with other sectors, however, there are limited technological measures or direct strategies for reducing non-CO_2 GHG emissions from agriculture in China (Lin et al., 2019).

FIGURE 4-24. PROJECTIONS OF N_2O AND CH_4 EMISSIONS FOR THE AFOLU SECTOR IN 1.5°C AND 2°C SCENARIOS.

Includes scenarios from GCAM-China, MESSAGEix-GLOBIOM, AGHG-INV, and PECE. The solid black line shows the historical emissions. The error bars illustrate the uncertainty of emission inventory data as provided in the official Chinese communications to UNFCCC (Sources: PRC First and Second Biennial Update Report on Climate Change in2016 and 2019). All projections have been harmonized to the GHG Inventory estimate for 2014, using a fixed harmonization factor that stays constant over time.



Transition to a healthier and more sustainable diet with lower environmental impacts. A transition to a sustainable diet would be of great value for achieving deep decarbonization, as international assessments have shown that the mitigation potential associated with dietary changes is large within China, which is on the order of 10 to 60 $MtCO_2eq$/yr by 2050 at US$125/$tCO_2eq$ (Frank et al., 2016).

Sustain and enhance China's forest carbon sink through continued efforts to afforest and re-forest the country. The Chinese LULUCF sector is a growing carbon sink, due largely to successful afforestation efforts, stringent protection of natural forests, enhancement of ecological systems, and adoption of strict ecological improvement measures. Given the key role that forest land plays in the Chinese LULUCF sector, securing and further enhancing the forest sink is key for safeguarding a low-carbon transition for the country. For example, in the 1.5°C (2°C) MESSAGEix-GLOBIOM scenario, national forest area increases by 34 Million hectares (27 Million hectares), by 2050 compared with 2015 levels. Afforestation and reforestation not only generate more carbon sinks, they also provide co-benefits related to many other ecosystem services, such as biodiversity and reduction of air and water pollutants. However, when planning these large-scale activities, it is important to properly assess the interlinkages between sectors and potential for the displacement of land-based activities. Land is inherently a finite resource. Extending the forest coverage may displace agricultural production and subsequently increase GHG emissions from other sectors.

A key uncertainty that would require further assessment is the potential for biomass production in China that could support bioenergy use to reduce CO_2 emissions across the energy sector while safeguarding and enhancing the land use sink. To date, there have been notable variations in projections of bioenergy potential, depending mainly on assumptions about land availability and inclusion of biomass feedstocks (e.g. Bauer et al., 2018; Jiang et al., 2019; Qin et al., 2018). It is essential to further assess the domestic potential across the full range of potential feedstocks, including forest residues, wood pellets, lignocellulosic crops, perennials, industrial by-products, agricultural residues, and to identify effective policies to mobilize these feedstocks while simultaneously avoiding potential negative impacts. Such an assessment can facilitate the discussions between scientific and policy communities.

Near-Term Challenges, Opportunities, and Actions

BOX 4-22. AFOLU: NEAR-TERM ACTIONS TO SUPPORT A LONG-TERM TRANSITION

- Continue to embrace sustainable agriculture by promoting circular agriculture, recycling of waste reduction, and increased resource use efficiency.
- Encourage the integration of new technologies and innovation, such as climate smart agriculture and artificial intelligence, in the agricultural sector.
- Continue to implement and enforce sustainable forest management to sustain and enhance the forest sink.
- Implement actions that provide synergies and actively consider the links between agriculture, water, pollution, biodiversity, diets and GHG emissions.

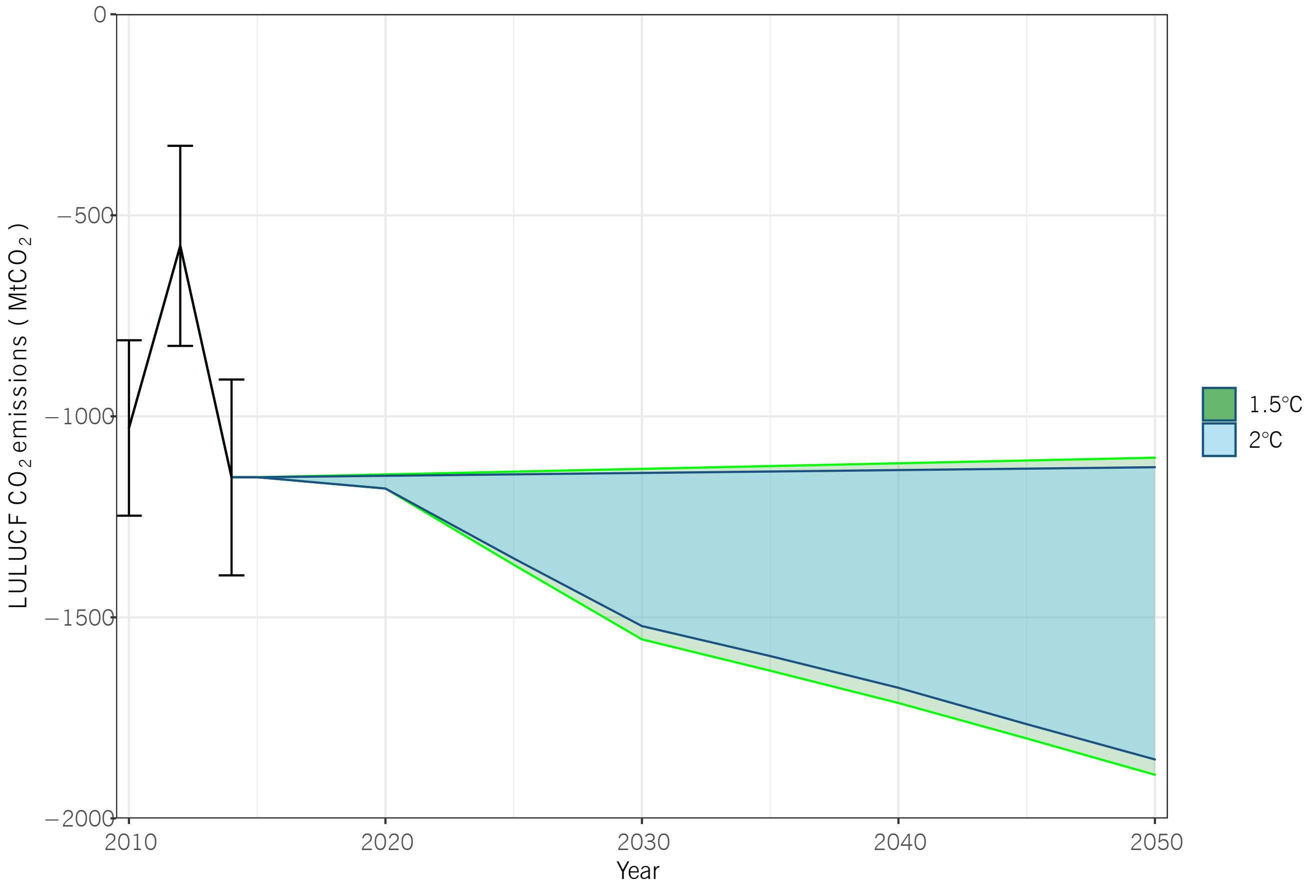
China will **Continue to embrace sustainable agriculture by promoting circular agriculture, recycling of waste reduction, and increased resource use efficiency.** The National Plan for Sustainable Development of Agriculture (2015-2030) clearly recognized environmental concerns as an integral part of national agricultural development in the coming years. It provides the framework for policies and actions, and sets out targets for ecological and circular agriculture development, waste reduction and recycling, resource use efficiency, and pollution reduction.

It is necessary to **encourage the integration of new technologies and innovation, such as climate smart agriculture and artificial intelligence, in the agricultural sector.** Technology and innovation will play an increasingly important role in agricultural development. However, Chinese agriculture still has room to better incorporate the latest science and technology. Innovation remains at a relatively low level. With breakthroughs and diffusion of more advanced technologies, technical innovation could greatly improve resource efficiency and mitigate the environmental impacts of Chinese agriculture. In particular, innovation and new technologies need to improve upon key crop-soil-water-nutrient balances, and policy innovations are required to encourage comprehensive integration of new technologies into farms across the country.

A crucial element of a short-term strategy is to **continue to implement and enforce sustainable forest management to sustain and enhance the forest sink.** The LULUCF is currently a net sink for China, but carbon neutrality in China will likely call for substantial carbon removals to offset residual fossil and non-biogenic emissions that are either too difficult or too costly to abate by other means. However, scenarios include a high uncertainty in the development of the LULUCF sink. In the 1.5°C (2.0°C) scenarios explored in this study, the LULUCF sink ranges from a stable development to an enhancement of the sink by 560 $MtCO_2$-eq (520 $MtCO_2$-eq) by 2050 compared to 2015 levels (see Figure 4-25). The high uncertainty mainly relates to differences in the number and variety of mitigation options included in the different modeling frameworks. In general, the larger the set of mitigation options included in the model, the larger the reported LULUCF sink needs to be to limit warming. Because afforestation and reforestation can take decades to generate more removals, it is critical to plan today for the long-term transitions to an enhanced sink and to take action without delay.

FIGURE 4-25. NET CO_2 EMISSIONS FOR THE LULUCF SECTOR IN 1.5°C AND 2°C SCENARIOS.

Includes scenarios from GCAM-China, MESSAGEix-GLOBIOM, and PECE. . The solid black line shows historical net CO_2 emissions. The error bars illustrate the uncertainty of emission inventory data as provided in the official Chinese communications to UNFCCC (Sources: PRC First and Second Biennial Update Report on Climate Change in2016 and2019; PRC National Communication, 2012). All projections have been harmonized to the GHG Inventory estimate for 2014, using a fixed harmonization factor that stays constant over time.



The most promising mitigation measures to secure and enhance the LULUCF sink (e.g. reduced impact logging, close-to-nature management, improved plantations, changes in harvest intensity, optimization of thinning). Because forests play such a crucial role in retaining the LULUCF sink, forest management plays a key role in the future development of the LULUCF sink. This means that continued application of sustainable, ecological, tree-species and site-specific management practices remain key in ensuring the viability of the forest carbon sink (Zhou et al., 2013). Improvements in forest management offer large mitigation potential and are a cost-effective approach that can be implemented without changes in tenure in numerous cases (Griscom et al., 2017). Sustainable forest management practices aimed at providing timber and/or different ecosystem services can increase removals and contribute to climate change adaptation (IPCC, 2020).

This means that policy makers need to further implement, enforce, and potentially incentivize the application of sustainable and ecological forest management practices amongst various practitioners. Approaches for implementing these practices are numerous and include legislating the application of site-specific management practices, enhanced enforcement where illegal practices occur, education of practitioners, implementation of forest certification schemes, and tightening control of biomass consumers. Many of these actions are also in synergy with actions that improve air quality and biodiversity, if handled in a manner appropriate for the local context.

Mitigation policies in the AFOLU sector should identify innovative ways of addressing challenges, including how to motivate the participation of millions of farmers and changes in their behavior. With 200–300 million households, each of which farms a few hectares of land, the agricultural system relies heavily on high-to-excessive inputs (Cui et al., 2018). In 2010, about 70% of Chinese farms were less than 2 ha, while on average in the rest of the world, about 7% of farms are less than 2 ha (Wu et al., 2018). The choice of options also needs to account for impacts on yields and material inputs, and robust institutional arrangements (Lin et al., 2019).

There are also substantial co-benefits for carbon mitigation from policies and technologies that raise water and nutrient efficiency or control the flow of pollution into water. It will be important to **enhance actions that provide synergies and actively consider the links between agriculture, water, pollution, biodiversity, diets, and GHG emissions,** for example, how to secure self-sufficiency of more than 90% of major food products.

BOX 4-23. FOOD SECURITY, WATER, BIODIVERSITY, AND CLIMATE MITIGATION

The benefits of reducing carbon emissions from the AFOLU sector extend well beyond climate mitigation. Many land-related mitigation options, such as nutrient management and waste management, have adaptation co-benefits, which can enhance the resilience of agriculture and help secure food supply (Fujimori et al., 2019). A transition to healthy and sustainable diets can also contribute to food security. However, mitigation policies in the AFOLU sector should be carefully designed so as to avoid significant yield losses. Afforestation or avoided deforestation can also reduce desertification and land degradation and enhance the provision of ecosystem services. But through the competition for land, it also poses risks for food security and could lead to food price increases (Kreidenweis et al., 2016).

5. THE ROLE OF THE FINANCIAL SECTOR IN A LONG-TERM STRATEGY

The financial sector is pivotal in China's low-carbon transition. One critical issue in the near term is how to finance this transition. Specifically, what innovative financial tools and policy instruments are available to transform the market and scale up clean energy investment? Financial institutions and policy makers should also plan for the long term to avoid lock-in and stranded assets. The current financial and regulatory system needs to adapt and factor in possible physical and transition risks associated with climate change.

Meanwhile, the risk-return profile of financial institutions may change significantly. Their assets could be affected by clean energy policies, new technologies, and physical impacts of climate change, implying weaker growth and lower asset returns. Financial institutions and organizations in which they invest need to consider a transition strategy that diversifies their investment portfolios (Section 5.1) and manages potential risks (Section 5.2). Policy makers also need to act proactively, creating enabling conditions for this transition.

BOX 5-1. KEY APPROACHES TO SUPPORT INVESTMENT IN CHINA'S LOW-CARBON TRANSITION

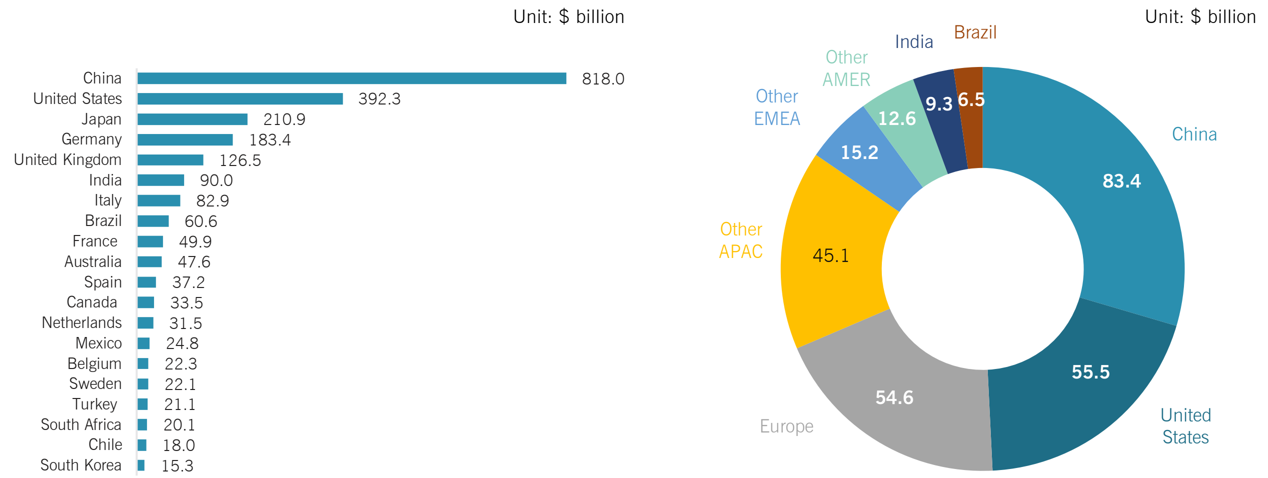
- Regulatory actions that provide price certainty in environmental markets and discourage unsustainable practices can significantly stimulate demand for green products and services among banks.
- Fiscal policies need to be adjusted to drive systematic change and overcome institutional inertia, by diversifying sources of government revenues at national, provincial, and local levels to reduce carbon entanglement, aligning fiscal and budgetary incentives with ambitious climate targets, and harnessing the power of public procurement and spending towards low-carbon transitions.
- A diversified set of financial instruments are needed for long-term transitions, including both established products and tools (e.g. bonds, grants, and loans) and innovative financial instruments (e.g. green bonds and green banks).
- Policy makers need to improve the financial system to support long-term transitions, such as enhancing greater market transparency and improving data disclosure, appropriately valuing risks in the financial system, and using fintech to create new opportunities for mobilizing private investment in climate finance.
- China's low-carbon transition needs to mobilize a substantial amount of investment from institutional investors, such as pension funds, insurance companies, sovereign wealth funds, and mutual funds.
- Successful public-private partnership can allow limited public dollars to go further by leveraging private dollars, facilitate low-cost market growth, and enable job creation and economic development.

5.1 FINANCING A LONG-TERM TRANSITION

China is leading the expansion of clean energy investment around the world. Between 2010 and 2019, nearly $2.7 trillion was invested globally in renewables (excluding large hydro), three to four times higher than the amount invested between the previous decades (UNEP and BNEF, 2020). China alone contributed to 30% of this growth and has remained the world's top investor in renewable energy installation since 2013 (Figure 5-1).

FIGURE 5-1. TOP 20 MARKETS IN RENEWABLE ENERGY CAPACITY INVESTMENT BETWEEN 2010 AND 2019 (PANEL A) AND INVESTMENT IN RENEWABLE ENERGY CAPACITY IN 2019 (PANEL B).

Investment estimates exclude investment in large hydro projects. Data are shown in billion 2019 U.S. dollars. The estimated values of investment in 2019 include estimates for undisclosed deals. China's renewable investment dropped from $143 billion in 2017 to $83.4 billion in 2019. (Source: UNEP and BNEF, 2020)



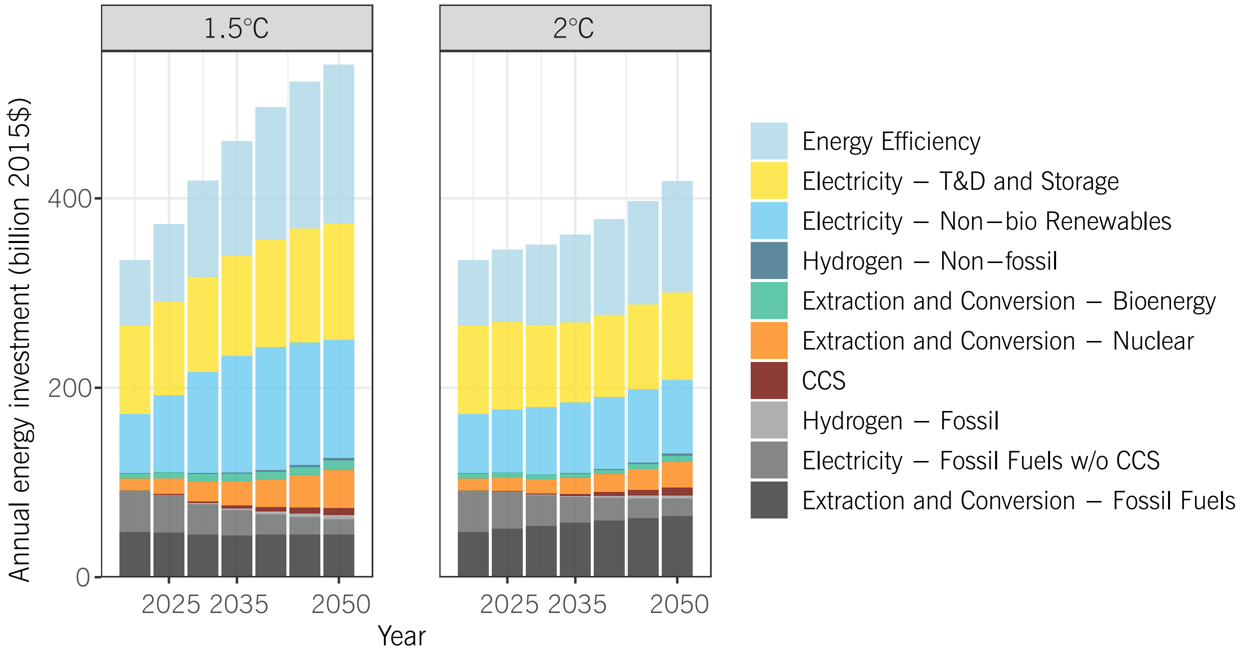
With this investment, China has paved a path for a low carbon transition. While fossil energy investments continue to dwarf investments into renewable energy and energy efficiency globally, China's clean energy investment has outweighed its fossil energy investment. In 2016, China's investment in renewable energy and energy efficiency was $167 billion, accounting for 55% of its total energy investment (the share of fossil investment was 34%), whereas clean energy investment represented only 33% of total energy investment globally (the share of fossil investment was 50%) (IEA, 2018).

However, a low-carbon transition in line with the new growth pathway requires further scaling up the clean energy investment, posing significant financial opportunities and challenges in both the near and long term. Globally, to meet the current national climate pledges under the Paris Agreement, McCollum et al. (2018) estimated that an extra $130 billion per year needs to be invested in energy efficiency and clean energy in the next decade; this increases to $460 billion per year in order to limit global temperature rise to 1.5°C, generating new investment opportunities.

Similarly, China needs a rapid upscaling and structural change of investments in energy infrastructure. Zhou et al. (2019) estimated that annual energy investment would increase to $540 billion to limit warming to 1.5°C ($420 billion for 2°C), compared to $340 billion in current policies/NDC scenarios. Meanwhile, to reach 1.5/2°C goals, the share of low-carbon investment in total energy investment will increase significantly. By 2035 annual low-carbon investment in China would need to grow by 40% (2°C) and 110% (1.5°C) from 2015 levels ($160 billion), reaching $220 billion (2°C) and $330 billion (1.5°C); it would need to grow $280 billion (2°C) and $420 billion (1.5°C) by 2050 (Figure 5-2). Rapid electrification and a low-carbon transition will require large investments in the electricity system that focus on renewable energy and generation with CCUS, transmission and distribution networks, and large-scale storage. Investments in energy efficiency will also increase rapidly, as there are significant low-cost opportunities to reduce emissions through efficiency improvements in buildings and industry (see Box 5-2).

FIGURE 5-2. CHINA'S ANNUAL ENERGY INVESTMENT BY CATEGORY IN 1.5°C AND 2°C SCENARIOS.

(Source: Zhou et al., 2019)



BOX 5-2. INVESTMENT NEEDS OF DIFFERENT SECTORS IN CHINA'S LOW-CARBON TRANSITION

Power sector

- Ramping up investment in renewable generation
- Ramping up investment in storage technologies
- Expanding and modernizing grid infrastructure and transmission systems
- Establishing dedicated funds to support a coal phase-out and just transition
- Increasing investment in other clean energy technologies (e.g. large scale hydro, CCUS, nuclear)
- Accelerating investment in smart technologies and renewable energy integration

Non-Electric Transformation

- Spurring investment in hydrogen R&D, new applications, and clean hydrogen supply and infrastructure
- Increasing investment in advanced biofuels

Buildings

- Expanding investment in building energy efficiency

Industry

- Expanding investment in industrial energy efficiency
- Upgrading industrial technologies/facilities (e.g. hydrogen, CCUS)
- Building a modernized industrial sector through innovative manufacturing and organization modes

Transportation

- Increasing investment in EV and other novel transportation technologies
- Investing in transport infrastructure to facilitate mode changes and integration of EVs and smart technologies

Investment decisions made today will directly impact transition pathways and costs in the future. The next five years are a critical window, as policy and investment decisions made now can shape the development trajectories in the next few decades. Investment in clean energy infrastructure needs to be scaled up substantially in the coming years to support a broader development and economic transition in China.

However, a number of barriers could obstruct this clean energy investment. These barriers include high upfront costs for customers, real and perceived investor risks, unrealistic financing terms that erode project economics, institutional and policy barriers, information asymmetries for both customers and investors, and inadequacy of traditional government subsidy programs to drive real market growth.

Changes in both policies and financial instruments are needed to overcome these barriers, and this is especially critical for underserved market segments, such as building energy efficiency and less mature technologies (e.g. CCUS, hydrogen). To overcome these barriers, we are offering the following key approaches for China to seize the opportunities to scale up investments and fulfill its low-carbon transition.

Regulatory actions that provide price certainty in environmental markets and discourage unsustainable practices can significantly stimulate demand for green products and services among banks. Moreover, coherent, long-term policy goals can de-risk deployment of clean energy technologies and mobilize more private capital to clean energy investment. Near- and long-term energy policies discussed in Section 4, if well implemented, can facilitate the growth of clean energy investment.

Fiscal policies need to be adjusted to ensure fiscal sustainability for a low-carbon future. Efforts are needed to make systematic change. This will include actions to diversify government revenue streams at national, provincial, and local levels to reduce carbon entanglement, design fiscal and budgetary incentives towards the carbon neutrality goal, and use public procurement and spending to drive markets towards low-carbon transitions (OECD et al., 2018). Public finance is critical in terms of creating market signals towards clean energy technologies, especially early-stage technologies that are promising but have higher risks (e.g. CCUS and hydrogen) (Mazzucato and Semieniuk, 2018).

Engaging private sector capital is critical to this transition. Financial and energy policy makers need to identify ways to engage the private sector in financing and developing clean energy infrastructure. This requires the creation of enabling conditions and policy frameworks, in particular, changes in the financial system. Enhancing greater market transparency and improving data on performance, risks, costs, and investment opportunities are essential to promote clean energy investment as an asset class and leverage more private sector investment. For example, China Securities Regulatory Commission (CSRC) released a timetable for introducing mandatory Environmental, Social, and Corporate Governance (ESG) disclosure for all listed companies as early as 2020, but there is still a long way to go. Appropriately estimating risks in the financial system by broadening risk concepts and time horizons can help investors plan for risks and opportunities associated with low-carbon transitions (see Section 5.2 for a discussion on risks). Digitalization also brings new opportunities for mobilizing private investment in climate finance (see Box 5-3). The Chinese government is actively engaging in international activities (e.g. Task Force on Climate-related Financial Disclosures (TCFD) and Network for Greening the Financial System) to reset the financial system in line with long-term transitions in China and globally.

BOX 5-3. DIGITALIZATION AND GREEN FINANCE: FINTECH PROMOTES LOW-CARBON DEVELOPMENT

Fintech has the potential to make it easier for private capital to invest in clean energy projects and scale up green finance in China. First, it facilitates the standardization and better management of contracts, which in turn reduces costs and facilitates the assessment and tracking of projects. Second, it strengthens the availability, transparency, and reliability of data, which could result in advanced analysis and better management of investment risks. Third, it disperses finance broadly and allows a wide range of investors to invest directly in low-carbon projects.

People's Bank of China (PBoC), for example, developed a Green Finance Information Management System (GFIMS) that collects and analyzes green finance flows across jurisdictions and allows for the central-level PBoC to standardize and develop strategic decisions for future green finance development. The GFIMS is an information management platform for green lending data. Enabled by big data, artificial intelligence, cloud computing, and other technologies, it functions as a repository for green lending data, statistics and analytics, regulations, and policy implementation strategies. PBoC is currently carrying out a pilot program in Huzhou. In the long term, the system can inform the development of the national green finance system, help financial regulators manage green finance information in real time, and provide data to support macro policymaking.

Sources: OECD et al., 2018; Paulson Institute, 2020.

China's low-carbon transition can succeed by mobilizing significant new investments from the private sector, especially institutional investors, such as pension funds, insurance companies, sovereign wealth funds, and mutual funds (EaP Green, 2017). While attitudes in this community have been changing rapidly, some institutional investors have not yet developed a strong appetite for clean energy investment due to lack of awareness and/or capacity. Regulators can continue to encourage these investors and other stakeholders to develop ESG products, report via ESG disclosure, and educate investors (Ma et al., 2020).

Established products and tools or innovative financial instruments can finance China's low-carbon transition. Established financing mechanisms, such as bonds, grants, and loans, can leverage proven pathways for infrastructure investment by adding environmental value. China launched the green bond market in 2016 and has issued 184 green bonds ($74 billion) since then, primarily covering air pollution control, transportation, and renewable energy. Meanwhile, green bonds only account for a small share (~2%) of total bond issuance in China and have great potential for growth. It is estimated that green bonds would need to make up 20% of total bond issuance in China to meet the market need for clean energy investment. To achieve this growth, several actions need to be taken to lower risks and reduce uncertainties, such as harmonization of taxonomy, improvement in standardization and information disclosure, engagement of institutional investors, and expansion to underserved markets such as green buildings (Ma et al. 2019).

Innovative financing mechanisms also need to be developed to accelerate clean energy investment. Green investment banks or clean energy finance authorities, for example, have been gaining growing interests globally in financing low-carbon transitions. A green investment bank is a public or quasi-public financial institution that provides financing options and market development tools in partnership with the private sector to encourage and hasten adoption of clean energy technologies, energy efficiency, or other low-carbon, climate-resilient infrastructure. It is an effective public-private partnership that helps address market barriers, facilitate low-cost market growth, enable job creation and economic development, and allow public dollars to go further (see Box 5-4).

BOX 5-4. GREEN INVESTMENT BANKS: INNOVATIVE PUBLIC-PRIVATE PARTNERSHIP TO FINANCE CLIMATE SOLUTIONS

A green investment bank, also known as a clean energy finance corporation or clean energy finance authority, is a public or quasi-public financial institution that leverages private capital to invest in low-carbon transitions and accelerate the growth of clean energy markets. Green banks usually include a mandate to mobilize private investment using public funds by intervening in the market to mitigate risks and enable transactions. Green banks in the U.S., for example, on average have the leverage ratio of 1:8 (for every $1 of public funds committed, private capital is attracted into the market for a total investment in green projects of $8), and this ratio can be as high as 1:20.

There are more than 16 green banks globally, from country to city level. Green banks can be capitalized with a variety of funding sources, including government appropriations and programs (such as repurposing funds from existing programs), utility funds (ratepayer funds, surcharges, etc.), revenues from carbon taxes and emissions trading schemes, and bond issuance. Once in operation, green banks take part in multiple activities including taking financing techniques such as credit support, co-investment, and securitization; offering financing products such as loans, leases, and credit enhancements; conducting market development such as technical assistance, turn-key product design and delivery, and access to information; and collecting, analyzing, and reporting data.

A bill for creating a national U.S. Green Bank (USGB) was introduced in the Congress in 2019, with the purpose of financing climate solutions at scale and bringing clean energy investment to underserved markets. If enacted as is, the USGB would deploy up to $35 billion in capital through the network of state and local green banks and is expected to mobilize $1 trillion towards climate actions. It would accelerate low-carbon transitions by directly investing in communities affected by fossil fuel phaseout and financing clean energy projects.

Source: Frech et al., 2020.

5.2 RISKS TO THE FINANCIAL SECTOR

The financial sector will be increasingly exposed to and impacted by the physical risks from climate change. Damages caused by more frequent and severe extreme events and long-term temperature change and sea level rise could reduce asset values and increase insurance payments, imposing both acute and chronic risks to the banking and insurance industries. In 2017, the overall losses caused by natural disasters amounted to roughly $340 billion, and insurers had to pay out a record $138 billion to cover the insured (Munich RE, 2018). This number was $52 billion in 2019 (Munich RE, 2020). To maintain financial stability, it is crucial for the financial sector to take into account the risks of climate change.

While mitigating the physical risks from climate change, low-carbon transition may also bring risks to the financial sector if they are not prepared for in advance or properly managed. China's low-carbon transition will entail extensive policy, regulatory, technology, and market changes to mitigate and adapt to climate change. These changes can pose different levels of market and reputational risks to banks, insurance companies, and asset owners. Transition risks are different across sectors, asset types, geographical regions, and time frames. A large-scale coal phase out in China (and Chinese investments overseas) could pose challenges to the financial system from extensive stranded assets and devaluation of the companies owning them, and these impacts are expected to be greater in certain regions.

The transition to a greener economy can also bring opportunities to the Chinese financial sector (see Figure 5-3). For example, there is growing evidence that organizations have successfully reduced operating costs by improving efficiency in production and distribution processes. Investment in new energy sources and technologies (e.g. wind, solar, CCUS, storage) brings new opportunities to the financial sector. Financial institutions can proactively seek opportunities in new markets or asset types to diversify their investment portfolio and prepare for the low-carbon transition. For example, Goldman Sachs and JPMorgan Chase recently announced restrictions on financing fossil fuel infrastructure. New opportunities can also be captured by underwriting or financing green bonds and infrastructure (e.g. low-carbon energy production, grid connectivity, or transport networks).

FIGURE 5-3. CLIMATE RELATED RISKS, OPPORTUNITIES, AND FINANCIAL IMPACTS.

(Source: TCFD, 2017)

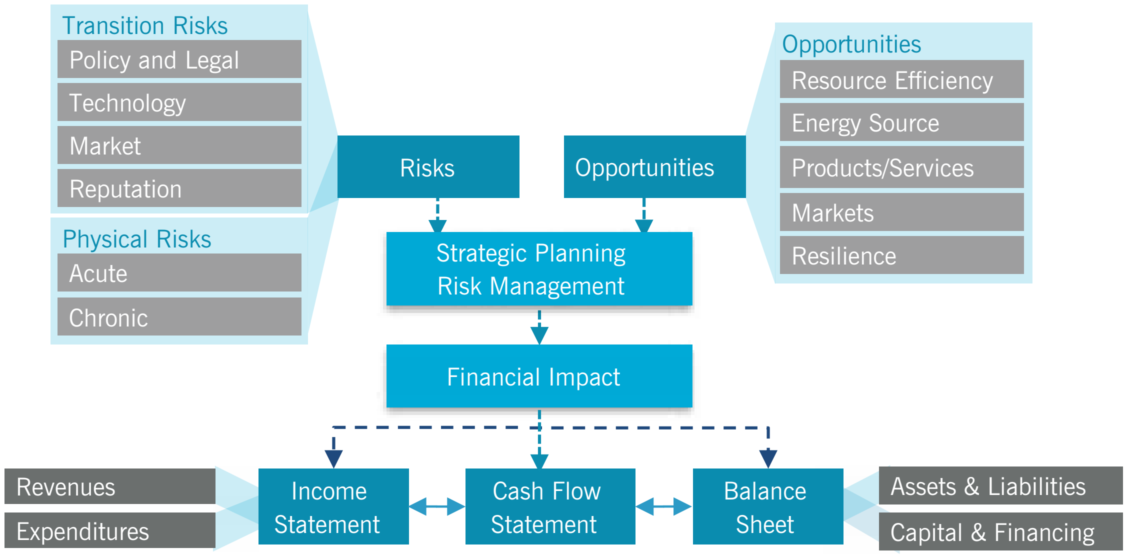
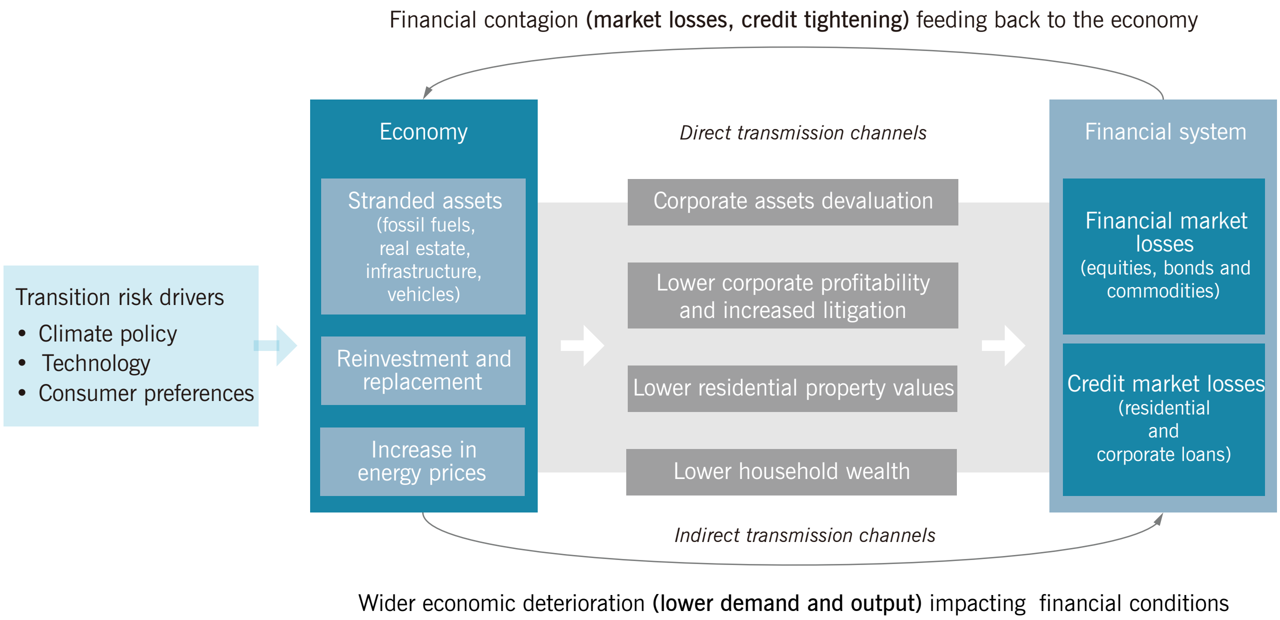


FIGURE 5-4. TRANSITION RISK STRESS TEST.

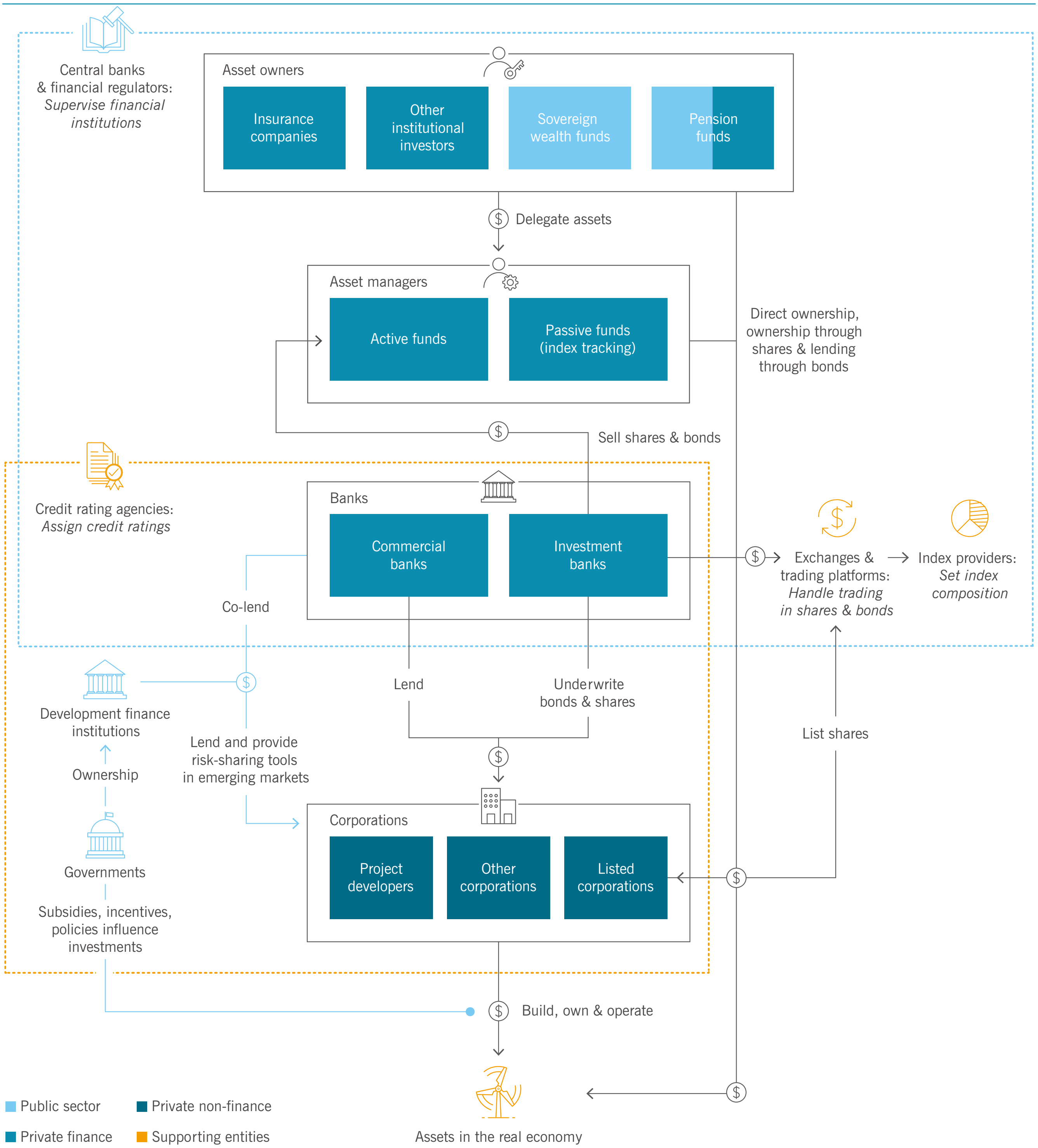
(Source: NGFS, 2020)



Financial institutions will need to take actions to facilitate the low-carbon transition and address physical and transition risks. To manage potential physical and transition risks, financial institutions need to: first, assess current investment portfolios exposed to these risks and explore opportunities to mitigate and diversify them; second, analyze potential financial impacts at the asset level, and evaluate options to improve resilience; and third, incorporate impacts of physical and transition risks into financial models and quantify returns, investment options, and exit strategy.

FIGURE 5-5. ROLES OF DIFFERENT FINANCIAL INSTITUTIONS IN MANAGING RISKS.

(Source: CFLI, 2019)



The Chinese central bank and other financial regulators are taking into account climate-related financial risks and undertaking policy designs and actions to echo the high-quality growth goal. China wants to take more leadership in international financial market rule setting and has made a good start. The PBoC attached great importance to climate-related risks and their links to macroeconomic stability. Deputy Minister of PBoC, Chen Yulu, has emphasized the potential risks that climate change will pose to financial stability on many occasions and has indicated that PBoC is incorporating climate risks into macro prudential assessment (MPA) and is investigating how the macroeconomy and the financial sector interact in response to the transition risks. Meanwhile, in the beginning of 2020, the China Banking and Insurance Regulatory Commission issued the *Guideline on High-quality Development of Banking, Insurance sectors,* and called for China's banks and other financial institutions to establish and improve the environmental and social risk management systems and enhance institutional capacity by setting up green finance departments to facilitate green lending and manage potential environmental and social risks. The goal of these actions is to ensure the high-quality development of the banking and insurance industries in response to China's economic downturn due to COVID-19, but, importantly, environmental and climate risk elements have become a priority in the credit granting process.

In May 2020, the PBoC, NDRC, and CSRC jointly released a draft guidance document that, for the first time, excludes "clean coal" and other fossil energy projects from being funded by green bonds. Delisted projects include ultra-low emissions retrofitting of coal-fired power plants, cleaner production and utilization of coal, retrofit and operation of flexible coal-fired power generation for peak shaving, facilities for unconventional oil and gas exploration and production, use of coalbed methane, and more. This is an important policy breakthrough that signals renewed momentum for further constraining coal growth in China.

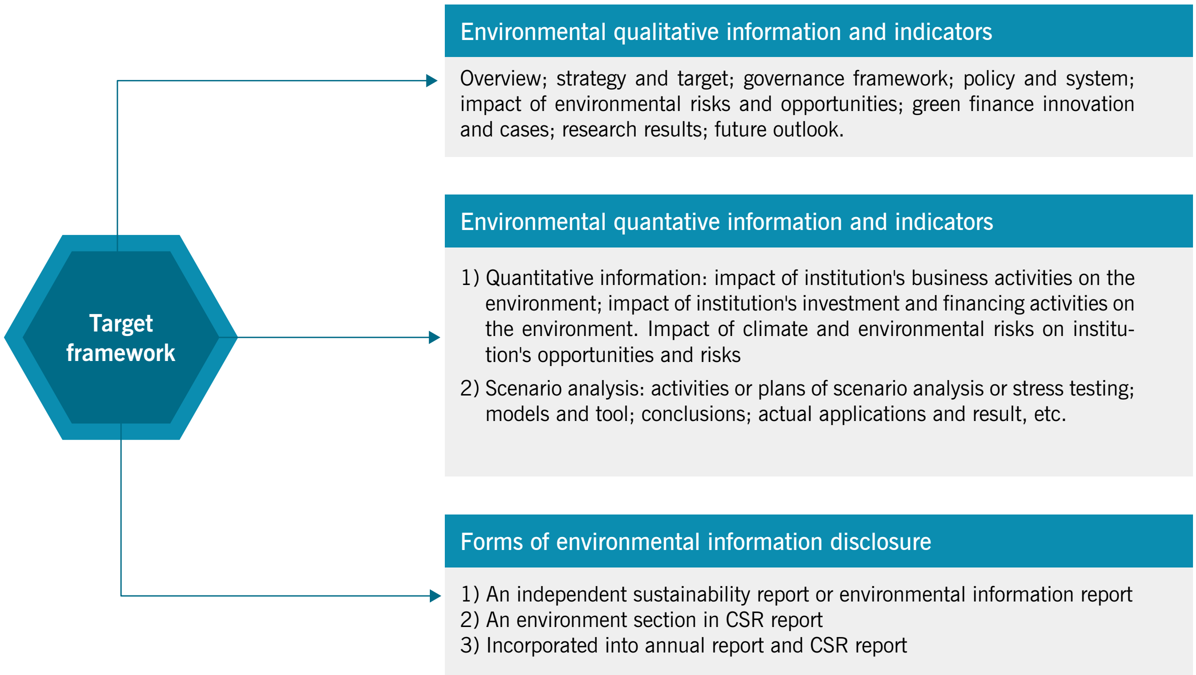
UK-China pilot on climate and environmental risk disclosure has made progress on the financial risk assessment for different financial institutions. This pilot will continue to expand and bring in more players. So far, the UK-China pilot has made several important breakthroughs. First, the pilot was expanded to include all financial sectors. The number of pilot participants increased from 10 to 13, covering all financial sectors, including banking, asset management and insurance. On the UK side, the government's Green Finance Initiative made an announcement requiring all listed companies and major asset management companies in the UK to disclose under the TCFD framework before 2022.

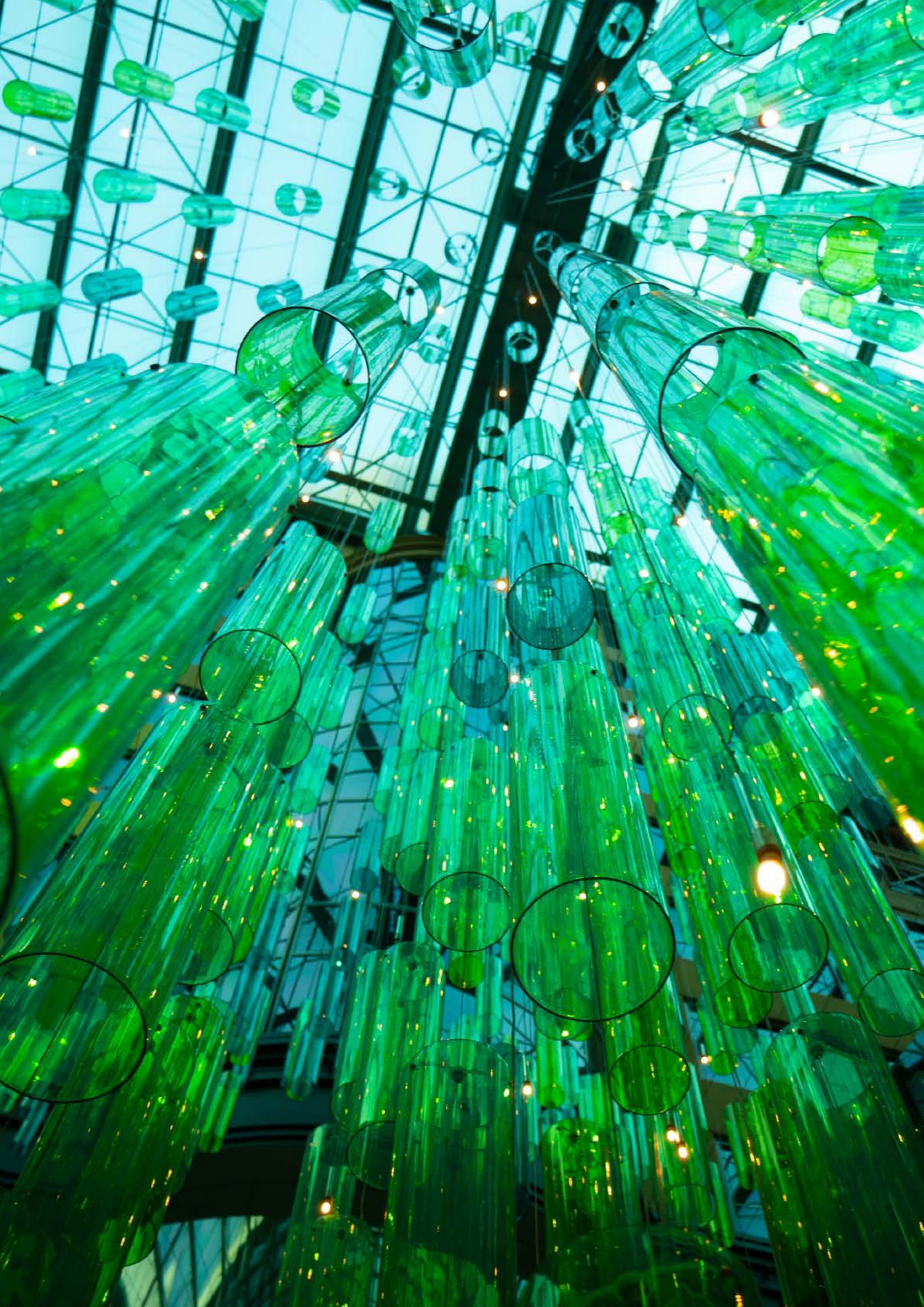
Second, the Chinese and UK participants disclosed climate and environmental information in accordance with TCFD recommendations and the Climate and Environmental Information Disclosure Framework developed in light of China's actual conditions. 2019 was the first phase of the Action Plan, and most of the Chinese participating institutions disclosed environmental information in separate disclosure reports.

Third, the pilot has been gradually increasing in influence. For example, Huzhou National Green Finance Reform Pilot Zone made overall disclosures with reference to the UK-China pilot framework. Moreover, financial institutions including ICBC, Industrial Bank, and China Emissions Exchange (CEEX), in accordance with the requirements of the PBoC, formed a task force of standards formulation that published the Guidelines for Financial Institution Environmental Information Disclosure on the basis of the pilot practices and results. Last, but not least, the pilot participants have taken part in international standard-setting and discussion.

FIGURE 5-6. 2019 PROGRESS REPORT OF UK-CHINA CLIMATE AND ENVIRONMENTAL INFORMATION DISCLOSURE PILOT.

(Source: UK-China Climate and Environmental Information Disclosure Pilot 2019 Progress Report, 2019)





6. CONCLUSIONS

China is poised today to accelerate its movement on a new growth pathway toward a clean, vibrant economy that provides broadly shared benefits across China—and in doing so, it can also lead internationally on delivering solutions and making a major contribution to address global climate change. China's carbon neutrality goal makes clear the ultimate destination for the new growth pathway, and China's vision for an ecological civilization and its broad development objectives provide additional guideposts for how to reach this goal. In every sector across the Chinese economy, key long-term strategies can be linked to near-term actions that can put China on a course to lower emissions and green development. The research and analysis presented in this report demonstrates that the process of moving toward carbon neutrality can also provide a comprehensive basis for the significant economic transformation to reach broader national goals. Moreover, significant steps have already been taken to start moving toward this new growth pathway.

Nevertheless, the goal remains challenging. It will require significant planning, analysis, and policy actions to set the course and build the new economy to achieve the vision. The actions that China takes today will be critical to successfully implement this strategy. Opportunities for accelerating this transition exist across all sectors of the economy and industrial sectors.

While the overall scope of activity and next steps across the economy are relatively clear, additional discussions and analysis will be needed to refine our understanding of long-term pathways and near-term actions and to develop policy approaches that balance diverse needs. Broadly, additional areas for development include:

- **Shared vision for a New Growth Pathway.** China's new growth pathway, rooted in its pledge to reach carbon neutrality before 2060, will be most successful if benefits to China's development objectives are well understood and shared across the country and the economy. New insight will be needed to understand how this can be best achieved.

- **Industrial transitions.** China's industrial transition on a new growth pathway and associated efforts to reduce industrial emissions will take place in the context of industrial modernization, China's overall economic strategy, and an evolving role in international markets. New insights and scenarios are needed to understand possible pathways and strategies.
- **Full economy coal phaseout.** New opportunities exist to achieve a structured phase-out of coal-fired electricity; and a full phase will require eliminating coal in other sectors, such as industry, and addressing just transitions across the full coal supply chain. A fuller picture of these transitions both nationally and regionally is needed.
- **Sustainable finance.** Mobilizing finance will be critical for green growth and will depend on the development of energy, fiscal and monetary, and financial policies. A deeper understanding of frameworks to comprehensively address these needs and address the risks inherent in climate finance is needed.
- **Technology and technology transitions.** Successful technology development and deployment is at the heart of climate mitigation; many technologies are already changing the emissions and economic landscape, while others are on the horizon and hold great promise. Greater understanding is needed of which technologies will be most important and the key development, deployment, and management needs to support their use at scale.
- **Non-CO_2 gases.** Multiple opportunities exist to reduce China's overall emissions from GHGs other than CO_2, including methane, nitrous oxide, and HFCs. But these opportunities are not yet well understood in many industrial and energy sectors.
- **Province-level strategy and actions.** Cutting across all of these dimensions is the need to understand opportunities, strategies, and actions in the provinces. As China continues to build policies that help it transition toward a green economy, the provinces will be a critical link to implement them. Helping provinces understand their own opportunities will be an important component of an overall national strategy.

China's path forward is clear. While there are undoubtedly challenges, building a strategy on the new growth pathway will help achieve goals not only for the overall economy, health, clean air, and broader prosperity, but will also transform the economy toward decarbonization in line with China's goals. The outcomes of this pathway will provide benefits to China and demonstrate China's leadership in setting the world on a global pathway to successfully address climate change.

7. REFERENCES

1. Aggarwal, S., & Orvis, R. (2016). Grid Flexibility: Methods for Modernizing the Power Grid. https://energyinnovation.org/wp-content/uploads/2016/05/Grid-Flexibility-report.pdf
2. Bauer, N., Rose, S. K., Fujimori, S. et al. (2018). Global Energy Sector Emission Reductions and Bioenergy Use: Overview of the Bioenergy Demand Phase of the EMF-33 Model Comparison. Climatic Change, 1–16. https://doi.org/10.1007/s10584-018-2226-y
3. Bodnar, P., Gray, M., Grbusic, T. et al. (2020). How to Retire Early: Making Accelerated Coal Phaseout Feasible and Just. Rocky Mountain Institute. https://rmi.org/insight/how-to-retire-early.
4. Bowen, A., Kuralbayeva, K., Tipoe, E.L. (2018). Characterising Green Employment: The Impacts of 'Greening' on Workforce Composition. Energy Economics 72, 263–275. https://doi.org/10.1016/j.eneco.2018.03.015
5. BP. (2019). Statistical Review of World Energy 2019. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf
6. BP. (2020). Statistical Review of World Energy 2020. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf
7. Bridle, R., Kitson, L., Duan, H., Sanchez, L., & Merrill, T. (2017). At the Crossroads: Balancing the Financial and Social Costs of Coal Transition I]in China. International Institute for Sustainable Development. Global Subsidies Initiative. https://www.iisd.org/system/files/publications/crossroads-balancing-financial-social-costs-coal-transition-china.pdf
8. Caldecott, B., Sartor, O., Spencer, T. (2017). Lessons from Previous 'Coal Transitions' High-level Summary for Decision-makers. IDDRI and Climate Strategies. https://www.iddri.org/sites/default/files/import/publications/coal_synthesisreport_v04.pdf
9. China Electricity Council (CEC). (2016). Yearly Statistics of China Power Industry 2016.
10. CEC. (2017). Yearly Statistics of China Power Industry 2019.
11. CEC. (2018). Yearly Statistics of China Power Industry 2019.
12. CEC. (2019). Yearly Statistics of China Power Industry 2019.
13. CEC. (2020). Yearly Statistics of China Power Industry 2020.
14. Chen, Y., Shen, H., Smith, K. R. et al. (2018a). Estimating Household Air Pollution Exposures and Health Impacts from Space Heating in Rural China. Environment International, 119, 117–124. https://doi.org/10.1016/j.envint.2018.04.054
15. Chen, X., Xiao, R., Yan, S., Li, B. et al. (2018b).Statistics Survey Analysis Report of China Expressway Transportation 2017. China Communication Press.
16. Cheng, J., Tong, D., Zhang, Q. et al. (2020). Pathways of China's PM2.5 air quality 2015-2050, submitted to National Science Review
17. China Academy of Transportation Sciences (CATS). (2020). Research on Low-carbon Emissions Strategies and Pathway of China's Transport Sector. Internal report: unpublished
18. China Coal Cap project. (2019). China Coal Cap Project - Thirteenth Five-Year Plan Coal Cap Mid-term Review and Outlook. http://coalcap.nrdc.cn/datum/info?id=86&type=1
19. China Council for an Energy Efficient Economy (CCEEE). (2019). China Energy Efficiency 2018.
20. China Electric Power Planning and Engineering Institute (EPPEI). (2019). China Electricity Development Report 2019.

21. China Merchants Securities. (2020). New Infrastructure Drives Demand for Upstream Metal Products. https://finance.sina.com.cn/roll/2020-07-03/doc-iircuyvk1855033.shtml.2020-07-03(2020-10-24)

22. Climate Finance Leadership Initiative (CFLI). (2019). Financing the Low-Carbon Future: A Private-Sector View on Mobilizing Climate Finance. https://greenfinanceplatform.org/research/financing-low-carbon-future-private-sector-view-mobilizing-climate-finance

23. Communist Party of China (CPC) Central Committee. (2020). Proposals for Formulating the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035. http://www.gov.cn/zhengce/2020-11/03/content_5556991.htm

24. Cui, R., N. Hultman, K. Jiang, H. et al. (2020). A High Ambition Coal Phaseout in China: Feasible Strategies through a Comprehensive Plant-by-Plant Assessment. Center for Global Sustainability: College Park, Maryland. 37 pp.

25. Cui, Z., Zhang, H., Chen, X. et al. (2018). Pursuing Sustainable Productivity with Millions of Smallholder Farmers. Nature, 555(7696), 363–366. https://doi.org/10.1038/nature25785

26. Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term Economic Growth Projections in the Shared Socioeconomic Pathways. Global Environmental Change, 42, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

27. Du, Y., Ge, Y., Ren, Y. et al. (2018). A Global Strategy to Mitigate the Environmental Impact of China's Ruminant Consumption Boom. Nature Communications, 9. https://doi.org/10.1038/s41467-018-06381-0

28. EaP Green. (2017). Unlocking Private Finance for Energy Efficiency and Greener, Low-carbon Growth. OECD Publishing. https://www.oecd.org/environment/outreach/Discussion%20Paper%20Brussels%2029-30%20June%20Final.pdf

29. Energy Research Institute (ERI). (2020). Research on Industrial Sector Transformation and Upgrading and Low-Carbon Emission Strategies and Approaches.

30. Fei, T. (2018). Coal transition in China. Options to Move From Coal Cap to Managed Decline under an Early Emissions Peaking Scenario. IDDRI and Climate Strategies. https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Rapport/20180609_ReportCOAL_China_0.pdf

31. Frank, S., Havlík, P., Stehfest, E.et al. (2018). Agricultural Non-CO_2 Emission Reduction Potential in the Context of the 1.5 °C Target. Nature Climate Change, 9(1), 66–72. https://doi.org/10.1038/s41558-018-0358-8

32. Frech, J., Lou, J., Yu, S. et al.(2020). Public-Private Partnership and Clean Energy Finance: the Green Bank Model. Center for Global Sustainability, University of Maryland, College Park, MD. 51pp.

33. FTSE Russell. (2018). Investing in the Global Green Economy: Busting Common Myths. https://content.ftserussell.com/sites/default/files/research/fr_investing_in_the_global_green_economy.pdf

34. Fujimori, S., Hasegawa, T., Krey, V. et al. (2019). A Multi-Model Assessment of Food Security Implications of Climate Change Mitigation. Nature Sustainability, 2(5), 386–396. https://doi.org/10.1038/s41893-019-0286-2

35. Gales, B., Hölsgens, R. (2017). Coal Transition in the Netherlands. IDDRI and Climate Strategies. https://www.iddri.org/en/publications-and-events/report/coal-transition-netherlands

36. Gilfillan, D., Marland, G., Boden, T., and R. Andres. (2019). Global, Regional, and National Fossil-Fuel CO_2 Emissions. https://energy.appstate.edu/CDIAC

37. Global Energy Monitor. (2020). Global Coal Plant Tracker. https://endcoal.org/global-coal-plant-tracker/

38. Griscom, B. W., Adams, J., Ellis, P. W. et al. (2017). Natural Climate Solutions. PNAS, 114(44), 11645-11650. https://doi.org/10.1073/pnas.1710465114, https://doi.org/10.5281/zenodo.883444

39. Hamshere, P., Sheng, Y., Moir, B. et al. (2014). What China wants: Analysis of China's food demand to 2050. ABARES conference paper 14.3. Canberra. March.

40. He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020a). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. Nature Communications, 11(1), 2486. doi:10.1038/s41467-020-16184-x https://www.nature.com/articles/s41467-020-16184-x

41. He, G., Lin, J., Zhang, Y. et al. (2020b). Enabling a Rapid and Just Transition away from Coal in China. One Earth, 3(2), 187-194. doi:10.1016/j.oneear.2020.07.012

42. He, J., Li, Z., Zhang, X. (2020c). China's Low Carbon Development Strategy and Transformation Path: A Synthesis Report. 2020. Institute of Climate Change and Sustainable Development, Tsinghua University. 2020.

43. Herpich, P., Brauers, H., Oei, P.-Y. (2018). A Historical Case Study on Previous Coal Transitions in Germany. IDDRI and Climate Strategies. https://www.iddri.org/en/publications-and-events/report/coal-transition-germany

44. Huang, H., Roland-Holst, D., Springer, C. et al. (2018). Emissions Trading Systems and Social Equity: A CGE Assessment for China. Applied Energy 235 (November 26, 2018): 1254–65. https://doi.org/10.1016/j.apenergy.2018.11.056

45. Huang, H., Roland-Holst, D., Springer, C., Cai, W. (2019). How Will an Emissions Trading System Affect Household Income and Social Equity? A CGE-Based Case Study of China.Energy Procedia 158 (February 2019): 4017–22. https://doi.org/10.1016/j.egypro.2019.01.838.

46. Huang, H., Roland-Holst, D., Wang, C., Cai, W. (2020). China's Income Gap and Inequality under Clean Energy Transformation: A CGE Model Assessment. Journal of Cleaner Production 251, 119626. https://doi.org/10.1016/j.jclepro.2019.119626

47. International Energy Agency (IEA). (2018). World Energy Investment 2018. https://www.iea.org/reports/world-energy-investment-2018

48. IEA. (2019a). China Power System Transformation: Assessing the Benefit of Optimised Operations and Advanced Flexibility Options. https://webstore.iea.org/china-power-system-transformation

49. IEA. (2019b). CO_2 Emissions from Fuel Combustion 2019. https://webstore.iea.org/co_2-emissions-from-fuel-combustion-2019

50. IEA (2019c). World Energy Balances and Statistics. https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics

51. IEA. (2020a). CO_2 Emissions from Fuel Combustion for China. https://www.iea.org/data-and-statistics?country=CHINAREG&fuel=CO_2%20emissions&indicator=CO_2BySource

52. IEA. (2020b). Global Energy Review 2020: The Impacts of the COVID 19 Crisis on Global Energy Demand and CO_2 Emissions. https://www.oecd-ilibrary.org/energy/global-energy-review-2020_a60abbf2-en

53. IEA. (2020c). Tracking Power 2020. https://www.iea.org/reports/tracking-power-2020

54. IEA. (2020d). World Energy Balances 2020. https://www.iea.org/reports/world-energy-balances-overview

55. Intergovernmental Panel on Climate Change (IPCC) (1990). IPCC First Assessment Report. IPCC, Geneva: WMO.

56. IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf

57. IPCC. (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp. https://www.ipcc.ch/sr15/chapter/spm/

58. IPCC. (2019). Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

59. International Renewable Energy Agency (IRENA). (2019a). Innovation Landscape Brief: Electric-vehicle Smart Charging. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_EV_Smart_Charging_2019.pdf?la=en&hash=E77FAB7422226D29931E8469698C709EFC13EDB2

60. IRENA. (2019b). A New World: The Geopolitics of the Energy Transformation. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2019/Jan/A-New-World-The-Geopolitics-of-the-Energy-Transformation

61. IRENA. (2020). Renewable Energy and Jobs – Annual Review 2020. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2020/Sep/Renewable-Energy-and-Jobs-Annual-Review-2020

62. Jiang, D., Hao, M., Fu, J., Liu, K., & Yan, X. (2019). Potential Bioethanol Production from Sweet Sorghum on Marginal Land in China. Journal of Cleaner Production, 220, 225–234. https://doi.org/10.1016/j.jclepro.2019.01.294

63. Jiang, Y., Zhou, Z., & Liu, C. (2018). The Impact of Public Transportation on Carbon Emissions: A Panel Quantile Analysis Based on Chinese Provincial Data. Environmental Science and Pollution Research, 26(4), 4000–4012. https://doi.org/10.1007/s11356-018-3921-y

64. Kreidenweis, U., Humpenöder, F., Stevanović, M. et al.(2016). Afforestation to Mitigate Climate Change: Impacts on Food Prices under Consideration of Albedo Effects. Environmental Research Letters, 11(8), 085001. https://doi.org/10.1088/1748-9326/11/8/085001

65. Lal, R. (2018). Sustainable Intensification of China's Agroecosystems by Conservation Agriculture. International Soil and Water Conservation Research, 6(1), 1–12. https://doi.org/10.1016/j.iswcr.2017.11.001

66. Li, Y., Lukszo, Z., & Weijnen, M. (2016). The Impact of Inter-Regional Transmission Grid Expansion on China's Power Sector Decarbonization. Applied Energy, 183, 853-873. doi: https://doi.org/10.1016/j.apenergy.2016.09.006

67. Li, M., Zhang, D., Li, C.-T. et al. (2018). Air Quality Co-Benefits of Carbon Pricing in China. Nature Climate Change, 8(8), 750. https://doi.org/10.1038/s41558-018-0241-7

68. Li, N., Chen, W., Rafaj, P. et al. (2019). Air Quality Improvement Co-benefits of Low-Carbon Pathways toward Well Below the 2 °C Climate Target in China. Environmental Science & Technology, 53(10), 5576–5584. https://doi.org/10.1021/acs.est.8b06948

69. Li, X., Fan, Y., & Wu, L. (2017). CO_2 Emissions and Expansion of Railway, Road, Airline and In-Land Waterway Networks over the 1985–2013 Period in China: A Time Series Analysis. Transportation Research Part D: Transport and Environment, 57, 130–140. https://doi.org/10.1016/j.trd.2017.09.008

70. Li, Y., Zeng, B., Wu, T., & Hao, H. (2019). Effects of Urban Environmental Policies on Improving Firm Efficiency: Evidence from Chinese New Energy Vehicle Firms. Journal of Cleaner Production, 215, 600–610. https://doi.org/10.1016/j.jclepro.2019.01.099

71. Lin, J., Khanna, N., Liu, X., Teng, F., & Wang, X. (2019). China's Non-CO_2 Greenhouse Gas Emissions: Future Trajectories and Mitigation Options and Potential. Scientific Reports, 9. https://doi.org/10.1038/s41598-019-52653-0

72. Lin, J., Xu, L., & Gang, H. (2020). Regional Electricity Demand and Economic Transition in China. Utilities Policy, 64, 101047. doi: https://doi.org/10.1016/j.jup.2020.101047

73. Liu, L., Wang, K., Wang, S., Zhang, R., and Tang, X (2018). Assessing Energy Consumption, CO_2 and Pollutant Emissions and Health Benefits from China's Transport Sector through 2050. Energy policy, 116, 382-396. https://doi.org/10.1016/j.enpol.2018.02.019

74. Liu, J., Kiesewetter, G., Klimont, Z. et al. (2019a). Mitigation Pathways of Air Pollution from

Residential Emissions in The Beijing-Tianjin-Hebei Region in China. Environment International, 125, 236–244. https://doi.org/10.1016/j.envint.2018.09.059

75. Liu, J., Wang, K., Xiahou, Q. et al. (2019b). China's Long-Term Low Carbon Transition Pathway under the Urbanization Process. Advances in Climate Change Research, 2019. https://www.sciencedirect.com/science/article/pii/S167492781930108X

76. Liu, J., Xiahou, Q., Wang, K. et al. (2019c). Research on Mid-to-long-term Low Carbon Development Pathway of China's Industry Sector (in Chinese). China Soft Science, 2019(11):31-41+54.

77. Liu, Z., Ciais, P., Deng, Z., Lei, R. et al. (2020). Near-real-time Monitoring of Global CO_2 Emissions Reveals the Effects of the COVID-19 Pandemic. Nature communications, 11(1), 5172. https://doi.org/10.1038/s41467-020-18922-7

78. Lu, X., Cao, L., Wang, H. et al. (2019). Gasification of Coal and Biomass as A Net Carbon-Negative Power Source for Environment-Friendly Electricity Generation in China. Proceedings of the National Academy of Sciences, 116(17), 8206–8213. https://doi.org/10.1073/pnas.1812239116

79. Lugovoy, O., Feng, X., Gao, J. et al. (2018). Multi-model Comparison of CO_2 Emissions Peaking in China: Lessons from CEMF01 Study, 2018. Advances in Climate Change Research, Volume 9, Issue 1, 2018, Pages 1-15. https://www.researchgate.net/publication/323248522_Multi-model_comparison_of_CO_2_emissions_peaking_in_ChinaLessons_from_CEMF01_study

80. Ma, D., Chen, W., Yin, X. and Wang, L. (2016). Quantifying the Co-Benefits of Decarbonization in China's Steel Sector: An Integrated Assessment Approach. Applied energy, 162, 1225-1237. https://doi.org/10.1016/j.apenergy.2015.08.005

81. Ma, J., Liu, J., Chen, Z., & Xie, W. (2019). China's Green Bond Market. Research Center for Green Finance Development.Beijing. https://www.climatebonds.net/resources/reports/china-green-bond-market-2019-research-report

82. Ma, J., Cheng, L., Chen, Y., & Wu, Y. (2020). China's Pioneering Green Finance. Beijing. http://eng.pbcsf.tsinghua.edu.cn/upload/default/20200321/d566b30adccb62eab7a0e67cc656fa3f.pdf

83. Mazzucato, M., & Semieniuk, G. (2018). Financing Renewable Energy: Who is Financing What and Why it Matters. Technological Forecasting and Social Change, 127, 8–22. https://doi.org/10.1016/j.techfore.2017.05.021

84. McCollum, D. L., Zhou, W., Bertram, C. et al. (2018). Energy Investment Needs for Fulfilling the Paris Agreement and Achieving the Sustainable Development Goals. Nature Energy, 3(7), 589–599. https://doi.org/10.1038/s41560-018-0179-z

85. Ministry of Ecology and Environment (MEE). (2018). Bulletin of China's Ecological Environment Status 2018.

86. Ministry of Transport (MOT). (2020). 2005-2019 Statistical Bulletin on the Development of the Transportation Industry. http://www.mot.gov.cn/fenxigongbao/hangyegongbao/index_1.html

87. Ministry of Human Resources and Social Security (MHRSS). (2019). The New Occupations released by MHRSS, SAMR, and NBS. http://www.mohrss.gov.cn/SYrlzyhshbzb/dongtaixinwen/buneiyaowen/201904/t20190403_313788.html

88. Mohler, D., & Sowder, D. (2017). Chapter 23 - Energy Storage and the Need for Flexibility on the Grid. In L. E. Jones (Ed.), Renewable Energy Integration (Second Edition) (pp. 309-316). Boston: Academic Press.

89. Munich RE. (2018). A stormy year – Natural disasters in 2017. https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/topics-geo-2017.html

90. Munich RE. (2019). Tropical Cyclones Cause Highest Losses Natural Disasters of 2019. https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/natural-disasters-of-2019-in-figures-tropical-cyclones-cause-highest-losses.html

91. Muro, M., Tomer, A., Shivaram, R., & Kane, J. W. (2019). Advancing Inclusion through Clean Energy Jobs. https://www.brookings.edu/research/advancing-inclusion-through-clean-energy-jobs/

92. Nam, K.-M., Waugh, C. J., Paltsev, S., Reilly, J. M., & Karplus, V. J. (2013). Carbon co-benefits

of Tighter SO2 and NOx Regulations in China. Global Environmental Change, 23(6), 1648–1661. https://doi.org/10.1016/j.gloenvcha.2013.09.003

93. National Bureau of Statistics (NBS). (2018). China Statistical Yearbook 2018. China Statistics Press, Beijing. http://www.stats.gov.cn/tjsj/ndsj/2018/indexeh.htm

94. NBS. (2019). China Statistical Yearbook 2019. China Statistics Press, Beijing. http://www.stats.gov.cn/tjsj/ndsj/2019/indexeh.htm

95. NBS. (2020). Increase of 2019 Retail Sales in China. http://www.stats.gov.cn/tjsj/zxfb/202001/t20200117_1723391.html

96. Network for Greening the Financial System (NGFS). (2020). Guide for Supervisors Integrating Climate-related and Environmental Risks into Prudential Supervision. https://www.ngfs.net/en/guide-supervisors-integrating-climate-related-and-environmental-risks-prudential-supervision

97. OECD/The World Bank/UN Environment (2018), Financing Climate Futures: Rethinking Infrastructure, OECD Publishing, Paris, https://doi.org/10.1787/9789264308114-en.

98. OECD. (2019). Innovation and Business/Market Opportunities Associated with Energy Transitions and a Cleaner Global Environment. https://www.oecd.org/g20/summits/osaka/OECD-G20-Paper-Innovation-and-Green-Transition.pdf.

99. Paul Institute. (2020). How a Local Chinese Bank Used Fintech to Go Green. https://www.paulsoninstitute.org/green-finance/green-scene/how-a-local-chinese-bank-used-fintech-to-go-green/

100. PRC First and Second Biennial Update Report on Climate Change in 2016 and 2018

101. PRC First, Second and Third National Communication in 2004, 2012 and 2018

102. Purohit P., Höglund L., & Wagner F. (2018). Impacts of the Kigali Amendment to Phase-down Hydrofluorocarbons (HFCs) in Asia. IIASA Report. Laxenburg, Austria. http://pure.iiasa.ac.at/id/eprint/15274/

103. Qin, Z., Zhuang, Q., Cai, X. et al. (2018). Biomass and Biofuels in China: Toward Bioenergy Resource Potentials and Their Impacts on the Environment. Renewable and Sustainable Energy Reviews, 82, 2387–2400. https://doi.org/10.1016/j.rser.2017.08.073

104. Roelfsema, M., van Soest, H.L., Harmsen, M. et al. (2020). Taking Stock of National Climate Policies to Evaluate Implementation of the Paris Agreement. Nature Communication 11, 2096 https://doi.org/10.1038/s41467-020-15414-6

105. Sartor, O. (2018). Implementing coal transitions: Insights from Case Studies of Major Coal-Consuming Economies. https://www.iddri.org/en/publications-and-events/report/implementing-coal-transition-insights-case-studies-major-coal

106. Shaanxi Meteorological Administration (SN-CMA). (2020). Emissions of Four Main Kinds of HCFCs Peaked by 2015. http://sn.cma.gov.cn/xwmk/qxkp/202003/t20200318_1494675.html

107. Shi, Y., Sun, J., Wu, L. (2018). Analysis on the Synergistic Effect of Sustainable Development of Coal Industry under 1.5 °C Scenario. Advances in Climate Change Research 9, no. 2 (June 2018): 130–37. https://doi.org/10.1016/j.accre.2018.05.003

108. State Grid Energy Research Institute (SGERI). (2018). China Energy and Electricity Outlook.

109. Task Force on Climate-related Financial Disclosures (TCFD). (2017). Recommendations of the Task Force on Climate-related Financial Disclosure. https://assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf

110. Tsinghua University Building Energy Research Center (THUBERC). (2016). 2016 Annual Report on China Building Energy Efficiency. China Architecture and Building Press, Beijing.

111. THUBERC. (2019). 2019 Annual Report on China Building Energy Efficiency. China Architecture and Building Press, Beijing.

112. THUBERC. (2020). 2020 Annual Report on China Building Energy Efficiency. China Architecture and Building Press, Beijing.

113. Tong, D., Zhang, Q., Liu, F. et al. (2018). Current Emissions and Future Mitigation Pathways of Coal-Fired Power Plants in China from 2010 to 2030. Environmental Science & Technology, 52(21), 12905–12914. https://doi.org/10.1021/acs.est.8b02919

114. Tong, D., Cheng, J., Liu, Y. et al. (2020). Dynamic Projection of Anthropogenic Emissions in China: Methodology and 2015–2050 Emission Pathways under A Range of Socio-Economic, Climate Policy, and Pollution Control Scenarios. Atmospheric Chemistry and Physics, 20(9), 5729–5757. https://doi.org/10.5194/acp-20-5729-2020

115. U.S. Energy Information Administration (EIA). (2018). Residential Demand Module - NEMS Documentation. Available from: https://www.eia.gov/analysis/pdfpages/m067index.php

116. U.S. EIA. (2020). Short-Term Energy Outlook. https://www.eia.gov/outlooks/steo/report/

117. UK-China Climate and Environmental Information Disclosure Pilot. (2019). UK-China Climate and Environmental Information Disclosure Pilot 2019 Progress Report. https://www.unpri.org/download?ac=10546

118. United Nations Framework Convention on Climate Change (UNFCCC). (2019). National Inventory Submissions. https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019

119. United Nations, Department of Economic and Social Affairs, Population Division (UN-DESA) (2018). World Urbanization Prospects 2018. https://population.un.org/wup/

120. UN-DESA. (2019). World Population Prospects 2019, Volume II: Demographic Profiles. (ST/ESA/SER.A/427). https://population.un.org/wpp/graphs/1_Demographic%20Profiles/China.pdf

121. UNEP & BNEF. (2020). Global Trends in Renewable Energy Investment 2020. https://www.fs-unep-centre.org/wp-content/uploads/2020/06/GTR_2020.pdf

122. van den Berg, N. J., van Soest, H. L., Hof et al. (2020). Implications of Various Effort-Sharing Approaches for National Carbon Budgets and Emission Pathways. Climatic Change, 162(4), 1805–1822. https://doi.org/10.1007/s10584-019-02368-y

123. Wang, Q. (2018). Energy Data. iGDP supported by Energy Foundation China.

124. Wang, Q. (2020a). Energy Data of 2019 supported by Energy Foundation China.

125. Wang, Y., Xiahou, Q., Wang, K. (2020b). The Impact of Renewable Energy Development on Industrial Materials and Carbon Emissions in China. http://www.globalchange.umd.edu/iamc/wp-content/uploads/2020/01/31_wang.pdf

126. Wilkes, A. & Zhang, L. (2016). Stepping Stones towards Sustainable Agriculture in China: An Overview of Challenges, Policies and Responses. IIED, London. http://pubs.iied.org/14662IIED

127. World Bank. (2020). China Overview. https://www.worldbank.org/en/country/china/overview

128. World Development Indicators (WDI) | DataBank. (2020). [GDP per capita, PPP], World Bank. https://databank.worldbank.org/source/world-development-indicators

129. Wu, Y., Xi, X., Tang, X. et al. (2018). Policy Distortions, Farm Size, and the Overuse of Agricultural Chemicals in China. Proceedings of the National Academy of Sciences, 115(27), 7010–7015. https://doi.org/10.1073/pnas.1806645115

130. Xie, C., Bai, M., & Wang, X. (2018). Accessing Provincial Energy Efficiencies in China's Transport Sector. Energy Policy, 123, 525–532. https://doi.org/10.1016/j.enpol.2018.09.032

131. Xin, L. (2018). Prediction of Food Consumption and Grain Demand in Chinese Mainland. Chinese Journal of Engineering Science, 20(5), 135. https://doi.org/10.15302/j-sscae-2018.05.020

132. Xinhuanet. (2017, November 3). President Xi Jinping's Speech Delivered at the 19th National Congress of the Communist Party of China. Xinhuanet. http://www.xinhuanet.com/english/special/2017-11/03/c_136725942.htm

133. Xinhuanet. (2020, September 22). Xi Focus: Xi Announces China Aims to Achieve Carbon Neutrality before 2060. Xinhuanet. http://www.xinhuanet.com/english/2020-09/23/c_139388764.htm

134. Xu, Y., Li, J., & Wan, J. (2017). Agriculture and Crop Science in China: Innovation and Sustainability. The Crop Journal, 5(2), 95–99. https://doi.org/10.1016/j.cj.2017.02.002

135. Xu, J.D., Xie, S.X., Han, A.H. et al. (2019). Forest Resources in China–the 9th National Forest Inventory. National Forestry and Grassland Administration, Beijing, 29.

136. Xu, M., & Singh, S. (2020, April 20). China's April Electricity Consumption Rebounds as Lockdown Measures Ease. Reuters. https://www.reuters.com/article/china-power/chinas-april-electricity-consumption-rebounds-as-lockdown-measures-ease-idUSL4N2C81C1

137. Yang, J., Li, X., Peng, W., Wagner, F., & Mauzerall, D. L. (2018). Climate, Air Quality and Human Health Benefits of Various Solar Photovoltaic Deployment Scenarios in China in 2030. Environmental Research Letters, 13(6), 064002. https://doi.org/10.1088/1748-9326/aabe99

138. Yang, Z., Peng, J., Wu, L. et al. (2020). Speed-guided Intelligent Transportation System Helps Achieve Low-Carbon and Green Traffic: Evidence from Real-World Measurements. Journal of Cleaner Production, 268, 122230. https://doi.org/10.1016/j.jclepro.2020.122230

139. Yashiro, T. (2009). Overview of Building Stock Management in Japan. CSUR-UT Series: Library for Sustainable Urban Regeneration, 15–32. https://doi.org/10.1007/978-4-431-74093-3_2

140. Yu, S., Horing, J., Liu, Q. et al. (2019). CCUS in China's Mitigation Strategy: Insights from Integrated Assessment Modeling. International Journal of Greenhouse Gas Control, 84, 204–218. https://doi.org/10.1016/j.ijggc.2019.03.004

141. Yu, S., Yarlagadda, B., Siegel, J. E., Zhou, S., & Kim, S. (2020a). The Role of Nuclear in China's Energy Future: Insights from Integrated Assessment. Energy Policy, 139, 111344. https://doi.org/10.1016/j.enpol.2020.111344

142. Yu, J., Shao, C., Xue, C., & Hu, H. (2020b). China's Aircraft-Related CO_2 Emissions: Decomposition Analysis, Decoupling Status, and Future Trends. Energy Policy, 138, 111215. https://doi.org/10.1016/j.enpol.2019.111215

143. Yu, Y., Feng, K., Hubacek, K., & Sun, L. (2016). Global Implications of China's Future Food Consumption. Journal of Industrial Ecology, 20(3), 593–602. https://doi.org/10.1111/jiec.12392

144. Yuan, J., Xi, X., Meng, Z. et al. (2020). the Study on the Diversified Paths to Improve the Flexibility of China's Power System. https://www.greenpeace.org.cn/wp-content/uploads/2020/11/%E3%80%902020%E5%B9%B411%E6%9C%88%E6%9B%B4%E6%96%B0%E7%89%88%E6%8A%A5%E5%91%8A%E4%B8%8B%E8%BD%BD%E3%80%91.pdf

145. Zeng, W. S., Tomppo, E., Healey, S. P., & Gadow, K. V. (2015). The National Forest Inventory in China: History - Results - International Context. Forest Ecosystems, 2(1). https://doi.org/10.1186/s40663-015-0047-2

146. Zhongying, W., & Sandholt, K. (2019). Thoughts on China's Energy Transition Outlook. Energy Transitions, 3(1), 59-72. doi:10.1007/s41825-019-00014-w

147. Zhou, L., Wang, S., Kindermann, G. et al. (2013). Carbon Dynamics in Woody Biomass of Forest Ecosystem in China with Forest Management Practices under Future Climate Change and Rising CO_2 Concentration. Chinese Geographical Science, 23(5), 519–536. https://doi.org/10.1007/s11769-013-0622-9

148. Zhou, S., Wang, Y., Yuan, Z., & Ou, X. (2018). Peak Energy Consumption and CO_2 Emissions in China's Industrial Sector. Energy Strategy Reviews, 20, 113–123. https://doi.org/10.1016/j.esr.2018.02.001

149. Zhou, W., McCollum, D. L., Fricko, O. et al. (2019). A Comparison of Low Carbon Investment Needs between China and Europe in Stringent Climate Policy Scenarios. Environmental Research Letters, 14(5), 054017. doi:10.1088/1748-9326/ab0dd8

Energy Foundation

Learn more at:
www.efchina.org