GETTING TO NET ZERO

CHINA REPORT

PATHWAYS TOWARD CARBON NEUTRALITY

A REVIEW OF RECENT STUDIES ON MID-CENTURY EMISSIONS TRANSITION SCENARIOS FOR CHINA

A report led by
California-China Climate Institute (CCCI)

in collaboration with
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SERIES OVERVIEW

This series explores ways in which the United States and China can coordinate their near-term and mid-term efforts to achieve carbon neutrality by around the middle of this century, based on a review of deep decarbonization pathways studies in both countries. The series includes three reports: a synthesis report that develops a framework and recommends milestones for U.S.-China coordination on carbon neutrality, and two supporting reports that review and analyze recent deep decarbonization studies in the United States and China, respectively. This report contains the China review and analysis.

ABOUT THE CALIFORNIA-CHINA CLIMATE INSTITUTE

The California-China Climate Institute was launched in September 2019 and is a University of California-wide initiative housed jointly at UC Berkeley's School of Law (through its Center for Law, Energy & the Environment) and the Rausser College of Natural Resources. It is Chaired by Jerry Brown, former Governor of the State of California, and Vice-Chaired by the former Chair of the California Air Resources Board Mary Nichols. The Institute also works closely with other University of California campuses, departments and leaders. Through joint research, training and dialogue in and between California and China, this Institute aims to inform policymakers, foster cooperation and partnership and drive climate solutions at all levels.

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EXECUTIVE SUMMARY

As China signals its intention to strive towards meeting its commitment of peaking carbon dioxide (CO_2) emissions before 2030 and reaching carbon neutrality by 2060, recent modeling analyses by leading Chinese academic institutions and energy policy think-tanks highlight that multiple pathways exist to meet these goals, but will require an unprecedented scale and scope of transformation of the country's energy system. These analyses provide insights on the pace and scale of technology development and deployment, as well as the role for supporting policies, needed to meet China's domestic goals and support global efforts to meet a below 2°Celsius (C) temperature target.

Even before the September 2020 announcement of China's 2060 net carbon neutrality target, several Chinese universities and influential think-tanks that advise national energy policy development had started to explore deep decarbonization pathways consistent with the Paris Agreement goals. These modeling analyses and scenario projections represent some of the earliest findings related to the possible implications of 1.5°C and 2°C-compatible pathways for China that have informed China's carbon neutrality target. More recently, a multi-institution, multi-disciplinary analysis of 1.5°C compatible pathways for China led by Tsinghua University was published in late 2020, along with a December 2020 synthesis report of existing 1.5°C and 2°C scenarios led by Energy Foundation China that included multiple Chinese and international modeling teams. Two other international teams have analyzed deep national decarbonization pathways for China, with CO_2 emissions results in line with the Chinese studies.

This review and comparative assessment of 10 scenario pathways toward 2060 net carbon neutrality provides an understanding of the required level of technological development and deployment to meet this goal. It also highlights commonalities and variations in the underlying decarbonization strategies and policy support needed to realize this unprecedented transformation. This, in turn, helps inform the development of a framework for supporting coordination on carbon neutrality between the United States (U.S.) and China, including identifying technology pathways, common milestones, and priority areas for dialogue, alignment of goals and research and development spending, and international leadership.

Our comparative review of selected recent China-specific outlooks with 1.5°C or 2°C-compatible pathways or explicit net carbon neutrality goals found variations in the underlying assumptions about macroeconomic trends, energy-related activity drivers and outlooks, technological adoption, as well as methodological differences in the use of integrated global climate assessment models versus China-specific top-down and bottom-up energy models. Despite these differences, several overarching trends emerged.

Despite continued economic growth, projected energy demand reduction through energy efficiency and reduction in energy-consuming activity are expected.

- China's final energy consumption is likely to peak by 2025 in most 1.5°C scenarios and by 2030 in most 2°C scenarios, with the outlook for 2050 final energy demand ranging from staying flat to up to 30% reduction from today's level. This is notable given that all studies expect China's economy (in terms of gross domestic product, GDP) to increase by 3.5 to 4-fold from today's level, to reach the equivalent of nearly double the current U.S. economy.

- Different outlooks for low carbon energy technology adoption and integration contribute to a greater range in primary energy demand projections, with different peak years varying from 2025 to scenarios where primary energy plateaus by or continues to grow through 2050.

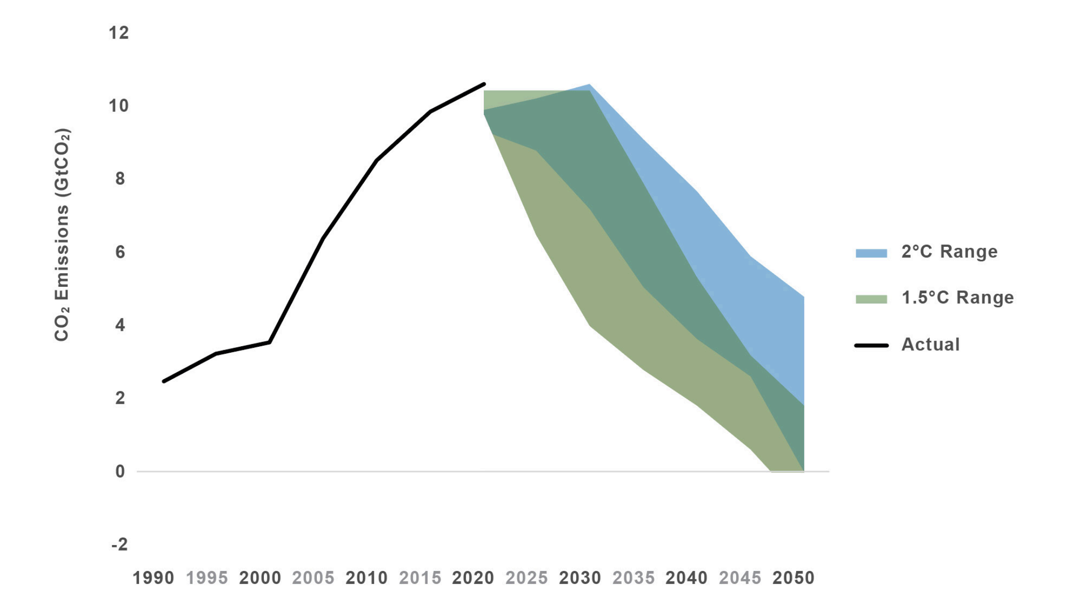
To achieve these energy reductions, energy efficiency and energy demand reduction are seen as key decarbonization strategies.

- Virtually all of the reviewed studies expect continuation of energy efficiency improvement at a pace consistent with recent trends, but the technical potential for future efficiency improvements varies greatly by end-use sector (buildings, transport, industry), ranging between 13 – 60% by 2050 depending on current efficiency of the sector. For instance, while China's cement industry is already efficient with more limited future gains, the diverse chemicals industry has greater remaining technical efficiency potential.
- Energy demand reduction is expected through structural change in industry toward less energy-intensive production and recycling materials through adoption of circular economy concepts, urban planning, lifestyle changes, and integration of innovative technologies. However, all studies reviewed lack detailed strategies or quantitative assessments at the more granular end use sector level for how to achieve these reductions (e.g., what actions can be taken to reduce how much of the emissions in order to decide near term and long-term priorities).

All of the 1.5°C and 2°C pathways suggest that CO_2 emissions will need to peak over the next decade, with dramatic reductions from current levels between 2030 and 2050.

Figure ES-1 illustrates the historical growth in energy-related CO_2 emissions, showing a four-fold increase from just over 2 gigatons of carbon dioxide ($GtCO_2$) in 1990 to an estimated 10.6 $GtCO_2$ in 2020. The blue shaded area shows the range of scenarios from the 2°C compatible studies, while the green shaded area represents the range of 1.5°C compatible studies reviewed in this report.

Figure ES-1 | Energy-Related CO2 Emissions in China: Historical (1990-2020) and Projected (1.5°C and 2 °C compatible, 2020-2050)



- All reviewed studies found that emissions of CO_2 peak between 2020 and 2030, with most studies finding the steepest drop in CO_2 emissions between 2030 and 2040.
- Nearly all 1.5°C-compatible scenarios find that CO_2 emissions needs to have peaked by 2020, while 2°C compatible scenarios find that CO_2 peaks by 2030.
- The remaining CO_2 emissions in 2050 depend heavily on assumptions about deployment of negative emission technologies, but reflect dramatic reductions of 50-100% below current levels in just the next 20 to 30 years.

The differences in energy and CO_2 emissions results highlight not only various underlying assumptions about the pace of technological improvements, adoption of innovative new technologies, and outlook on consumption and behavior that contribute to divergent trends, but also that multiple pathways towards net carbon neutrality exist for China. Underlying these different possible trajectories of achieving net zero CO_2 emissions by 2050 are several overarching decarbonization strategies that affect multiple sectors, as well as similarities and differences in policy interventions, investments and finance, technological changes, and research, development and deployment seen as necessary to support this transition.

Electrification in parallel with power sector decarbonization is a key pillar for reducing CO_2 emissions to near or net zero by mid-century.

- Of all potential strategies for replacing fossil fuels, non-fossil electricity is believed to provide the largest near-term opportunities for CO_2 emissions reductions due to available technology options for multiple end-use applications.
- Studies expect total economy-wide electrification rates in the range of 40-70% by 2050. Variations in electrification rates depend on assumptions about the adoption of more expensive commercialized technologies (e.g., heat pumps, electric trucks) and non-commercialized technologies (e.g., electrifying shipping and aviation).
- Buildings have one of the greatest sectoral potential for electrification given multiple commercialized electric alternatives, with up to 80-85% electrification by 2050 in a few studies. In the transport and industrial sectors, most studies focused on selected end-uses in on-road transport and cement, steel, and chemicals industries with uncertain electrification potential for specific hard-to-decarbonize subsectors such as aviation, shipping, and high-temperature heating for industrial processes.

In parallel with electrification, rapid power sector decarbonization is crucial to deep decarbonization.

- Solar and wind power resources are considered by all studies to play the most important role in decarbonizing the power sector, with a significant increase in their combined share of total generation from today's 9% to the range of 34-73% across studies by 2050, depending mostly on the scalability of nuclear power.
- An unprecedented pace of new renewable capacity installation is needed from now through 2050 to achieve these generation shares, including some projections of doubling of current capacities by 2025 and annual *new additions* on the order of 130 gigawatts (GWs) each for solar and wind individually. This is adding the equivalent of double North America (U.S., Canada and Mexico)'s *total* installed solar capacity on an annual basis, and the same as adding North America's *total* installed wind capacity annually. Whether such increases are feasible in terms of resources, manufacturing capacity, and scalability of storage to address intermittence issues, remains uncertain.
- Nuclear power is expected to continue to play some role in China's future power supply, but there is less consensus in the reviewed studies on its future role, with its projected generation share ranging from remaining constant at today's 5% share to increasing significantly to 28% of generation by 2050.
- For 1.5°C-compatible pathways, a mix of renewable resources including biomass, hydro, and nuclear will be needed to provide non-fossil generation shares of around 90% by 2050.
- In most studies, coal and/or natural gas power generation is expected to have a very limited role with a range of 7-35% share combined by 2050, down significantly from today's 68% share, and with most of the generation equipped with carbon capture and sequestration (CCS).

In addition, biofuels and hydrogen are expected to be deployed in subsectors and end-uses difficult to electrify. However, the role of biofuels may be constrained by limited domestic resources while hydrogen faces uncertain timelines, costs, and feasibility of scaled-up production. Lower supply from these low-carbon fuels requires higher rates of electrification to reduce emissions to levels consistent with 1.5°C or 2°C temperature targets.

POLICY RECOMMENDATIONS AND GOALS

All of the reviewed studies provide some policy recommendations and/or indicative policy goals for 2050, including the potential use of carbon pricing (including carbon trading), quantitative reduction targets, fuel switching measures, government procurement and greater investment and regulatory support for innovation and energy infrastructure. Several reports targeting policymakers also provided specific policy recommendations to achieve the stated 2050 goals and targets, but most focused on near-term actions for the 14^{th} Five-Year Plan (FYP). A comparison of these recommended 14^{th} FYP targets with the draft 14^{th} FYP targets announced in March 2021 found that the energy intensity reduction target of 13.5% and CO_2 intensity reduction target of 18% are not in-line with (i.e., less ambitious than) the below 2°C and a 1.5°C compatible pathways. Some reports focused on mid-term policy goals for the supply sectors, while others focused on near and long-term sectoral strategies. However, policy recommendations or indicative goals to close the gap between near-term actions and long-term end goals needed for pathways consistent with 1.5°C or near net neutrality for China are largely missing.

UNCERTAINTIES

The wide range in possible energy and CO_2 emission pathways for China to approach net carbon neutrality around 2050, as well as variations in the projected adoption rates and timeline for key energy efficient and decarbonization technologies, highlight areas of uncertainties that have not been explored sufficiently. Reducing these uncertainties is critical to the success of China's carbon peaking and neutrality goals.

For institutional change and transformation of the energy system, there are inherent uncertainties around the progress of industrial structural change needed to further decouple economic and energy consumption growth, given historically stagnant progress in decreasing the industrial share of GDP and uncertain future role for export-driven growth. Similarly, there is general recognition of the need to reduce energy demand but the role of lifestyle and behavior changes in contributing to demand reduction has not been explicitly addressed in existing studies nor included in strategies or policy interventions for supporting carbon neutrality.

There are still large uncertainties in the projected cost reductions and scale of investment costs needed to widely deploy commercialized decarbonization technologies such as heat pumps and heavy-duty electric vehicles. At the same time, there is also significant uncertainty around the high research, development, and deployment costs needed to increase the scale of non-commercialized technologies such as synthetic fuels for aviation, hydrogen for transport and industry, and electrification of specific industrial processes to make the modeled carbon neutrality pathways possible.

In addition to CO_2 emissions, future trends in other greenhouse gas (GHG) emissions such as methane and F-gases and the potential for geological and terrestrial sequestration could also impact global temperature changes but are rarely discussed in existing carbon neutrality studies. This suggests a continued need for research into the potential interactions between CO_2 and other GHGs, such as the potential for reducing both CO_2 and methane emissions from oil and gas systems, and the extent of reliance on negative emission technologies and terrestrial sequestration in limiting future global temperature rise.

The greatest uncertainty, however, is whether any of these scenarios can actually be realized given China's current energy and CO_2 emissions trajectories. As seen in Figure ES-1, all future scenarios envision a rapid peaking followed by a dramatic decline in CO_2 emissions starting in 2020 or 2030 – unlike anything seen in recent history for China or any other country in the world.

Without sufficient additional research to understand and address these uncertainties in policy and technology development and deployment, there will be greater risks in relying on specific non-commercialized technologies and unproven CO_2 emission reduction pathways to meet a target of limiting the global average temperature increase to 1.5°C. Development of additional long-term scenarios that account for and address these uncertainties would be valuable.

Development of a framework for supporting coordination on carbon neutrality between the two largest emitting countries, the U.S. and China, can provide an opportunity to jointly explore and address these uncertainties. Collaboration and coordination on ongoing research and analysis can help to make longer-term outlook studies more robust regarding these uncertainties and provide a stronger evidentiary basis for governments to set nearer-term policy and targets. The potential opportunities for U.S-China coordination on carbon neutrality are explored further in the series synthesis report, Getting to Net Zero: U.S.-China Framework and Milestones for Carbon Neutrality.

CHAPTER ONE
INTRODUCTION

There is growing interest in how China, as the world's largest energy consumer and carbon dioxide (CO_2) emitter, can strive towards net carbon neutrality in support of efforts to limit the average global temperature increase to 1.5°C above pre-industrial levels by 2100. In September 2020, President Xi pledged that China would peak its total CO_2 emissions before 2030 and become carbon neutral by 2060. While the specific definition of "carbon neutrality" is still to be determined, this recent 2060 carbon neutrality goal provides a clear signal of China's intention to define a new pathway that strives toward reaching net zero CO_2, or possibly net zero greenhouse gas, emissions by 2060.

The comparative analysis presented here is based on reviews of recent journal articles as well as technical and synthesis reports that include national scenarios and outlooks for China to 2050, consistent with global 1.5°C or 2°C-compatible pathways or explicit net carbon neutrality goals. By comparing different recent analyses of modeled pathways for China, we identify plausible paces of energy and CO_2 emission reductions through multiple technology and policy pathways and at sectoral levels. This helps provide an understanding of the required level of technological development and deployment as well as supporting policy efforts needed for China to strive towards meeting its 2060 net neutrality goal.

We begin with a discussion of the methodology and data, followed by a review of the macroeconomic assumptions underlying each scenario. We compare overall national energy and CO_2 emissions outlooks as well as key strategies and proposed milestones for key indicators of energy use and decarbonization in the different studies. We identify key differences in modeling methodologies and approaches, such as the use of integrated global climate assessment models versus China-specific top-down and bottom-up energy models, as well as variations in the underlying assumptions about macroeconomic trends, energy-related activity drivers and outlooks. We conclude with a detailed discussion of near and long-term policy strategies needed to support the pathways laid out in the reviewed studies.

CHAPTER TWO
METHODOLOGY AND DATA

This comparative review focuses on ten mid-century scenarios for China presented in seven recent reports (Table 1). These include two studies published in academic papers in 2017 and 2018 that focus explicitly on pathways for meeting a 1.5°C and 2°C temperature target[1] and two policy-oriented reports published in 2019 that explore a below 2°C pathway with emphasis on renewable development and a zero-carbon economy by 2050 pathway.[2] In late 2020, two multi-institution, multi-disciplinary analyses that included explicit 1.5°C compatible pathways for China were released. Tsinghua University's Institute for Climate Change and Sustainable Development (ICCSD) released a summary report and related journal paper of the research it led with other Chinese government institutions on long-term low carbon development strategy and scenarios that included 2°C and 1.5°C pathways in October 2020.[3] In December 2020, Energy Foundation China published a synthesis report of existing and new transition scenarios, including explicit 2°C and 1.5°C-compatible scenarios for China, from multiple Chinese and international energy modeling and research teams.[4] We also include Lawrence Berkeley National Laboratory's (Berkeley Lab's) Continuous Improvement Scenario,[5] which is a mid-century scenario of continuous improvement as defined below and not explicitly a carbon neutrality or 1.5°C-compatible scenario. The projected 2050 CO_2 emissions of the Berkeley Lab scenario are in-line with high range of the reviewed 2°C scenarios.

In addition to the data and information included in their published academic papers or reports, the modeling teams for each of the reviewed scenarios provided specific requested data and information to us directly so that we could ensure the best possible comparability between the various values and trends that are reviewed in this report.

We group the scenarios into those defined as being compatible with an average global temperature increase of 1.5°C above pre-industrial levels by 2100 ("1.5°C Compatible Scenarios"), those consistent with (or below) an average global temperature increase to 2°C ("2°C Compatible Scenarios"), and two additional scenarios that did not explicitly consider a global temperature target in their scenario storylines. Rather, these two "other" studies modeled a scenario "assuming China adopts the maximum shares of today's commercially available, cost-effective energy efficiency and renewable energy supply by 2050" in the case of Berkeley Lab's Continuous Improvement Scenario and a "feasible transition to zero carbon economy" by 2050 in the case of the Energy Transition Commission and Rocky Mountain Institute report.

For the period 2020-2050, we compare national final energy, primary energy, and CO_2 projections from these ten scenarios, noting that is not possible to directly compare the primary energy values due to different assumptions used to convert renewable (including hydro) and nuclear energy to primary energy.

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1 Pan et al. 2017. Note this paper includes multiple scenarios based on different carbon allocation methodologies. Our analysis focuses on a high scenario based on Responsibility-Capability-Need and a low scenario based on Equality; Jiang et al. 2018.

2 CNREC 2019; ETC 2019.

3 Tsinghua 2020.

4 EFC 2020. Note that this report synthesized the results of a number of scenarios. Our analysis focuses only on the high (PECE V2.0) and low (MESSAGEix-GLOBOIM) 2050 CO2 emissions scenarios from this report, to capture the full range of results.

5 Zhou et al. 2020.

Table 1 | Summary of Selected China Mid-Century Scenarios

Study and Organization	Scenario Name	Energy and CO_2 Outlooks	De-carbonization Strategies	Policy Discussion
1.5°C Compatible Scenarios				
Tsinghua University Institute for Climate Change and Sustainable Development (ICCSD) (lead)'s China's Long-term Low Carbon Development Strategy and Transition Pathways (Tsinghua 2020)	Tsinghua ICCSD Pathways 1.5°C Scenario	x	x	x
Energy Foundation China (EFC, lead)'s Synthesis Report on China's Carbon Neutrality (EFC 2020)	EFC Synthesis 1.5°C Scenarios– Low (MESSAGEix-GLOBOIM) EFC Synthesis 1.5°C Scenario - High (PECE V2.0)	x	x	x
Jiang Kejun, He Chenmin, et al. (Energy Research Institute, Peking University) Carbon Management paper (Jiang et al. 2018)	ERI/PKU 1.5°C Scenario	x	x	
~2°C Compatible Scenarios				
China National Renewable Energy Centre of Energy Research Institute (CNREC)'s China Renewable Energy Outlook Report (CNREC 2019)	CNREC Below 2°C Scenario	x	x	x
Tsinghua University Institute for Climate Change and Sustainable Development (ICCSD) (lead)'s China's Long-term Low Carbon Development Strategy and Transition Pathways (Tsinghua 2020)	Tsinghua ICCSD Pathways 2°C Scenario	x	x	x
Pan Xunzhang, Chen Wenying, et al. (China University of Petroleum, Tsinghua University, etc.) Energy Policy paper (Pan et al. 2017)	CUP/Tsinghua 2°C Scenario - Low CUP/Tsinghua 2°C Scenario - High	x	x	
Other Scenarios				
Lawrence Berkeley National Laboratory's China Energy Outlook Report (Zhou et al. 2020)	Berkeley Lab CEO 2020 Continuous Improvement Scenario	x	x	
Energy Transition Commission (ETC) and Rocky Mountain Institute (RMI)'s China 2050: A Fully Developed Rich Zero-Carbon Economy Report (ETC 2019)	ETC Net Zero Carbon Emissions by 2050	x	x	x

2.1 Macroeconomic Assumptions

From the comparative analysis, it can be seen that achieving economy-wide net carbon neutrality for China will require an unprecedented transformation of the energy system, especially in light of the expected continued economic growth and urbanization over the next three decades (Table 2).

Table 2 | Comparison Of Economic Growth And Population Outlooks in Selected China Mid-Century Scenarios

Scenario	Economic Growth Outlook	Population Outlook
Tsinghua ICCSD Pathways 1.5°C Scenario	2020 – 2035: 4.8% annual average GDP growth 2050: achieve US constant $20,000 per capita GDP in 2050 (GDP will be 3.5x that of 2020 level)	
EFC Synthesis 1.5°C Scenario - Low	2030: GDP grows to $27 trillion (US$2010); 2050: GDP grows to $48 trillion (US$2010)	Peaks at 1.37 billion in 2030 and declines to 1.27 billion in 2050
EFC Synthesis 1.5°C Scenario - High	2020-2035: 5.0% annual average GDP growth 2050: GDP grows to $38.3 trillion and GDP per capita reaches $27893 (US$2010)	Peaks ~ 2030 at 1.43 billion, declines to 1.37 billion in 2050
ERI/PKU 1.5°C Scenario	2050: GDP grows to $40 trillion (US$2010)	Peaks between 2030 – 2040 at 1.47 billion, decreases to 1.44 billion with 79% urbanization in 2050
CNREC Below 2°C Scenario	2050: 4.2x growth in real GDP from 2018 levels to 380 trillion RMB	Reaches 1.38 billion in 2050, with 78% urbanization
Tsinghua ICCSD Pathways 2°C Scenario	2020 – 2035: 4.8% annual average GDP growth and reach US constant $20,000 per capita GDP 2050: GDP will be 3.5x that of 2020 level	
CUP/Tsinghua 2°C Scenario - Low CUP/Tsinghua 2°C Scenario - High	2030: GDP grows to $20 trillion (US$2010) 2050: GDP grows to $40 trillion (US$2010)	Peaks ~2030 at 1.45 billion, declines to 1.42 billion in 2050 with 72% urbanization
Berkeley Lab CEO 2020 Continuous Improvement Scenario	Scenarios not dependent on GDP except for value added in light industries; GDP assumptions consistent with Chinese macroeconomic projections	Peaks ~2030 at 1.43 billion, declines to 1.37 billion in 2050 with 78% urbanization
ETC 2050 Net Zero Carbon Emissions by 2050	2050: GDP per capita reaches 70% of 2017 U.S. level, with 2.5-3x larger economy than the 2019 U.S. levels	Peaks in late 2020s at 1.44 billion, declines to 1.36 billion in 2050

From 2020 through 2035, annual GDP growth is expected to slow but remain robust on the order of nearly 5% per year, with China approaching a similar quality of life as some developed countries by 2030.[6] By 2050, multiple studies expect China's total GDP to grow by 3.5 to over 4 times from current levels, possibly reaching between 270[7] - 380 trillion RMB[8] (U.S.$40 - $56 trillion in constant U.S.2010$), the equivalent of more than double the size of the current U.S. economy.[9] Similarly, there is general consensus among recent studies that China's population will peak in the late 2020s to around 2030s at 1.44 – 1.47 billion,[10] before declining to 1.36 – 1.44 billion in 2050.[11] Urbanization is expected to increase steadily from today's 60% share to nearly 80% share of total population by 2050.[12]

6 Tsinghua 2020; Jiang et al. 2018.

7 Jiang et al. 2018; Pan et al. 2017.

8 CNREC 2019. Conversion assuming RMB is expressed in 2010 constant term, though not specified in report.

9 ETC 2019.

10 Jiang et al. 2018; Pan et al. 2017; ETC 2019.

11 Jiang et al. 2018; Pan et al. 2017; CNREC 2019; ETC 2019.

12 Jiang et al. 2018; Pan et al. 2017; CNREC, 2019.

CHAPTER THREE

ENERGY AND CO2 EMISSIONS GROWTH OUTLOOKS

This review of these recent national studies on scenarios and pathways of near or net zero CO_2 emissions for China identifies multiple trajectories for energy and CO_2 emissions from now through 2050. The variations in outlook for both energy and emissions can be attributed to different underlying assumptions about energy-consuming activity levels and drivers, as well as different perspectives on technological and policy changes and adoption, including different roles for net carbon sinks. Some key findings from these studies are highlighted below.

3.1 Final Energy Consumption Trends

By 2050, the studies reviewed found a range in projected total final energy consumption in 2050 from 2180 million tonnes of coal equivalent (Mtce[13])[14] to ~3600 Mtce[15] (see Figure 1 and Table 3).

Two of the 1.5°C scenarios show final energy consumption peaking in 2020 or earlier, declining to be between 2500 and 2550 Mtce in 2050, while the high scenario in the EFC Synthesis Report showed final energy peaking in 2040 and dropping to 3561 Mtce in 2050 and both the Tsinghua ICCSD 1.5°C and 2°C scenarios showed final energy peaking around 2030 at the same level.

The Tsinghua ICCSD 2°C scenario projects 2050 final energy to be 2765 Mtce, lower than the other three 2°C scenarios that find 2050 final energy at levels between 3046 Mtce and 3584 Mtce. In addition to the Tsinghua ICCSD scenario, two other 2°C scenarios also expect China's total final energy consumption to peak at or around 2030,[16] while another 2°C scenario shows peaking in 2045 at 3512 Mtce.[17] Final energy consumption peaks in 2034 at 3490 Mtce in Berkeley Lab's Continuous Improvement Scenario.[18]

The decline or flattening in final energy consumption[19] from 2020 to 2050 in all studies, while national GDP is projected to continue to grow at 3-5% annually, reflects the importance of decoupling energy consumption and economic growth. An important assumption in these studies is thus that, as the economy continues to grow, the share of energy-intensive industrial sectors will decline proportionally over time as the economy shifts toward more of a service sector-driven model of growth.

[13] Million tonnes of coal equivalent (Mtce) is the conventional energy unit used in China. 1 Mtce = 29.27 million GJ.

[14] ETC 2019.

[15] Pan et al. 2017.

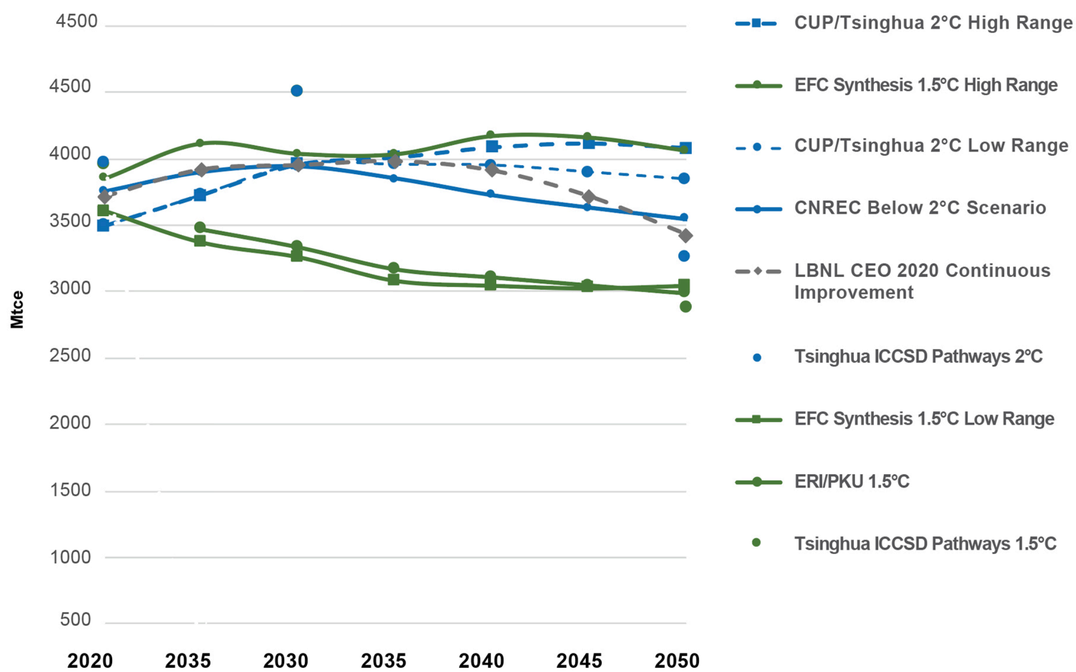
[16] Pan et al. 2017; CNREC 2019.

[17] Pan et al. 2017.

[18] Zhou et al. 2020.

[19] Final energy use does not include the energy used to produce hydrogen, biofuels, and to run CCS facilities.

Figure 1 | Comparison of China's Final Energy Consumption Projections in Selected China Mid-Century Scenarios



Note: Milestone values are provided by the study authors or taken from text in the selected studies. Tsinghua ICCSD Pathways 1.5°C and 2°C Scenarios have the same 2020 and 2030 points.

Table 3 | Comparison of China's Final Energy Consumption Projections in Selected China Mid-Century Scenarios

Unit: Mtce	2020	2025	2030	2035	2050	Peak Year
Tsinghua ICCSD Pathways 1.5°C	3469	*	4005	*	2382	~2030
EFC Synthesis 1.5°C Scenarios - Low	3107	2871	2761	2584	2548	~2020
EFC Synthesis 1.5°C Scenarios - High	3353	3614	3538	3535	3561	2040
ERI/PKU 1.5°C Scenario	2981	2975	2839	2671	2488	2020 or earlier
CNREC Below 2°C Scenario	3253	3396	3438	3349	3046	2030
Tsinghua ICCSD Pathways 2°C	3469	*	4005	*	2765	~2030
CUP/Tsinghua 2°C Scenario - Low	2996	3229	3460	3455	3346	2030
CUP/Tsinghua 2°C Scenario - High	2996	3229	3460	3512	3584	2045
Berkeley Lab CEO 2020 Continuous Improvement Scenario	3217	3410	3433	3450	2843	2034
ETC 2050 Net Zero Carbon Emissions by 2050					2180	

Note: 2020 actual final energy use value is not yet available. | * data not provided for intermediate years

3.2 Primary Energy Consumption Trends

There is a greater range in the outlook for primary energy consumption trends, owing partially to different scenarios of renewable adoption and integration, as well as the different methods used by the studies to convert electricity to primary energy.[20] Projected primary energy values for each scenario are provided in Table 4, but these estimates cannot be directly compared due to different assumptions used to convert renewable (including hydro) and nuclear energy to primary energy. Instead, we focus on the trends in terms of when primary energy consumption peaks.

Primary energy consumption in the EFC Synthesis 1.5°C Low Scenario peaks around 2020, followed by the CNREC Below 2°C Scenario which peaks in 2025. Berkeley Lab's Continuous Improvement Scenario shows a peak in 2029, while the Tsinghua ICCSD study's 1.5°C scenario peaks "around 2030" and 2°C scenario peaks around 2035. The ERI/PKU 1.5°C scenario plateaus after 2035 and both the High and Low CUP/Tsinghua 2°C Scenarios found no peak in primary energy consumption through 2050.

Table 4 | Comparison of China's Primary Energy Consumption Projections in Selected China Mid-Century Scenarios

Unit: Mtce	2020	2025	2030	2035	2050	Peak Year
Tsinghua ICCSD Pathways 1.5°C	4948	5500	5980	5650	5000	Around 2030
EFC Synthesis 1.5°C Scenarios - Low	4361	3467	3073	2914	3170	Around 2020
EFC Synthesis 1.5°C Scenarios - High	4616	4826	4617	4433	3848	2025
ERI/PKU 1.5°C Scenario	4391	4494	4467	4688	4667	Plateau after 2035
CNREC Below 2°C Scenario	4476	4610	4432	4025	3536	2025
Tsinghua ICCSD Pathways 2°C	4948	5500	5980	6060	5196	Around 2035
CUP/Tsinghua 2°C Scenario - Low	4017	4456	4900	5206	6241	No peak by 2050
CUP/Tsinghua 2°C Scenario - High	4017	4456	4900	5237	5807	No peak by 2050
Berkeley Lab CEO 2020 Continuous Improvement Scenario		5275	5351	5267	3817	2029
ETC 2050 Net Zero Carbon Emissions by 2050					2464	

Note: 2020 actual primary energy use was 4980 Mtce (National Bureau of Statistics of China 2021) using the China coal power plant conversion method for converting primary electricity to standardized energy units. These primary energy consumption totals are taken directly from each study, and have not been adjusted to account for methodological differences in converting electricity to standardized energy units. The studies that used the direct equivalent conversion method (consistent with the Intergovernmental Panel on Climate Change) are: EFC 1.5°C Synthesis Scenarios (Low and High), CNREC Below 2°C Scenario, Berkeley Lab CEO 2020 Continuous Improvement Scenario, and the ETC 2050 Net Zero Carbon Emissions by 2050 scenario. The studies that used China's coal substitution method (as shown in italics) are: Tsinghua ICCSD Pathways 1.5°C and 2°C Scenarios and the CUP/Tsinghua 2°C Scenarios (Low and High). The ERI/PKU 1.5°C Scenario study used the physical energy content method (consistent with the International Energy Agency).

[20] To calculate primary energy, electricity units need to be converted to standardized energy units. China uses a power plant coal consumption method of using the average heat rate of coal power plants for the given year for converting non-fossil electricity, while the U.S. and other countries generally use direct equivalent (IPCC convention) or physical energy content method (IEA convention) for converting non-fossil electricity. Because the conversion method is not explicitly stated in most studies, we have not normalized the conversion method for electricity. More details on conversion methods can be found in Lewis et al. 2015.

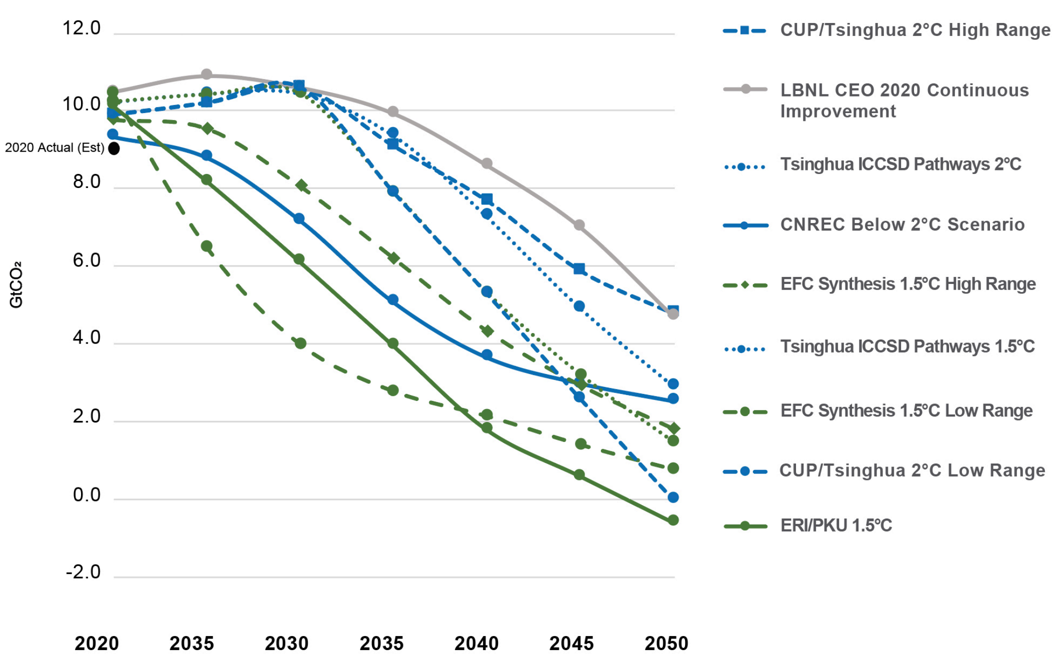
3.3 CO2 Emissions Projection Trends

All of the scenarios reviewed projected rapid declines in CO_2 emissions during the 2020 to 2050 period, with most studies showing the steepest drop in CO_2 emissions between 2030 and 2040[21] (see Figure 2 and Table 5). By 2050, the remaining CO_2 emissions in the 1.5°C scenarios range from -0.59 GtCO2[22] to 1.81 Gt CO_2.[23] If the high range of 2°C compatible pathways and the scenario without a specific temperature target (i.e., Berkeley Lab CEO 2020 Continuous Improvement) where net carbon neutrality is not reached until after 2050 are also considered, then the CO_2 range for 2050 is from 0 to 4.8 $GtCO_2$[24] compared with estimated 2020 emissions of 10.62 metric tons carbon dioxide ($MtCO_2$).

In terms of CO_2 emissions peaking, about half of the reviewed studies show trends that indicate that the CO_2 emissions peak year was either before 2020 or in 2020 since they are on a downward trajectory from 2020 to 2050. The exceptions are the Berkeley Lab CEO 2020 Continuous Improvement that peaks a little after 2025, the Tsinghua ICCSD Pathways 1.5°C and 2°C scenarios and the CUP/Tsinghua 2°C Scenarios (low and high range) that all find CO_2 emissions peak in 2030.[25]

Three of the scenarios reach zero CO_2 emissions while another projects negative CO_2 emissions in 2050. In addition to the decarbonization strategies discussed below, these scenarios generally also incorporate the use of carbon capture and sequestration to different extents.

Figure 2 | Comparison of China's CO_2 Emissions Projections in Selected China Mid-Century Scenarios



Note: Milestone values are provided by the study authors or taken from text in the selected studies and/or interpolated between data points from charts in selected studies when data were not provided. 2020 CO_2 total shown is actual estimated CO_2 emissions based on Berkeley Lab analysis. 2020 modeled values from different scenarios may vary.

The differences in energy and CO_2 emissions results in recent mid-century mitigation studies highlight not only the various underlying factors that contribute to divergent trends, but also

21 EFC 2020; Jiang et al. 2018.

22 Jiang et al. 2018.

23 CNREC 2019.

24 Pan et al. 2017; Zhou et al. 2020.

25 Tsinghua 2020. Pan et al. 2017.

that multiple pathways towards net carbon neutrality are possible for China. Underlying these different possible trajectories of achieving net zero CO_2 emissions by 2050 are several overarching decarbonization strategies that affect multiple sectors, as well as similarities and differences in policy interventions, investments and finance, technological changes, and research, development and deployment seen as necessary to support this transition.

Table 5 | Comparison of China's CO2 Emissions Projections in Selected China Mid-Century Scenarios

Unit: Mtce	2020	2025	2030	2035	2050	Peak Year
Tsinghua ICCSD Pathways 1.5°C	10.25	10.43	10.46	7.93	5.32	~2030
EFC Synthesis 1.5°C Scenarios – Low	10.44	6.49	4.00	2.79	0.78	2020
EFC Synthesis 1.5°C Scenarios – High	9.78	9.56	8.07	6.21	1.81	2020
ERI/PKU 1.5°C Scenario	10.13	8.20	6.12	3.96*	-0.59	2020
CNREC Below 2°C Scenario	9.34	8.80	7.18	5.08	2.53	2020
Tsinghua ICCSD Pathways 2°C	10.25	10.45	10.46	9.38	7.29	~2030
CUP/Tsinghua 2°C Scenario – Low	9.90	10.20	10.6	7.90	0	2030
CUP/Tsinghua 2°C Scenario – High	9.90	10.20	10.6	9.10	4.80	2030
Berkeley Lab CEO 2020 Continuous Improvement Scenario	10.49	10.90	10.60	9.93	4.70	2025
ETC 2050 Net Zero Carbon Emissions by 2050					0	

Note: 2020 actual was 10.62 $MtCO_2$

* interpolated

CHAPTER FOUR

OVERVIEW OF KEY DECARBONIZATION STRATEGIES FOR CHINA

4.1 Energy Efficiency Improvement and Activity Reduction

Building on the success of continuous energy efficiency improvements across multiple sectors in China over the last two decades, virtually all of the Chinese studies reviewed expect energy efficiency to continue to play a role in helping China decarbonize. Most of the studies expect near-term energy efficiency improvements to continue at a pace that is at least consistent with recent policy-driven trends. For the 14th FYP period, for instance, total end-use energy efficiency improvements of 10% – 30% are expected, depending on the end-use sector.[26] Recent studies have also recommended energy intensity (as measured in energy/GDP) reduction goals for the 14th FYP period ranging from 14-15%[27] to 19%.[28] One possible long-term target that has been offered is 80% reduction in energy/GDP from 2005 levels by 2050.[29]

In the longer term, as China approaches and possibly surpasses existing international advanced energy efficiency levels in multiple sectors, there is also recognition that significant efficiency improvements may be technically limited. For example, for the cement and steel sectors where energy efficiency levels are already quite high in China, one study found future sectoral efficiency improvements of only 13 – 20% are expected through 2050.[30] The more diverse chemicals sector, in contrast, has greater potential for 20-25% efficiency improvement by 2050.[31] Besides industry, there is also significant potential for increasing the energy efficiency of key building and transport end-use technologies. For the buildings sector, which is the sector with the highest forecast energy growth, continued adoption of high efficiency heating, cooling, and lighting technologies can reduce building energy consumption intensity by 50-60% (or by as much as 80% for new buildings) by 2050.[32] Similarly, opportunities have been identified to improve rail, water, and air transport energy efficiency by 10-30% in the 14th FYP period.[33]

To achieve 2050 energy goals, it is necessary to achieve energy efficiency improvements and to reduce the demand for energy-consuming activity in the mid- to long-term as China continues its economic transition and development. From a consumption perspective, this further includes transitioning to more sustainable demand through structural change, urban planning, and lifestyle changes.[34] Specifically, this strategy can be realized in the building sector by further decarbonizing building material manufacturing, which can reduce the embodied energy of buildings, extending building lifetimes, and reducing building material needs.

For the industrial sector, a major driving force expected for reducing industrial demand is structural change from heavy to light industries as China advances its economic transition on the way to

26 EFC 2020.

27 Tsinghua 2020.

28 CNREC 2019.

29 Tsinghua 2020.

30 ETC 2019.

31 Ibid.

32 ETC 2019.

33 EFC 2020.

34 Ibid.

becoming a consumer society. Improved utilization efficiency and circularity, particularly for the fertilizer and chemicals industries, and increased material efficiency and material substitution for traditional heavy industrial products, are additional strategies proposed for mitigating expected growth in industrial energy demand. More recently, accelerating industrial digitalization integration with informatization is also being proposed as a possible strategy for further restructuring manufacturing sectors. Similarly, for the transport sector, integration of innovative technologies including big data, 5G, artificial intelligence, blockchain, and supercomputing with both transport infrastructure and vehicles are expected to facilitate the transition towards smart and shared transport systems.[35] The utilization of smart transport systems combined with urban planning, policies, and strategies to promote mode shifting to public transit are all expected to help reduce annual mileage traveled by private vehicles.

The dual strategies of end-use energy efficiency improvement and reduction in sector-specific energy demand activities will reduce total energy demand, which helps reduce the burden on electrification, power sector decarbonization, and low-carbon fuels to achieve carbon neutrality.

4.2 Electrification

In all potential net carbon neutrality pathway studies for China, electrification in parallel with power sector decarbonization is seen as a key pillar to reducing China's CO_2 emission levels to near or net zero over the next three to four decades (Table 6). Of all potential strategies for replacing fossil fuels, electricity is believed to be able to provide the largest near-term opportunities for CO_2 emissions reductions due to available technology options for multiple end-use applications. The

Table 6 | Comparison of China's CO2 National and Sectoral Electrification Rates in Selected China Mid-Century Scenarios

Unit: Electrification Rate (%)	2035	2050			
	Total	Total	Buildings	Industry	Transport
Tsinghua ICCSD Pathways 1.5°C Scenario	>30%	70%	77%	69%	57%
EFC Synthesis 1.5°C Scenarios - Low	43%	61%	75%	63%	33%
EFC Synthesis 1.5°C Scenarios - High	35%	49%	56%	48%	40%
ERI/PKU 1.5°C Scenario		58%	Urban Res: 70%	49%	39%
CNREC Below 2°C Scenario	48%	66%	58%	51%	39%
Tsinghua ICCSD Pathways 2°C Scenario		55%	63%	58%	24%
CUP/Tsinghua 2°C Scenario - Low	32%	51%	69%	54%	15%
CUP/Tsinghua 2°C Scenario - High	31%	43%	62%	45%	12%
Berkeley Lab CEO 2020 Continuous Improvement	34%	40%	56%	41%	11%
ETC 2050 Net Zero Carbon Emissions by 2050		68%	75%	73%	42%

Note: Electrification rate is generally defined as the share of electricity consumption out of total national or total sectoral final energy consumption, but the specific definition of "electricity" consumed may differ.

35 EFC 2020.

decarbonization of electricity generation will be a necessary enabling condition for electrification to reduce energy-related CO_2 emissions, bolstered by the increasing cost-competitiveness of renewable energy with fossil generation in recent years. The reviewed studies project economy-wide (total) electrification rates of 40-70% in 2050.

The electrification potential for different end-use sectors will depend largely on the market and technological status of available electric alternatives to traditional fuel-based technologies. Of all the end-use sectors, the building sector is seen as having the greatest potential for electrification, with multiple commercialized technologies available as electric alternatives for heating, water heating, and cooking that have traditionally relied on coal, natural gas, liquified petroleum gas, and biomass in China. For rural residential buildings, 100% heat pump adoption for heating and water heating and electric cookers are considered necessary for full electrification but will face cost and other barriers.[36] For urban residential buildings, electrifying district heating will be more challenging given its scale of use in the coldest climate zones, but significantly increased heat pump adoption along with electric boilers and heat storage are expected to increase electrification.[37] In aggregate, electricity is shown in the different scenarios to account for 56% to 77% of the building sector's total final energy consumption by 2050, and 96% by 2100 even under a less aggressive 2°C-compatible pathway.[38]

In the transport sector, there is a dichotomy in electrification potential between the relatively well-known applications of road and rail transport, and the more uncertain potential for electrification in shipping and aviation. For road transport, most studies expect near or full electrifying of new passenger and freight vehicles in the mid-to-long term through adoption of battery electric and fuel cell vehicles. This is expected to begin with electric cars dominating new sales and potentially accounting for as much as 14% of the entire car stock by 2025,[39] followed by increased electrification of the auto, bus and trucking fleets through 2050. Some studies are impartial as to the future potential of battery electric versus fuel cell technologies for electrification, while others focus more on hydrogen fuel cell technologies as the solution for electrifying longer-distance trucking and bus travel.[40] However, despite a general expectation of increased electrification of on-road transport, there are still variations in the outlook on the scale and pace of deployment that impacts the overall electrification rate of all transport. The 1.5°C compatible studies project overall transport electrification to range from 33-57% in 2050, while the 2°C compatible studies find a lower electrification rate of 11%-39% in 2050. For shipping and aviation, the nascent state of electric technologies such as battery electric motors for river and coastal shipping or applications based on the synthesis of hydrogen and CO_2 using zero-carbon electricity for aviation contributes to greater divergence and less details on outlooks for electrification potential in these harder to decarbonize subsectors. The uncertainties in these two subsectors in turn impact the overall decarbonization outlook for the transport sector.

There is greater uncertainty around industry electrification potential, with most existing analyses focused on technological options for electrifying the largest, most energy-intensive sub-sectors including cement, steel, and chemicals. Increased recycled steel for electric arc furnaces and use of direct electrolysis to reduce iron or hydrogen-based direct reduction of iron are two key strategies considered for the iron and steel industry. Utilization of zero-emission sources (including direct electrification and hydrogen) as heat inputs for cement production is a strategy considered in some studies, but its scale-up potential is uncertain due to its current high costs. For the chemicals sector, there is hope that multiple power-to-X production routes can be applied to ammonia and methanol production using hydrogen from zero-carbon electricity and CO_2 as feedstocks, but high-cost barriers also exist.[41] Based on the electrification potential for these key industrial sectors,

36 Jiang et al. 2018.

37 ETC 2019; CNREC 2019.

38 Pan et al. 2017

39 Jiang et al. 2018; CNREC, 2019.

40 ETC 2019; Jiang et al. 2018.

41 ETC 2019.

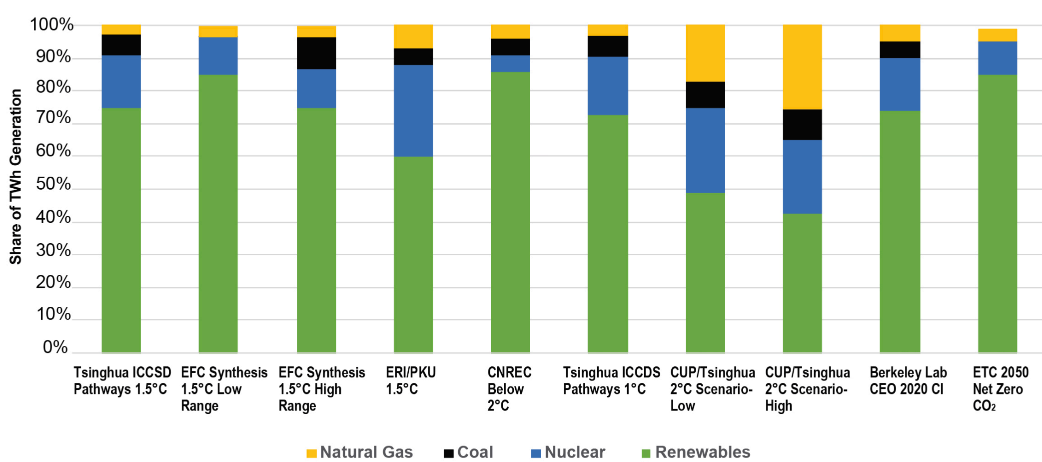
the studies project 48-73% electrification potential by 2050 for 1.5°C compatible or near to net zero carbon neutrality pathways,[42] a significant increase from current levels of around 20%, with a slightly lower range of 41%-58% for the 2°C compatible studies.

4.3 Power Sector Decarbonization

On the supply side, rapidly and fully decarbonizing China's power sector will be needed to not only meet the growing electricity demand with greater electrification, but also to produce electricity-based, low or net zero CO_2 emission fuels (Figure 3 and Table 7). All studies find that solar and wind resources will provide the bulk of non-fossil generation, with differing perspectives on the future roles for biomass and nuclear power. Notably, for multiple 1.5°C compatible scenarios, there is general consensus that the non-fossil generation share will need to reach around 90% by 2050, a nearly three-fold increase from the current share of 31%.

Solar and wind power are considered by all studies to be key to the clean energy transition for the power sector, and could contribute between 34-73% of total electricity generation by 2050. Hydropower could contribute an additional 9-18% share of electricity generation by 2050, biomass could contribute between 0-8%, and differing perspectives on the future of nuclear power translates into projected shares of 5% to 28% of generation by 2050. The scenarios further show that electricity generated from natural gas will range from 3-26% and coal-based electricity will range from 0-10% in 2050.

Figure 3 | Comparison of China's 2050 Power Generation Fuel Shares in Selected China Mid-Century Scenarios



Note: Renewables shown include solar, wind, hydro, and biomass. Coal and/or natural gas shown may include CCS.

Given the large reliance of the future power grid on variable renewable generation, pumped hydro, battery storage, and hydrogen production are all considered for providing power system flexibility. For example, the Energy Foundation Synthesis Report found that by 2030, electric vehicles alone can provide a storage capacity of 3.5 terawatt-hour (TWh) and a flexible load of nearly 690 GW.[43] The ETC study finds that pumped hydro storage could provide 412 GW (up from today's 30 GW in China) and battery storage could provide 510 GW[44,45] of storage capacity by 2050. In most studies, there is expected to be a very limited role for coal and/or natural gas power generation with less

[42] Tsinghua 2020; EFC 2020; ETC 2019.

[43] EFC 2020.

[44] ETC 2019.

[45] For comparison, the total global installed energy storage capacity is currently 174 GW.

than 10% share combined, and with most of the generation equipped with carbon capture and sequestration (CCS).

In terms of installed capacity, the unprecedented pace of new installations needed for renewables to meet the high non-fossil generation shares by 2050 are shown in Table 8. Over the next four years, both solar and wind installed capacity will need to double from current levels to reach interim goals for 2025 under CNREC's Below 2°C Scenario. From 2025 to 2035, the pace of renewable capacity additions will need to be further accelerated, with nearly 130 GW per year of new additions in wind and solar individually.[46] This pace is the same as adding the equivalent of double North America's total installed solar capacity on an annual basis, and the same as adding North America's total installed wind capacity annually.[47] Of the non-fossil generation capacities, there is greater divergence in perspectives on the future growth of nuclear and biomass installed capacities, ranging from little growth through 2050 under some scenarios to 10-fold increase in nuclear capacity by 2050.

Table 7 | Comparison of China's 2050 Power Generation in Selected China Mid-Century Scenarios

Unit: TWh Generation (%)	Solar	Wind	Bio-mass	Hydro	Nuclear	Coal	Natural Gas	Total TWh	Non-Fossil % of TWh
China 2020 Actual	3%	6%		18%	5%	65%	3%	7,624	32%
Tsinghua ICCSD Pathways 1.5°C Scenario	22%	40%	2%	10%	16%	6%	3%	14,780	91%
EFC Synthesis 1.5°C Scenarios - Low	33%	38%	2%	12%	12%	0%	3%	16,278	96%
EFC Synthesis 1.5°C Scenarios - High	35%	24%	6%	10%	12%	10%	4%	15,774	87%
ERI/PKU 1.5°C Scenario	17%	21%	8%	14%	28%	5%	7%	>14,000	87%
CNREC Below 2°C Scenario	24%	49%	1%	12%	5%	5%	4%	15,527	91%
Tsinghua ICCSD Pathways 2°C Scenario	23%	37%	2%	11%	18%	7%	3%	13,100	91%
CUP/Tsinghua 2°C Scenario - Low	15%	23%	2%	9%	26%	8%	17%	16,882	75%
CUP/Tsinghua 2°C Scenario - High	13%	21%	0%	9%	23%	9%	26%	15,476	65%
Berkeley Lab CEO 2020 Continuous Improvement	19%	28%	2%	18%	16%	5%	6%	10,978	90%
ETC 2050 Net Zero Carbon Emissions by 2050	29%	35%	7%	14%	10%	0%	4%	~15,000	96%

Note: China 2020 actual data calculated from 2020 China Electric Power Industry Statistics

46 CNREC 2019.

47 The combined total installed solar and wind capacity for the U.S., Canada, and Mexico was 70 GW and 124 GW in 2019, respectively, based on the BP 2020 Statistical Review.

Table 8 | Comparison of China's Total Installed Non-Fossil Power Generation Capacities by Fuel in Selected China Mid-Century Scenarios

Unit: TWh Generation (%)	Solar			Wind			Biomass	Nuclear
	2025	2035	2050	2025	2035	2050	2050	2050
Tsinghua ICCSD Pathways 1.5°C Scenario	367*		2367	383*		2740	52	327
EFC Synthesis 1.5°C Scenarios - Low	940	2392	3368	747	1693	2519	30	255
EFC Synthesis 1.5°C Scenarios - High	499	1211	2595	355	755	1469	135	279
ERI/PKU 1.5°C Scenario			2246			1486	250	554
CNREC Below 2°C Scenario	532	1825	2803	507	1763	2636	54	100
Tsinghua ICCSD Pathways 2°C Scenario	367*		2204	383*		2312	38	327
CUP/Tsinghua 2°C Scenario - Low	310	800	1938	390	1000	1855		583
CUP/Tsinghua 2°C Scenario - High	310	650	1586	390	870	1522		464
Berkeley Lab CEO 2020 Continuous Improvement	270	675	1920	397	774	1217	34	221
ETC 2050 Net Zero Carbon Emissions by 2050			2500			2400	230	230

* extrapolated from 2020 and 2030 data

The installation of CCS technologies to capture CO2 emissions from power generation is another commonly considered decarbonization strategy, and includes applications primarily for the remaining fossil fuel power generation but also for biomass generation in some scenarios. The future extent and pace of CCS deployment in the power sector varies by scenario, ranging from over 600 GW of biomass, natural gas combined cycle, and coal power generation capacity equipped with CCS by 2050[48,49] to 500 GW of natural gas capacity with CCS by 2050.[50] In terms of projected CO2 capture capacity through CCS in the power sector, existing scenarios see potential capture of 880 MtCO2 to 1000 MtCO2.[51]

4.4 Scaling up Deployment of Alternative Clean Fuels

For subsectors that are difficult to decarbonize and for end-uses that cannot yet be electrified, it is expected that additional clean fuels including biofuels and hydrogen can be deployed to further the switch away from fossil fuels. This includes biofuels as an alternative to oil products for shipping and aviation transport, and ammonia for long-distance shipping.[52] However, because of China's limited domestic resources for bioenergy, its ultimate deployment in different sectors will depend on sectoral prioritization and the technologies that can increase the efficiency of biomass conversion to energy or of biomass energy use. Some existing studies find that biomass could account for 6%

48 Jiang et al. 2018.

49 EFC 2020 (High Scenario).

50 ETC 2019.

51 Tsinghua 2020; ETC, 2019.

52 ETC 2019.

to 20% of total primary energy consumption,[53] while another study found significant variation in the outlook for biomass's share ranging from 0.3% to 18.8% depending on the scenario definition.[54] Varying degrees of hydrogen utilization in industry as a potential feedstock replacement, and in transport for long-haul transport and shipping are also possible, but the timeline, cost and feasibility of scaled-up hydrogen production is more uncertain. Existing scenarios suggest that hydrogen could account for 2.3% of total final energy consumption by 2035[55] and between 2% to 9% by 2050,[56] and as much as 3-18% of industrial energy consumption by 2050.[57]

4.5 Terrestrial and Geological Sequestration

Several studies also consider the potential, albeit somewhat uncertain, contribution of geological and terrestrial carbon sequestration in their neutrality pathway studies. Two studies relied on CO_2 sequestration of greater than 1 $GtCO_2$ per year, from either geological sequestration capacity or reduction through large-scale CCS applications in the power sector (1.6 $GtCO_2$) and cement and steel sectors (250 $MtCO_2$) by 2050.[58] Scenarios included in the EFC synthesis study also considered potential net carbon sinks of over 1 $GtCO_2e$ through agriculture, forestry, and other land use sectors by 2050, and found high uncertainty on future development of land use change and forestry sector sinks that could range from stable development to enhanced sink by 560 $MtCO_2e$ by 2050 compared 2015 to meet a global 1.5C goal.[59]

53 CNREC 2019; EFC 2020 (High Scenario); Jiang et al. 2018; ETC 2019

54 Pan et al. 2017

55 CNREC 2019

56 Pan et al. 2017; CNREC 2019; Jiang et al. 2018; ETC 2019.

57 EFC 2020.

58 ETC 2019; Jiang et al. 2018.

59 EFC 2020.

CHAPTER FIVE
POLICIES TO SUPPORT NET NEUTRALITY PATHWAYS

Of the net neutrality studies reviewed, all of the studies provided some policy recommendations and/or indicative policy goals for 2050. At the macroeconomic level, several studies mention the need for carbon pricing (including carbon trading) to significantly drive down CO_2 emissions across multiple sectors.[60]

Other common policy instruments considered in multiple studies for supporting net neutrality pathways include:

- Quantitative targets for reducing energy and CO_2 intensities
- Regulations such as mandatory efficiency and/or fuel standards
- Phasing out fossil fuels and adopting cleaner energy sources (including electricity) for specific sectors or end-uses
- Government procurement policies
- Greater investment and regulatory support for technological innovation and smart and clean energy infrastructure development

However, only selected reports targeting policymakers included specific policy recommendations for overcoming existing barriers and supporting the transitions needed to achieve the 2050 goals and targets for net neutrality. Of the studies that discussed policy implications of and/or policy needs for their scenarios,[61] most focused specifically on near-term policy targets and recommendations for the 14th Five-Year Plan (FYP) period. Virtually no studies included explicit mid-term policy recommendations or goals to connect the gap between near-term actions and long-term end goals needed for pathways consistent with 1.5°C or near net neutrality for China. The only mid-term policy goals that have been laid out are primarily focused on the supply sectors, such as renewable capacity targets. While quantitative targets for 2050 are included in all of the studies reviewed, only one study[62] discussed the longer-term policy actions needed to achieve these 2050 goals.

5.1 Near-term Policy Goals and Recommendations

In terms of overarching national policy targets and recommendations for the 14th FYP period, there are slight variations between studies, depending on their underlying assumptions, methodologies, and perspectives on the longer-term outlook needed to achieve net neutrality.

[60] Jiang et al. 2018; Pan et al. 2017; ETC 2019.

[61] CNREC 2019; EFC 2020; Tsinghua 2020.

[62] ETC 2019.

5.2 Economy-wide Policy Recommendations

In terms of economy-wide targets, only two of the reviewed studies specifically address the energy and CO_2 emissions intensity reductions needed during the 14^{th} FYP period for China to be on a 1.5°C compatible pathway. The Tsinghua ICCSD Pathways 1.5°C Scenario suggests a 14-15% reduction in energy intensity (energy/GDP), while the CNREC Below 2°C study finds that a higher intensity reduction of 19% is needed.[63]

For 2025 CO_2 emissions, the variation between these two studies' projections is even larger, suggesting differing near-term perspectives on fuel mix changes, ranging from 8.8 $GtCO_2$ in the CNREC study to 9.3 $GtCO_2$ in the Tsinghua ICCSD 1.5°C scenario.[64] Similarly, these differences carry through to different CO_2 intensity reduction goals for 14^{th} FYP period, ranging from 19-20% reduction in Tsinghua's study to 27% reduction in CNREC's study for a below 2°C pathway.[65]

Table 9 compares these values to those in the newly released draft of China's 14^{th} FYP, showing that the energy intensity reduction target of 13.5% and CO_2 intensity reduction target of 18% are not in-line with the below 2°C and a 1.5°C compatible pathways.

Table 9 | Comparison of 14th Five-Year Plan Values

	14^{th} FYP Period Energy Intensity Reduction (Mtce/GDP)	14^{th} FYP Period CO_2 Intensity Reduction (CO_2/GDP)	2025 CO_2 Emissions ($GtCO_2$)
Tsinghua ICCSD Pathways 1.5°C Scenario	14-15%	19-20%	10.4
CNREC Below 2°C Scenario	19%	27%	8.8
Draft 14th Five Year Plan	13.5%	18%	

5.3 Energy Supply Policy Recommendations

The CNREC study also included more intermediate targets, including continuous rapid declines of 24% and 37% needed in coal consumption during the 15^{th} and 16^{th} FYP periods, respectively, to achieve future intensity reduction targets.[66] To meet these short-term and long-term policy goals, the CNREC study focused primarily on policies to increase renewable adoption in the heating and power sectors. These include specific policies to promote integration of renewable energy in the power grid, such as integrated long-term planning and five-year electricity demand forecasts, priority for power system flexibility, and improving integration of industrial demand response and storage. It also emphasized the need to avoid new coal capacity – in order to meet the continuous reductions in coal consumption it sees as necessary for a 1.5°C scenario – and to further reduce non-technical (e.g., regulatory) costs of renewables as renewable subsidies are phased-out. More significant policy support is seen as needed for shifting to renewables for heating, including prioritizing renewable heating for district heating, improving the test and certification for renewable heating products, and promoting market-oriented approaches to encourage more private enterprises to enter the clean heating sector.

63 CNREC 2019; Tsinghua 2020.

64 Ibid.

65 Ibid.

66 CNREC 2019.

5.4 Demand Sector Policy Recommendations

The EFC Synthesis Report provided more detailed policy goals and recommendations for demand sectors, focusing primarily on near-term actions that can support the long-term sectoral strategies it has laid out for feasible carbon neutrality pathways.[67]

BUILDINGS

For buildings, most of the near-term policy actions focus on continuing to improve existing policies of mandatory building and equipment standards and labeling, and coal phase-out in rural residential buildings. Additional policies to encourage passive technologies and reduce the size of commercial buildings, as well as deploying smart technologies to enable demand response and grid flexibility, are also recommended.

INDUSTRY

For industry, the recommended near-term policies primarily focus on optimizing industrial structure and reducing over-capacity and further improving energy efficiency. In particular, these include increasing the rate of overall capacity utilization in major industrial sectors by more than 5% during the 14th FYP period and optimizing industry structure to avoid additional increases in total capacity. On the demand side, demand management measures are also recommended to help further control the output of and energy efficiency to produce industrial products. To meet its recommended 14th FYP's overall 15% energy efficiency improvement target for industry, the EFC study emphasizes the need for policy actions to prioritize energy efficient technology deployment and to reach international advanced levels for most industrial efficiency indicators. In terms of fuel switching, a 5% increase in the overall industrial electrification rate is recommended for the 14th FYP period.

TRANSPORT

For transport, most of the recommended near-term actions focus on improving freight efficiency and fuel switching, as passenger efficiency and electrification are already progressing well. These include accelerating the use of railways and waterways for long-distance freight and developing additional policies to support intelligent transportation systems and innovations in transportation demand management. There are also significant near-term policy opportunities for increasing non-road transport energy efficiency, with potential improvements of 10-15% for rail, 10-20% for waterways, and 10-30% for air transport by 2025.

These near-term demand sector policy recommendations emphasize the need to continue and build on the current pace of existing policies and programs focused on increasing end-use energy efficiency and reducing the impact of energy consumption drivers. At the same time, they also focus on beginning to invest in and encourage additional decarbonization strategies such as smart and passive building technologies, intelligent and innovative transportation systems, and facilitating industrial structural change needed to meet longer-term transitions towards carbon neutrality.

5.5 Long-term Policy Recommendations

Of the studies reviewed, only the ETC study provide insights on specific policy recommendations for the long-term beyond the 14th FYP period and the 2030s. Specifically, the ETC study emphasized longer-term policy planning changes and actions needed to achieve the 2050 goals it identified, but made it clear that it would not attempt to lay out more detailed policy actions needed in different

[67] EFC 2020.

stages of transitions.[68] Rather, it focuses on the longer-term sectoral policy recommendations needed to support the strategies it has laid out for China's transformation towards a zero-share of total GDP. While near and mid-term infrastructural investments as part of the Belt and Road Initiative may delay the structural change, it is assumed to be inevitable as China becomes a higher income economy.

In the power sector, the study identified the need for multiple policy measures to help increase the pace of wind and solar investment by two to four times. These include clear commitments to reduce the CO_2 emissions intensity of electricity with intermediate 2030 and 2040 targets, a multi-pronged approach of using auctions, continued power market reform, dedicated infrastructure investment to support quantitative growth targets for renewable power, and policy support for innovation in multiple storage technologies. For industry, its policy recommendations focused on promoting circular economy and efficiency improvements through public procurement, favoring zero-carbon materials in public infrastructure, regulation of plastics sorting and recycling, and bans on plastic export, landfill, and incineration to significantly increase plastics recycling.

For buildings, additional policies to promote efficiency and electrification are seen as necessary, including strong regulation of insulation, heating and cooling standards for buildings, setting clear targets for phasing out coal and gas heating, and promoting mandatory heat pump installation wherever feasible.

Most of the transport policy recommendations focus on surface transport, where multiple policy mechanisms can drive decarbonization. Specific policy recommendations for decarbonizing surface transport include setting clear targets to shift from internal combustion engine vehicles towards electric vehicles while leaving the policy choice open for battery versus fuel cell vehicles, setting a timetable for banning new internal combustion engine (ICE) vehicle sales, and increasing investment in charging and hydrogen refueling networks, high-speed rail and subways. For shipping and aviation, zero or low carbon fuel mandates are mentioned as one potential policy option for accelerating fuel switching in these harder to decarbonize sectors.

5.6 Remaining Uncertainties

As illustrated by the wide range in possible pathways for China to approach carbon neutrality around 2060, as well as the reliance of most of these pathways on some negative emissions technologies, there are multiple areas of uncertainties that could influence China's future energy and emission trajectories.

While there is general consensus around future population growth and urbanization trends, there is greater uncertainty around the progress of **industrial structural change** needed to allow further decoupling of economic growth and energy consumption growth. Despite continued past declarations of the importance of industrial structure change, industry represented the same share of value added in China's total GDP – 41% - in 2018 that it represented in 1990.[69] Besides some specific 14th FYP policy recommendations focused on reining in overcapacity in heavy industries, there is still a large gap in how best to facilitate and expedite the necessary industrial structural change. Key links to industrial structural change are urbanization and China's continued role as a global exporter of manufactured goods; existing studies did not explicitly address the relationship between urbanization and energy intensity or the future of China's export-driven model of growth in energy and emission trajectories.

Another area of uncertainty that has not been thoroughly addressed in existing studies is the projected **cost reductions and scale of investment costs needed for commercialized decarbonization technologies.** On the issue of future costs, most of the studies reviewed discussed cost projections for the energy supply sector, but very few studies made explicit their underlying

68 ETC 2019.

69 Zhou et al, 2020.

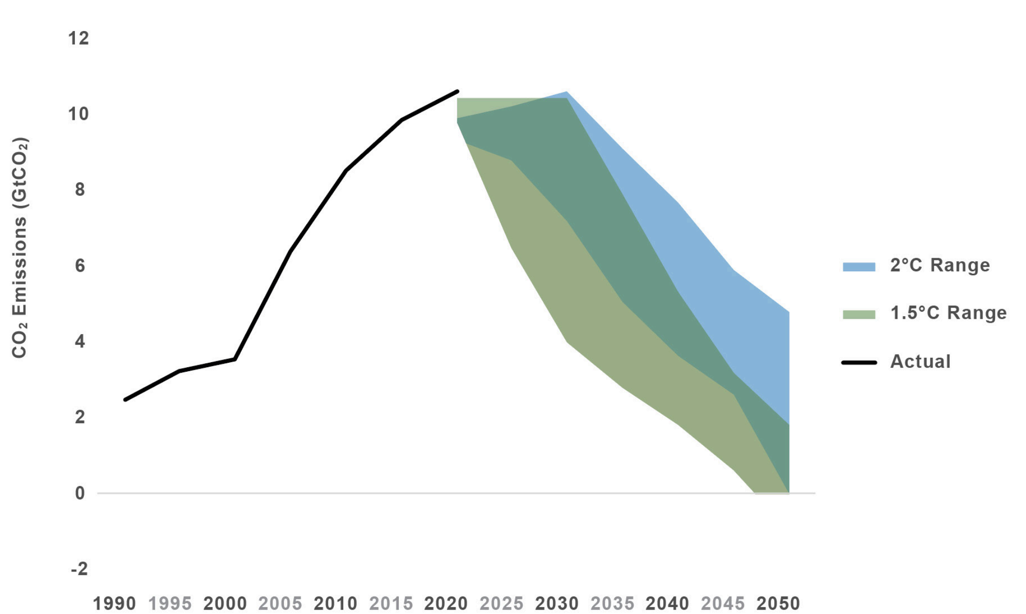
assumptions about learning curves and expected cost reductions for end-use technologies, particularly those expected to be deployed rapidly and widely to achieve decarbonization such as heat pumps and heavy-duty electric vehicles. If the costs of these technologies do not decrease as quickly as expected, then greater investment and policy support will be needed to overcome high upfront cost barriers while scaling up adoption.

At the same time, there is also significant uncertainty around the **high research, development, and deployment costs needed to increase the scale of non-commercialized technologies** such as synthetic fuels for aviation and electrification of specific industrial processes to make the modeled net neutrality pathways possible.

Lastly, while some studies allude to the need **for lifestyle and behavior changes** such as sustainable consumption and mobility changes in net neutrality pathways, it is unclear the degree to which these are already included in assumptions about activity changes and technology adoption in the scenarios. If behavior and lifestyles changes are already included in existing scenarios, then more specific near-term policy recommendations are needed to ensure that these changes will happen.

While a few studies address the contribution of **non-energy CO_2 emissions and potential for terrestrial sequestration** in meeting 1.5°C goals, only the most recent Tsinghua and EFC synthesis study addressed the need for reducing both energy-related CO_2 and non-CO_2 (particularly from non-energy sectors) greenhouse gas emissions such as methane, nitrous oxide, and F-gases. To reach the 1.5°C limit on global temperature increase, reductions are needed across all greenhouse gases and not only CO_2 emissions that have dominated existing scenario studies. The later net CO_2 emissions reach zero, the greater the need for substantial reductions in non-CO_2 emissions and reliance on negative emission options after 2050.[70] There are also close interactions between CO_2 and energy-related non-CO_2 greenhouse gases, such as contribution of coal phase-out to reducing coal-based methane emissions, that are not necessarily recognized in setting future targets or in developing policy recommendations. Without sufficient additional research to address these uncertainties, there will be greater risks in relying on specific CO_2 emission pathways to meet a target of limiting global average temperature increase to 1.5°C.

Figure 4 | Energy-Related CO2 Emissions in China: Historical (1990-2020) and Projected (1.5°C and 2 °C compatible, 2020-2050)



70 EFC 2020.

In addition to these uncertainties, there is also limited analysis on physical resource availability for biomass, uranium, critical materials, etc. in China and globally. The availability of these resources may pose barriers for scale-up of alternative energy technology development and potential global competition for the same materials.

The greatest uncertainty, however, is whether any of these scenarios can actually be realized given China's current energy and CO_2 emissions trajectories. Figure 4 illustrates the historical growth in energy-related CO_2 emissions, showing a four-fold increase from just over 2 $GtCO_2$ in 1990 to an estimated 10.6 $GtCO_2$ in 2020. The blue shaded area shows the range of scenarios from the 2°C compatible studies, while the green shaded area represents the range of 1.5°C compatible studies reviewed in this report. All future scenarios envision a rapid peaking followed by a dramatic decline in CO_2 emissions starting in 2020 or 2030 – unlike anything seen in the history of China or any other country in the world.

Without sufficient research to address the uncertainties outlined above, there will be greater uncertainties in the degree of success of relying on specific non-commercialized technologies and unproven CO_2 emission reduction pathways to meet a target of limiting the global average temperature increase to 1.5°C. Development of a framework for supporting coordination on carbon neutrality between the U.S. and China can provide an opportunity to jointly explore and address these uncertainties. Collaboration and coordination on ongoing research and analysis can help to make longer-term outlook studies more robust regarding these uncertainties and provide a stronger evidentiary basis for governments to set nearer-term policy and targets.

CHAPTER SIX
CONCLUSIONS

Our comparative review of selected recent China-specific outlooks with 1.5°C or 2°C-compatible pathways or explicit net carbon neutrality goals identifies key differences in modeling methodologies and approaches. These include the use of integrated global climate assessment models versus China-specific top-down and bottom-up (with potentially much greater end-use detail) energy models, as well as variations in the underlying assumptions about macroeconomic trends, energy-related activity drivers and outlooks. Despite these differences, several overarching trends emerged.

China's final energy consumption is projected to peak by 2025 in most 1.5°C scenarios and by 2030 in most 2°C scenarios, with the outlook for 2050 final energy demand ranging from staying flat to up to 30% reduction from today's level. This is notable given that all studies expect China's economy to increase by 3.5- to 4-fold from today's level, to reach the equivalent of nearly double the current U.S. economy. Different outlooks for renewable adoption and integration contribute to a greater range in primary energy demand (which reflect changes in the carbon intensity of supply) projections, and different peak years varying from 2025 to later. For CO_2 emissions projections, the reviewed studies all found CO_2 peaks between 2020 and 2030, with nearly all 1.5°C-compatible scenarios finding that CO_2 emissions needs to have peaked by 2020, while 2°C compatible scenarios find that CO_2 peaks by 2030. Most studies find the steepest drop in CO_2 emissions between 2030 and 2040. The remaining amount of CO_2 emissions in 2050 depends, in part, on assumptions about emission targets and deployment of negative emission technologies.

The differences in energy and CO_2 emissions results highlight not only various underlying assumptions about pace of technological improvements and adoption of innovative new technologies and outlook on consumption and behavior that contribute to divergent trends, but also that multiple pathways towards net carbon neutrality exist for China. Underlying these different possible trajectories of achieving net zero CO_2 emissions by 2050 are several overarching decarbonization strategies that affect multiple sectors.

Energy efficiency and energy demand reduction:

- Virtually all studies expect continuation of energy efficiency improvements at a place consistent with recent trends, but potential for future technical efficiency improvements vary between 13 – 60% by 2050 by sector depending on how efficient the sector already is.
- Energy demand reductions are also expected through structural change in industry and circular economy, urban planning, lifestyle changes and integration of innovative technologies, but lack detailed strategies for how these changes could occur or quantitative assessments of their magnitude.

Electrification of end-use sectors:

- Electrification in parallel with power sector decarbonization is a key pillar to reducing CO_2 emissions to near or net zero by mid-century, with studies expecting total national electrification rates of between 40-70% in 2050.

- Buildings has the greatest sectoral potential for electrification, with up to 56-77% electrification by 2050 in some studies. In transport and industrial sectors, electrification potential is less certain and mostly focused on selected end-uses in road transport and cement, steel, and chemicals industries.

Power sector decarbonization:

- Solar and wind are considered by all studies to play the most important role in decarbonizing the power sector, and could contribute anywhere from 34-73% of total electricity generation by 2050, depending partially on the outlook for other non-fossil generation.
- An unprecedented pace of new renewable capacity installations is needed from now through 2050, including some projections of doubling of current capacities by 2025 and annual new additions on the order of 130 GW for solar and wind individually. This amounts to adding the equivalent of North America's total installed wind capacity and double its total installed solar capacity, on an annual basis.
- For nuclear, there is greater range in its expected share in the 2050 decarbonized power system, from 5% to 28% of generation.
- In most studies, there is expected to be a limited role for coal and/or natural gas power generation with 7-35% share combined, and with most of the generation equipped with carbon capture and sequestration (CCS).

In addition, biofuels and hydrogen are expected to be deployed in subsectors and end-uses that are difficult to electrify, but biofuel's role may be constrained by limited domestic resources while hydrogen deployment faces uncertain costs, timeline, and feasibility of scaled-up production.

All of the reviewed studies provided some economy-wide policy recommendations and/or indicative policy goals for 2050, including the potential use of carbon pricing (including carbon trading), quantitative reduction targets, fuel switching measures, government procurement and greater investment and regulatory support for innovation and energy infrastructure. Several reports targeting policymakers also provided specific policy recommendations to achieve the stated 2050 goals and targets, but most focused on near-term actions for the 14th FYP. Some reports focused on mid-term policy goals for the supply sectors, while others focused on near and long-term sectoral strategies. However, policy recommendations or indicative goals to close the gap between near-term actions and long-term end goals needed for pathways consistent with 1.5°C or near net neutrality for China are largely missing.

The wide range in possible pathways for China to approach net neutrality around 2050 and reliance on some negative emission technologies further highlight additional areas of uncertainties that have not been explored sufficiently. These include:

- Ability and policy means to realize the **industrial structural change** needed to further decouple economic and energy consumption growth, given historically stagnant progress and uncertain future role for export-driven growth,
- Actual pace of **cost reductions and scale of investment costs needed for commercialized decarbonization technologies,**
- **Quantification of high research, development and deployment costs needed to increase the scale of non-commercialized technologies and alternative fuels (e.g., hydrogen, biofuels)** to address hard-to-decarbonize sectors and processes, particularly in transport and industry,

- The role of **lifestyle and behavior changes in contributing to demand reduction**, and need for supporting strategies or policy interventions, and
- Uncertain **future trends in non-energy CO_2 emissions and non-CO_2 emissions, and geological and terrestrial sequestration potential**, that may impact meeting the 1.5°C goal despite CO_2 emission reductions.

The greatest uncertainty, however, is whether any of these scenarios can actually be realized given China's current energy and CO_2 emissions trajectories. China's energy-related CO_2 emissions grew four-fold in the thirty years between 1990 and 2020, but all future scenarios envision a rapid peaking followed by a dramatic decline in CO_2 emissions starting in 2020 or 2030 in order to approach near zero net emissions by 2050. Development of a framework for supporting coordination on carbon neutrality between the U.S. and China can provide an opportunity to jointly explore the challenging energy system transformation needed and to address remaining uncertainties. Collaboration and coordination on ongoing research and analysis can help to make longer-term outlook studies more robust to these uncertainties and provide a stronger evidentiary basis for governments to set nearer-term policy and targets.

CHAPTER SEVEN
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