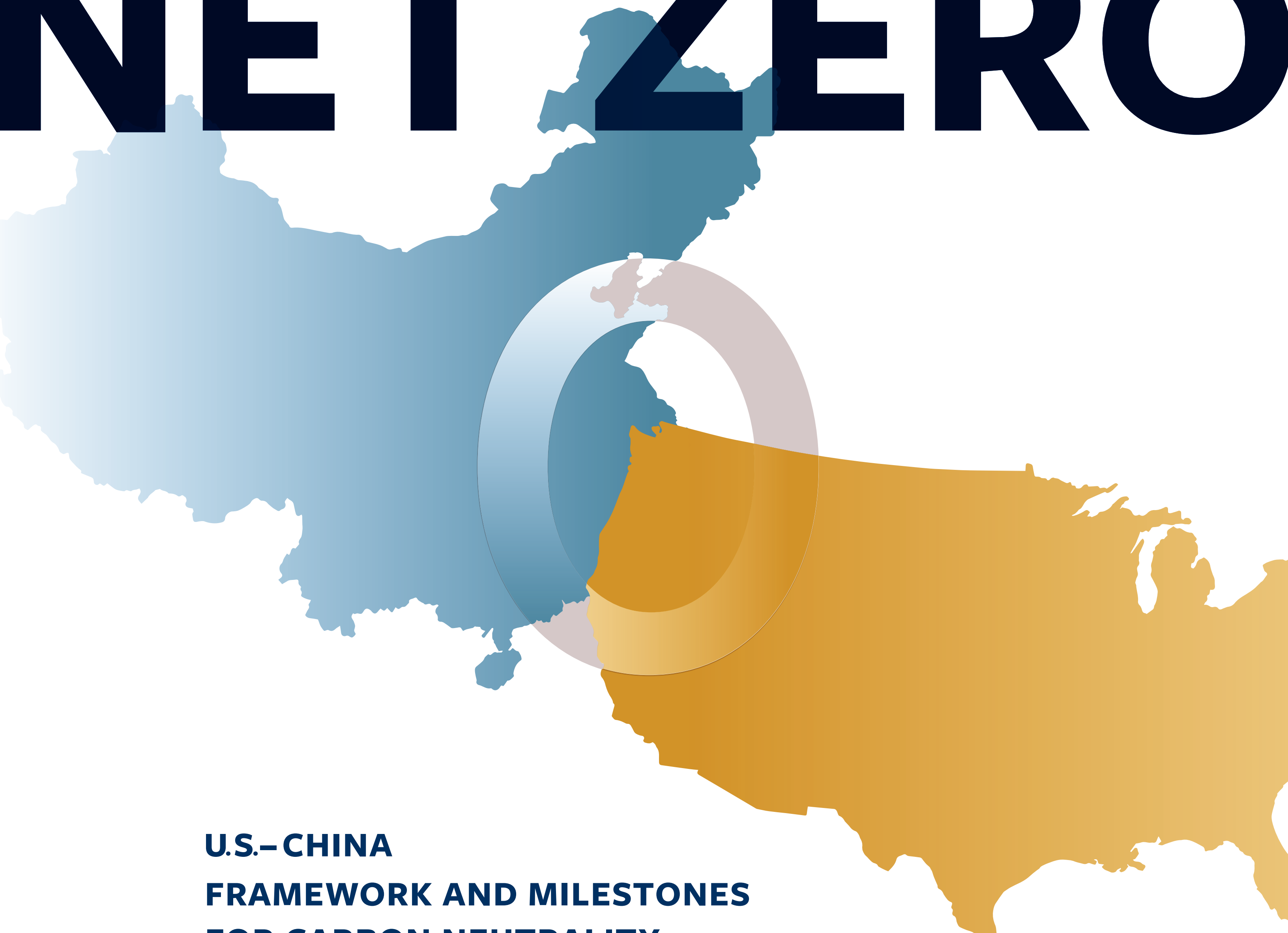
GETTING TO NET ZERO



U.S.–CHINA FRAMEWORK AND MILESTONES FOR CARBON NEUTRALITY

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

In collaboration with
Energy and Environmental Economics, Inc. (E3)
and Lawrence Berkeley National Laboratory (LBNL)

MAY 2021

REPORT AUTHORS

California-China Climate Institute

Dr. Fan Dai, Dr. Fredrich Kahrl, Dr. Jessica Gordon, Jennifer Perron, Yuqing Zhu

E3

Rawley Loken, Amber Mahone

Lawrence Berkeley National Laboratory

Nina Khanna, Dr. Nan Zhou, Lynn Price

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 proposes 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 U.S.-China framework and milestones for carbon neutrality.

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.

ACKNOWLEDGMENTS

This report is part of a "Getting to Net Zero" series that looks at possible pathways for the U.S. and China to work together in achieving their carbon neutrality targets. The policy reports are sponsored by the Hewlett Foundation and produced by a partnership of the California-China Climate Institute at the University of California, the China Energy Group at Lawrence Berkeley National Laboratory, and E3.

The authors would like to thank Xiliang Zhang of Tsinghua University, Dan Farber, Max Auffhammer and Ken Alex of UC Berkeley, Alex Wang of the UCLA School of Law, Vance Wagner of the Energy Foundation China, Jim Williams of the University of San Francisco, Mark Levine and David Fridley of the Lawrence Berkeley National Laboratory for their review, feedback and contribution to this report.

CONTENTS

> *"Getting to net zero is the challenge of our time, but it's also a historic opportunity to make our future better. Every single government, business and organization has a part to play, but it's the United States and China that will determine how far we go. Read this report closely and let's get to work—together."*
>
> \- California-China Climate Institute Chair Jerry Brown and Vice Chair Mary Nichols

EXECUTIVE SUMMARY

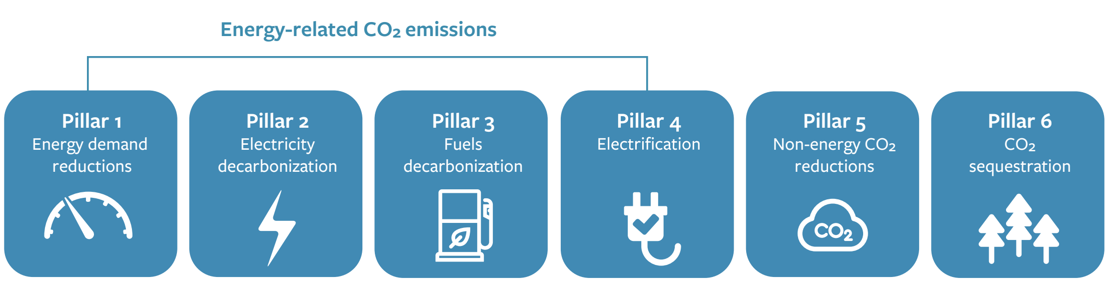
Global momentum and ambition around climate action are now higher than they have been since the 1990s. The European Union (EU) announced in 2019 that it would be climate neutral by 2050, China announced in September 2020 that it would be carbon neutral by 2060, the United States announced a 2050 carbon neutrality target through executive order in January 2021, and a growing number of U.S. states have set mid-century carbon neutrality targets, following California's lead in 2018.

National and subnational collaboration between the United States and China can accelerate this momentum and support achievement of longer-term carbon neutrality goals. The two countries are the world's dominant greenhouse gas (GHG) emitters, its largest economies, and their bilateral relationship was instrumental to formation of the Paris Agreement. Collaboration could take many forms, but, at a minimum, it requires coordination: transparent and shared milestones to gauge progress; regular dialogue and exchange; a shared understanding of research, development, and deployment (RD&D) priorities; and coherent international leadership.

This report provides a framework for supporting coordination on carbon neutrality between the United States and China, identifying shared technology pathways, common milestones, and priority areas for dialogue, RD&D, and international leadership. The analysis in the report is based on a review of recent mid-century deep decarbonization and carbon neutrality studies for the United States and China. In both countries, these studies have begun to shed light on the kinds and pace of technological transitions needed to achieve carbon neutrality by mid-century.

Despite their different national contexts, the United States and China will have similar approaches for achieving carbon neutrality, reflected in six "pillars" that span energy-related carbon dioxide (CO_2) emissions, non-energy CO_2 emissions, and CO_2 sequestration (Figure 1). Although this report focuses on CO_2 emissions, significant reductions in non-CO_2 GHG emissions will also be necessary in both countries by mid-century to limit increases in global average temperatures.[1]

Figure 1 | Six Pillars For Achieving Carbon Neutrality



1 Non-CO2 GHG reductions could be included in Pillar 5.

Our review of recent studies suggests that, for each pillar, the United States and China are expected to have similar high-level strategies for reaching their carbon neutrality goals, described in Table 1.

In tandem, and in both countries, these strategies could result in 80% to 90% reductions in fossil fuel consumption by mid-century, relative to current levels of consumption. Higher levels of remaining fossil fuel consumption would translate into greater reliance on geological CO_2 sequestration.

Table 1 | High-Level Strategies For Achieving Carbon Neutrality By Pillar

PILLAR	HIGH-LEVEL STRATEGY
1. Energy demand reductions	Flattening or reducing per capita final energy consumption through electrification, end-use efficiency, and conservation
2. Electricity decarbonization	Reducing CO_2 emissions from electricity generation by more than 95% by 2050
3. Fuels decarbonization	Reducing CO_2 emissions from solid, liquid, and gaseous fuels by more than 50% by 2050
4. Electrification	Doubling to tripling economy-wide electrification rates by 2050
5. Non-energy CO_2 emission reductions	Reducing CO_2 emissions from industrial processes through process or materials changes or carbon capture and storage (CCS)
6. CO_2 sequestration	Maintaining or expanding terrestrial CO_2 sinks and developing geological CO_2 sinks

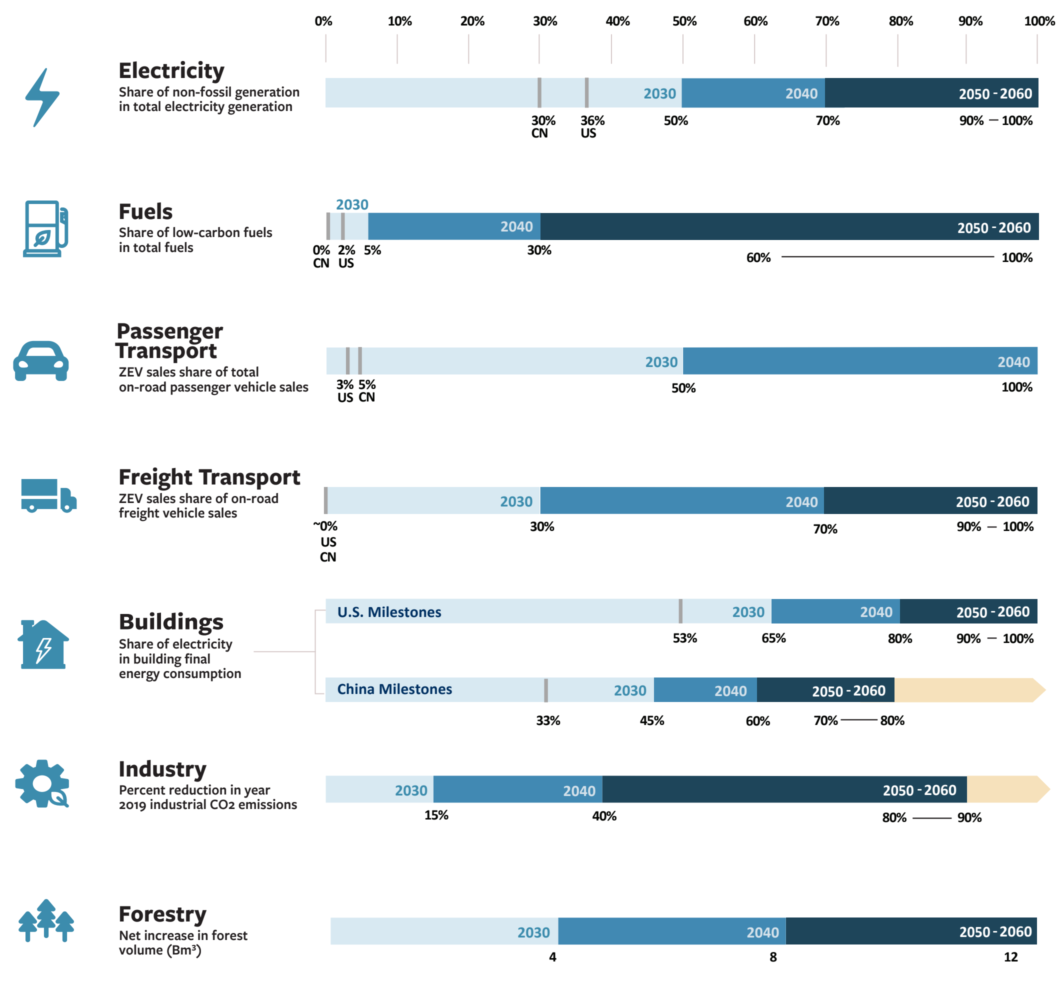
Similar long-term goals and high-level strategies suggest that the United States and China can develop shared carbon neutrality milestones for 2030, 2040, and 2050-2060. Unlike international commitments, milestones are transparent, non-binding measures of progress toward long-term goals. They help to set minimum levels of policy ambition over time, providing a clear signal to producers and consumers on the expected pace and scale of technological change. Having a shared set of milestones for both countries would provide a powerful common point of reference, facilitating innovation, larger markets, and cost reductions for zero emissions technologies.

This report proposes seven categories of common milestones and target levels for the United States and China in 2030, 2040, and 2050-2060 (Figure 2). The proposed target levels for each category of milestone are largely the same for both countries, and are consistent with national and provincial policies in China, state-level policies and proposed federal policies in the United States, and longer-term carbon neutrality goals in both countries (Section 3.4, *Milestones*). The advantage of common target levels for both countries is in the power of its simplicity. However, even if the United States and China choose different target levels for these milestones, having commonly-defined measures of progress would itself be a significant achievement. These milestones can guide both national and state-provincial policy and can be adapted and updated over time.

Measured in terms of national policies for 2025 and 2030, China is closer to being on a trajectory to meet these target milestone levels than the United States, which currently lacks a national climate policy framework or coherent sector-specific policies. In terms of state- and provincial-level implementation, however, leading U.S. states are in a stronger position to meet milestones than their counterparts in China. Several U.S. states, such as California and New York, have developed expertise in long-term planning, policymaking, and regulation in response to carbon neutrality goals. In China, provinces have only just begun to develop the planning, policymaking, and institutional capacity to meet a national carbon neutrality goal. These differences suggest that the United States' and China's strengths are complementary and provide a strong rationale for subnational collaboration as a complement to collaboration at the bilateral level.

To achieve nearer-and longer-term milestones, the United States and China will need to overcome a range of policy and technology gaps, from the institutional challenges of expanding renewable generation to terawatt (TW) scale to the manufacturing and adoption challenges around a 20-fold increase in electric vehicle (EV) sales by 2030. At a high level, the two countries have similar gaps, particularly technology gaps, even though their economic, societal, and demographic contexts are quite different (Section 3.5, *Key Technology Strategies, Policy Focus, and Policy and Technology Gaps*).

Figure 2 | Recommended Carbon Neutrality Milestones for the United States and China



Notes: Vertical grey bars represent base year (2018) values, where applicable. Target values for each period are shown below each period marker. See the main text for sources and how these values were determined.

Similar policy and technology gaps underscore the value of U.S.-China coordination on carbon neutrality: If the world's two largest economies can direct their attention and resources to the same problems at the same time, even if they work in parallel, the chances of finding solutions will be much higher. To this end, we identify four potential areas of U.S.-China coordination.

- **Common milestones** which would provide clear signals to producers and consumers and would create larger markets for zero emission technologies that encourage innovation and drive down costs.

- **Dialogue and technical exchange** which would seek to build confidence and trust, create shared understanding of technology pathways and high-level strategies to achieve carbon neutrality, and share implementation experience.
- **RD&D prioritization** which would identify common and complementary priority areas for RD&D spending, helping to focus RD&D, encourage healthy competition, and increase the chances of breakthrough technologies.
- **International leadership** which would promote solutions for reducing CO_2 emissions in international shipping and aviation, seek to align U.S and China interests on international technology transfer and development assistance, and begin conversations around the creation of a system of international governance for the global CO_2 sink.

Activities in these four areas could take place through a Carbon Neutrality Working Group, a natural successor to the U.S.-China Climate Change Working Group (2013-2017). This Working Group could complement regular trilateral dialogue with Europe and support ongoing global climate negotiations.

Coordination on carbon neutrality does not require the United States and China to resolve their differences around trade and intellectual property, though doing so would likely reduce the costs of meeting GHG emissions goals in both countries. Instead, it only requires that the two countries recognize that they have common goals, similar paths to achieving those goals, and a shared interest in harmonizing the pace and scale of technological change along those paths. By working together, the United States and China will be able to achieve far more than either country could in isolation.

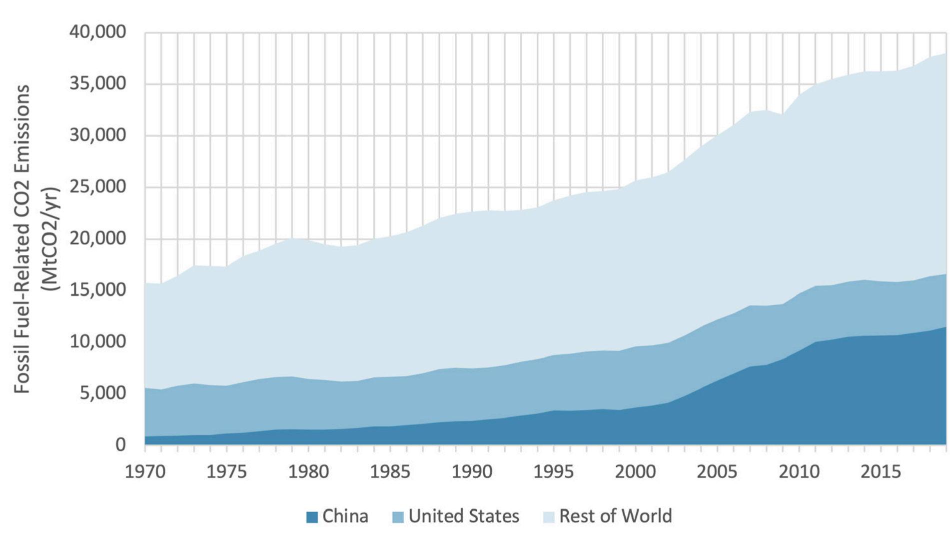
CHAPTER ONE
INTRODUCTION

1.1 Report Overview

The Intergovernmental Panel on Climate Change (IPCC) projects that meeting the Paris Agreement goals of "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" will require all countries to achieve net zero CO_2 emissions by around the middle of this century, with significant accompanying reductions in non-CO_2 greenhouse gas (GHG) emissions.[2]

For the world to achieve GHG emission reductions on this scale by mid-century, the United States and China must play leading roles in policy, technological innovation, investment and technology adoption, and international governance. Together, the two countries currently account for more than 40% of global fossil fuel-related CO_2 emissions (Figure 3). Given the scale and scope of this emission reduction challenge, neither country will likely be able to succeed and lead without the other; at a minimum, coordination and some level of cooperation between them will be critical.

Figure 3 | Fossil Fuel-Related CO2 Emissions, China, U.S., and Rest of World, 1970-2019



Source: Data are from the Emission Database for Global Atmospheric Research (EDGAR) database, https://www.eea.europa.eu/themes/air/links/data-sources/emission-database-for-global-atmospheric.

In the near term, the most important areas of U.S.-China coordination will be in identifying common measures of progress, establishing regular dialogue and technical exchange, developing a shared

2 IPCC (2019).

understanding of priorities for RD&D, and coordinating international leadership. Coordination can build trust and confidence, create larger markets for zero emissions technologies and drive reductions in their costs, facilitate dialogue around common problems, focus and increase the scale of R&D for "missing" technologies, spur CO_2 emission reductions in international aviation and shipping, support GHG emission reductions and increases in terrestrial sinks in middle-income countries, and further the development of institutions needed for international governance of CO_2 sinks.

This report develops a framework to support coordination between the United States and China on mid-century carbon neutrality goals, drawing on reviews of recent deep decarbonization and carbon neutral pathways studies in both countries. The framework focuses on three areas:

- *Strategies and milestones.* What are the different technology strategies and milestones (2030, 2040, 2050-2060) that would be needed to achieve carbon neutrality in both countries by around mid-century?
- *Policy and technology gaps.* What are the technological and policy gaps to achieving carbon neutrality?
- *Opportunities for coordination.* Where should the United States and China focus their collaborative efforts?

The report includes four sections:

- **Introduction** which provides an overview of the report and its motivation, as well as a definition of carbon neutrality used throughout the report.
- **Framework Building Blocks** which describes the five main elements of our framework for U.S.-China coordination: pillars, sectors and activities, time horizons, policy strategies, and milestones.
- **A Shared Framework and Milestones for Carbon Neutrality** which compares high-level strategies for carbon neutrality, develops intermediate and long-term milestones for both countries, and identifies areas for coordination.
- **Conclusions** which offers concluding thoughts.

The analysis in this report is supported by reviews of recent deep decarbonization and carbon neutral pathways studies in both the United States and China, which are companion reports in this series.[3]

1.2 Motivation

This report responds to a combination of need and opportunity. In its 2019 report, *Global Warming of 1.5°C,* the IPCC emphasized the 2020s as a critical transition period for reorienting national energy and industrial systems to meet the Paris Agreement's temperature goals.[4] During the last five years, innovations in energy and information technologies have driven down the cost of renewable energy, zero emission vehicles, and building energy technologies to levels that have made them increasingly cost-competitive with fossil fuel alternatives. Since 2018, both of these factors have contributed to governments' increased climate policy ambition.

[3] Loken et al. (2021); Khanna et al. (2021).

[4] The IPCC projected that "Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO2 emissions start to decline well before 2030 (high confidence)." IPCC (2019), p. 18.

In China, this increased ambition is reflected in recent national commitments. In September 2020, China's President Xi Jinping pledged that China would achieve carbon neutrality before 2060 and would peak CO_2 emissions "before" 2030, instead of "by" 2030 per China's commitment under the Paris Agreement.[5]

In the United States, climate and energy policy ambition has been driven by a subset of states. Since 2018, a growing number of states — California, Hawaii, Louisiana, Maine, Massachusetts, Michigan, Montana, Nevada, New York, Virginia, and Washington — have committed to carbon neutrality goals by mid-century.[6] A larger number of states have set mid-century 100% clean energy goals.[7] At a federal level, the Biden administration signed an executive order in January 2021 committing the United States to a 2050 carbon neutrality goal.[8]

With this increased momentum, the next two to three years present a window of opportunity for making substantive progress on the transitions needed to limit the impacts and risks of climate change.

1.3 Defining Carbon Neutrality

Narrowly defined, 'carbon neutrality' is when anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 removals from the atmosphere.[9] The United States and China may, however, define carbon neutrality differently. In the United States, state legislation since the early 2000s has set carbon neutrality targets in terms of total GHG emissions rather than CO_2 emissions. The Chinese government has not yet specified how it will define carbon neutrality.

The IPCC's analysis of GHG emissions pathways to limit warming to 1.5°Celsius (C) found that global anthropogenic CO_2 emissions would need to reach net zero by around 2050 (2045-2055 interquartile range) and non-CO_2 GHG emissions would need to fall significantly by 2050, but not to zero.[10]

This report does not seek to provide a prescriptive definition of carbon neutrality. However, because the deep decarbonization and carbon neutrality studies that form the evidence base for this report focus more on CO_2 than non-CO_2 gases, the scope of this report is limited more narrowly to CO_2: energy-related CO_2 emissions, non-energy CO_2 emissions, and CO_2 sequestration. This narrower focus is not intended to diminish the importance of reducing non-CO_2 GHGs or suggest that the United States and China should not include non-CO_2 GHGs in their dialogue on climate change. In Section 3.6 (*Areas for U.S.-China Coordination*), we highlight areas where U.S.-China dialogue and exchange on non-CO_2 GHGs could be fruitful.

---

[5] Ministry Of Foreign Affairs (2020).

[6] For a list of state goals, see Natural Resources Defense Council, "Race to 100% Clean," https://www.nrdc.org/resources/race-100-clean, and Center for Climate and Energy Solutions, "U.S. State Greenhouse Gas Emission Targets," https://www.c2es.org/document/greenhouse-gas-emissions-targets/.

[7] Ibid.

[8] The White House (2021).

[9] Rogelj et al. (2015).

[10] IPCC (2019).

CHAPTER TWO
FRAMEWORK BUILDING BLOCKS

Even the most expert observer in 1980 could have been forgiven for failing to accurately predict the changes in global energy supply and demand that would emerge over the next four decades: a plateau in global energy demand following the fall of the Soviet Union in 1991; the rapid rise in demand following China's ascension to the World Trade Organization in 2001; sustained, innovation-led growth in global natural gas supplies over in the 2000s and 2010s; chronic construction and safety setbacks slowing the development of nuclear power; and impressive growth in solar photovoltaic (PV) and wind energy in the 2010s with accompanying steep declines in their costs.

The same will undoubtedly be true for the next 30 to 40 years: the technologies of 2060, and the societal forces that will shape them, are beyond the reasonable limits of prognostication. That being said, long-term planning and "visioning" will be indispensable to the success of a global project as ambitious as the transformation of the world's energy, industrial, and land use systems over less than half a century.

Achieving global carbon neutrality by mid-century will entail a level of ongoing focus and socio-technology "forcing" that is unparalleled in human history. It will require secular, sustained reductions in CO_2 emissions over time through continuous replacement of fossil fuel technologies and limits on industrial sources of CO_2. This means step changes rather than incremental change — zero emission vehicles rather than incremental improvements in the fuel efficiency of internal combustion engine vehicles, for instance.

Without long-term planning that explores the magnitudes and kinds of changes in technology, institutions, and behavior required to achieve steep reductions in CO_2 emissions, carbon neutrality will be an elusive goal. Long-term planning provides a means to maintain focus, a working understanding of the required pace and scale of technological change, and an evidentiary basis for policy strategies. Long-term planning studies also underpin the framework and milestones in this report.

The United States and China will take different policy approaches to carbon neutrality. The two countries' differences in economy, demography, administration, and political economy mean that policy strategies that are effective in one country may not be as relevant in the other. Despite their different paths, many of the core technologies needed to achieve carbon neutrality will likely be the same in the United States and China, and indeed globally. Common zero emission technologies are the result of a common global goal and an interconnected world where, despite recent protectionism, international trade tends to lead to technology convergence. Having common technologies suggests that the United States and China can drive technological innovation and cost reductions through strategic coordination that leads to focused, large-scale RD&D, larger markets, and manufacturing economies of scale for zero emissions technologies.

This model, where the United States, China, and the European Union develop and buy down the costs of technologies needed to reduce CO_2 emissions in middle-income countries, is implicit in mid-century goals. Without lower costs, the middle-income countries that will account for most of the world's growth in CO_2 emissions to 2050 are unlikely to sacrifice economic growth in order to reduce CO_2 emissions. Thus, without aggressive efforts to spur innovation in and reduce the costs of zero emissions technologies, the United States' and China's mid-century goals are less meaningful because middle-income countries are less likely to follow their lead.

Coordination on long-term carbon neutrality planning between the United States and China will be a key element of zero emissions technology innovation and cost reductions. Coordination on carbon neutrality does not require joint planning, policymaking, or investment. It only requires a shared understanding of technology pathways and sectoral transitions, which in turn can support common measures of progress, dialogue and exchange, some degree of alignment on RD&D priorities, and synchronized strategies for international leadership. This report aims to provide a foundation for this kind of coordination.

Our framework for carbon neutrality coordination has five components:

1. Pillars;
2. Sectors;
3. Time horizons;
4. Policy strategies;
5. Milestones.

2.1 Pillars

"Pillars" are high-level strategies for reducing GHG emissions.[11] Although different studies identify and focus on different pillars based on national or local context, there are generally six pillars: energy demand reductions, electricity decarbonization, fuels decarbonization, electrification, non-energy CO_2 emission reductions, and CO_2 sequestration. Each pillar can be assessed through high-level metrics (Table 2). These metrics are useful analytically, but in some cases may not be the most useful indicators of progress (*see Milestones*).

The contributions of these different pillars vary across different technology pathways. For instance, a technology pathway for reaching carbon neutrality that relies more on electrification will have less reliance on low-carbon fuels. A technology pathway that has larger residual energy-related CO_2 emissions will need have higher CO_2 sequestration to achieve neutrality.

The pillars and their metrics provide a reasonably simple and straightforward way to calculate total net CO_2 emissions (NC). The below equation first calculates final energy consumption as the product of per capita final energy consumption (PE) and population (PP), multiplies final energy consumption by the share of electricity (α) and fuels ($1-\alpha$) in final energy consumption and their respective gross emission factors (EF^e and EF^f),[12] and then adds electric and fuel CO_2 emissions to non-energy emissions (NE) and subtracts sequestered CO_2 emissions (CS).[13]

$$NC = PE \times PP \times \left[\alpha \times EF^e + (1-\alpha) \times EF^f\right] + NE - CS$$

To be carbon neutral (NC = 0), the amount of CO_2 sequestered must equal energy-related and non-energy CO_2 emissions.

$$CS = PE \times PP \times \left[\alpha \times EF^e + (1-\alpha) \times EF^f\right] + NE$$

Although countries have not yet established more formal definitions, most likely carbon neutrality will be defined as net zero CO_2 emissions over some period of time — for instance 5 or 10 years — to accommodate annual variability in the terrestrial CO_2 sink.

---

11 Williams et al. (2012); Williams et al. (2014).

12 There will be overlap between the electricity and fuel emission factors because electricity may be used to produce low-carbon fuels, such as hydrogen via electrolysis. Separate electricity and fuel emission factors can be calculated by first calculating CO2 emissions for final electricity and fuels, based on emission factors, and then dividing these by final electric and fuel energy consumption. Gross CO2 emission factors here do not include carbon capture and storage (CCS) at energy facilities, which is included separately in CS. An alternative approach would be to use net CO2 emission factors (net of CCS) and then limit CS to CO2 sequestration that is not associated with energy conversion, such as direct air capture.

13 CS here would also include carbon sequestered in building materials and plastics.

Table 2 | Six Pillars and Their Metrics

PILLAR	METRIC	METRIC UNIT*
ENERGY DEMAND REDUCTION Reducing energy demand through electrification, end-use efficiency, and conservation	Per capita final energy consumption	GJ/person
ELECTRICITY DECARBONIZATION Reducing CO_2 emissions from electricity generation by increasing the share of non-fossil generation	Gross emissions intensity of final electricity consumption	tCO_2/TJ
FUELS DECARBONIZATION Reducing CO_2 emissions from fuels through increasing the share of non-fossil energy in fuels	Gross emissions intensity of final fuel consumption	tCO_2/TJ
ELECTRIFICATION Increasing the share of electricity consumption in buildings, transportation, and industry	Electricity share of final energy consumption	% FEC
NON-ENERGY CO_2 EMISSION REDUCTION Reducing non-energy CO_2 emissions from industrial processes	Annual CO_2 emissions from industrial processes	$MtCO_2$/yr
CO_2 SEQUESTRATION Permanently sequestering CO_2 emissions in terrestrial ecosystems or geological sinks	Annual terrestrial or geological CO_2 sequestration	$MtCO_2$/yr

* Units: GJ is gigajoules, tCO_2 is metric tons of CO_2 and $MtCO_2$ is million metric tons of CO_2, TJ is terajoules, FEC is final energy consumption, yr is year.

Notes: The definitions of final electricity and final fuel consumption should be consistent with that used in electrification in its treatment of energy conversion and distribution losses. Non-energy uses of fuels, such as feedstocks, are typically included in final energy consumption and would thus be in "fuels."

This framework of pillars and metrics captures the tradeoffs in policy strategies to achieve a carbon neutrality target (Figure 4). For instance, higher final energy consumption (less energy demand reduction through electrification, end-use efficiency, and conservation) requires higher electricity and fuels decarbonization (lower EF values), more non-energy CO_2 emission reductions (lower NE values), and a greater reliance on CO_2 sinks (greater CS values). Higher fossil fuel consumption (lower electricity and fuels decarbonization) requires more energy demand reduction, more non-energy CO_2 emission reductions, and a greater reliance on CO_2 sinks.

Figure 4 | Illustration of Tradeoffs in Policy Strategies

	FEC	α	EF^e	EF^f	NE	CS
Less energy demand reduction (FEC, PE × PP ↑)	↑		↓	↓	↓	↑
Lower electrification (α ↓)	↓	↓		↓	↓	↑
Lower electricity decarbonization (EF^e ↑)	↓	↓	↑	↓	↓	↑
Lower fuels decarbonization (EF^f ↑)	↓	↓	↓	↑	↓	↑
Less non-energy CO_2 emission reduction (NE ↑)	↓		↓	↓	↑	↑

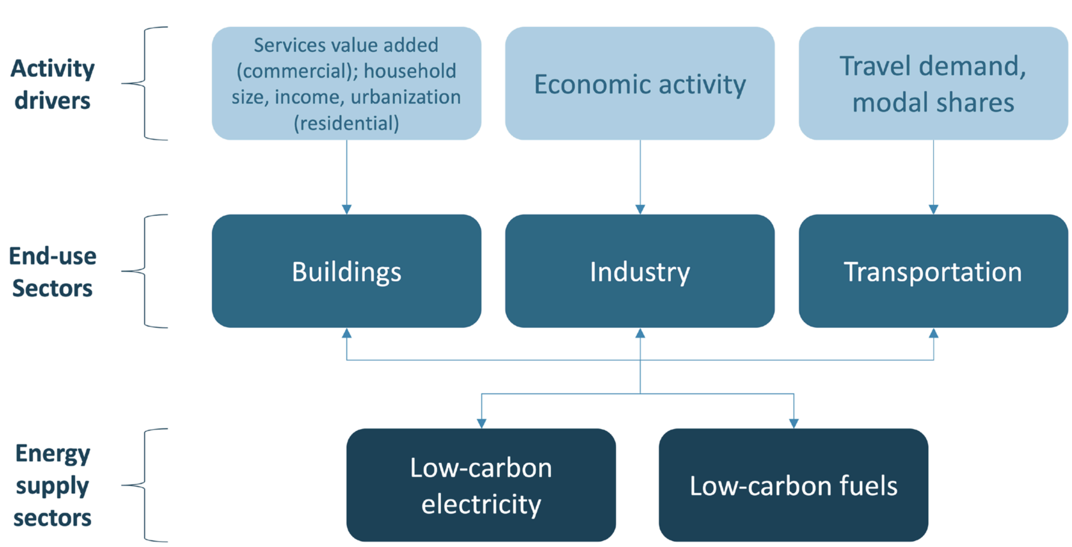
Notes: FEC is final energy consumption, is the economy-wide electrification rate, EF^e is the electricity emission factor, EF^f is the fuel emission factor, NE is non-energy CO_2 emissions, and CS is CO_2 sequestration.

2.2 Sectors

From a sectoral perspective, net CO_2 emission reductions can be organized into two energy supply sectors (electricity, non-electric fuels), three energy-end use sectors (buildings, industry, transportation), non-energy CO_2 emissions, and two CO_2 sinks (terrestrial and geological CO_2 sequestration).

CO_2 emissions within the energy end-use sectors are driven by energy consuming activities. For instance, travel demand and modal shares drive transportation energy use and emissions. Figure 5 shows activity drivers for each end-use sector and their relationship to energy end-use and supply sectors. Over a period of three to four decades, activity drivers are highly uncertain, highlighting the importance of adaptive policy and planning. Reductions in activity drivers, for instance lower travel demand from telecommuting or reduced industrial energy intensity due to lower materials throughput, are also an important form of conservation and are part of the energy demand reductions pillar.

Figure 5 | Activity Drivers, End-Use Sectors, and Energy Supply Sectors

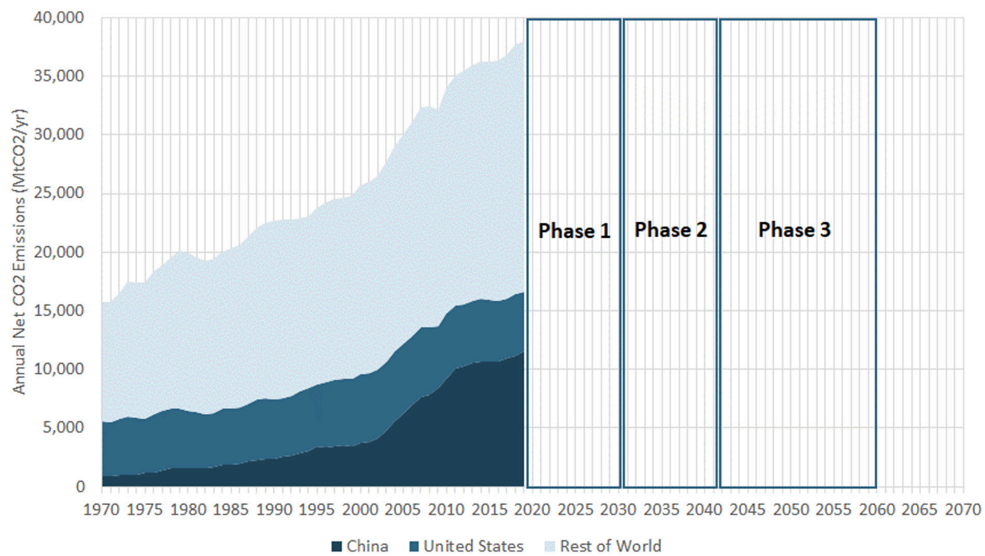


2.3 Time Periods

A focused approach to reducing CO_2 emissions over three to four decades requires a sense of the pace and sequencing of technological change over time, which can be aided by organizing the 2020 to 2060 time horizon into discrete periods. In this report, we organize time into three phases, shown in Figure 6.

Phase I covers the time period between 2020 and 2030, with a milestone date in 2030. Phase 2 covers the period between 2030 and 2040, with a milestone date in 2040. Phase III covers the time period between 2040 and 2060, with a longer time horizon that captures the final years of all carbon neutrality goals. Each phase requires a different policy focus and will pose different challenges.

Figure 6 | Illustration of Three Phases

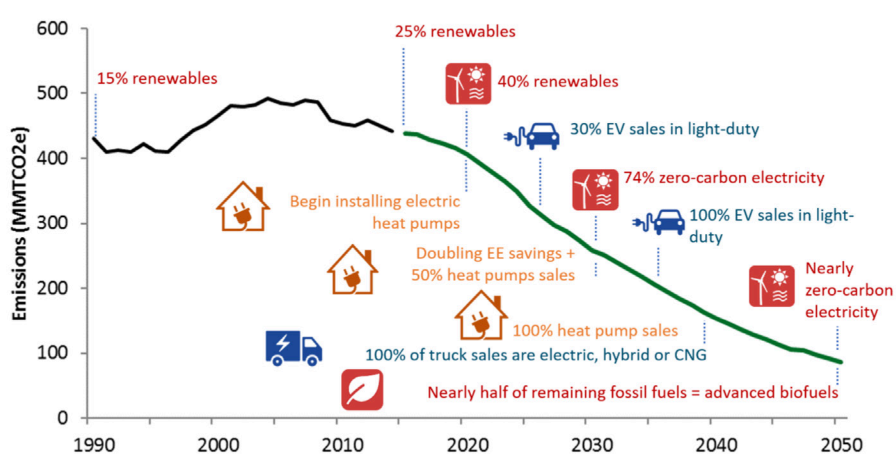


2.4 Milestones

Regardless of national context, the end point for carbon neutrality goals is the same: net zero CO_2 emissions. The fact that countries share similar timelines and technologies for carbon neutrality suggests that, at a high level, they should have some common milestones. For instance, what percentage of electricity should come from non-fossil sources by 2030 and 2040? Because the pace of CO_2 emission reductions is limited by the physical and financial inertia of infrastructure and equipment turnover, milestones are also likely to be best framed in terms of ongoing step changes.

Milestones provide a means to envision technology change over time and gauge progress against long-term goals. Figure 7 illustrates this aspect of milestones, showing key milestones in California's long-term decarbonization planning.

Figure 7 | Illustration of Key Milestones in California's Decarbonization Planning



Source: Figure is from E3, based on data from Mahone et al. (2018).

In this report, we develop a set of common milestones for the United States and China, across sectors, for each of the time periods identified above. These common milestones are not intended to be a template for binding commitments and can be adapted over time as technologies change. Nevertheless, milestones do provide transparency, high-level accountability, and metrics to track progress.

2.5 Policy Focus

'Policy focus' refers to the focus of policies to support the commercialization and deployment of zero emission technologies in different sectors during different time periods. Policy focus can be organized into three categories: deployment, market transformation, and RD&D (Table 3).

A sector may have more than one area of policy focus during a time period, but it will generally have a dominant focus. For instance, as discussed below, the electricity sector has commercially available, scalable zero emission technologies but requires continued RD&D to develop technologies to manage solar and wind variability and uncertainty. In this case, deployment is a dominant policy focus while RD&D is a secondary policy focus.

Table 3 | Policy Focus Areas

POLICY FOCUS	DESCRIPTION	EXAMPLE
RD&D	Zero emission technologies still require significant RD&D before they will be commercially viable	Advanced biofuels
Market transformation	Zero emission technologies may be close to commercial viability but require significant policy support, for instance, to enable supply chain development or manufacturing scale	Hydrogen
Deployment	Zero emission technologies are commercially viable and scalable but may require some policy support	Solar PV

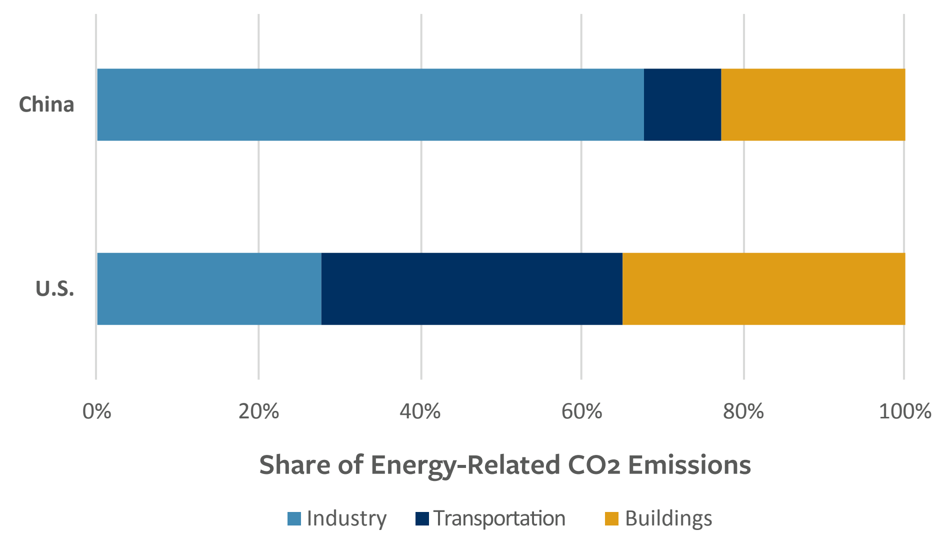
CHAPTER THREE
A SHARED FRAMEWORK and MILESTONES FOR CARBON NEUTRALITY

3.1 Key Differences between the United States and China

The United States and China have myriad differences, from economy to industrial organization, that will shape their carbon neutrality pathways. An understanding of some of the more fundamental differences is important for contextualizing the framework and milestones in this section.

Economic Structure And Energy Consumption. Over the last four decades, China's remarkable economic growth has been driven by investment, on the expenditure side of gross domestic product (GDP) and industry, on the production side of GDP. This industrial orientation of the Chinese economy means that industry is a significantly larger share of energy and CO_2 emissions in China than in the United States (Figure 8). It also means that what is arguably China's most important climate policy strategy, the shift toward a consumption-driven and services-oriented model of economic growth, is less relevant for the United States.

Figure 8 | Comparison of Energy-Related CO2 Emissions in China and the United States, 2019



Sources: Emissions for China are from LBNL estimates. Data from the United States are from Energy Information Administration, "U.S. Energy-Related Carbon Dioxide Emissions, 2019," https://www.eia.gov/environment/emissions/carbon/.

Industrial organization. In China, many of the firms that will be most affected by climate policy — electricity generators; grid companies; fossil fuel producers and refiners; steel, cement, and chemical producers — are fully or partially state-owned, whereas in the United States they are a mixture of private firms and regulated utilities. Additionally, agriculture and forestry in China are typically much smaller scale and often more subsistence-oriented than in the United States. These differences in industrial organization, political economy, and level of economic development will result in different policy approaches and tools to achieve the same sectoral goal, such as increasing non-fossil generation or increasing forest area.

Energy resource endowments. The most important difference in energy resource endowments between the United States and China is China's current lack of low-cost natural gas reserves, which has several implications. It means that the shift from primary coal to natural gas use in industry, buildings, and electricity that took place in the United States throughout the 20th century may be a less attractive strategy for improving air quality and reducing CO_2 emissions in China. Additionally, it may mean that strategies to "firm" renewable energy in China's electricity sector will be different than in the United States, where natural gas generation is often assumed to provide a reliable, backup (low utilization) energy resource even in 2050.[14]

Infrastructure age and growth. From the perspective of long-lived infrastructure, such as power plants, distribution networks, roads, factories, and buildings, China is a much younger country than the United States. For instance, the average age of coal-fired power plants in the United States is about 45 years, whereas in China it is around 15 years.[15] Additionally, China's infrastructure is expected to continue to expand more rapidly than in the United States over the next 10 to 20 years. China's younger infrastructure implies that the pace of technological change in China might be slower than in the United States, but China's higher expected growth implies that it will be particularly important in China to align new infrastructure investments with long-term carbon neutrality goals.

Demographics and population density. China has a much larger population, higher population density, and larger cities than the United States, though it is less urbanized. Higher population density means that some infrastructure strategies and transportation modes that have proved difficult in the United States, such as district heating, transit, and intercity rail, are the norm in China. These higher density solutions lend themselves to more centralized energy supply and local initiative and less concern over end-user adoption. For instance, cities in China can significantly reduce passenger transportation CO_2 emissions by procuring zero emission buses, rather than having to rely almost exclusively on policies to encourage adoption of zero emission cars, which will likely be the case in the United States. China's lower urbanization rate, 60% compared with 83% in the United States (2019), means that policymakers in China will place greater emphasis on urban infrastructure.[16]

3.2 Carbon Neutrality Pillars

In general, the U.S. and China studies reviewed in this report draw consistent conclusions on the kinds of strategies (pillars) and their level of effort (metric values) for achieving carbon neutrality. Table 4 compares pillar metrics for each country in 2050, based on two recent studies: a) the Central scenario (net zero CO_2 emissions) from *Carbon-Neutral Pathways for the United States* (Williams et al., 2021) and b) the 1.5°C scenario from *China's Long-term Low-carbon Development Strategy and Pathway* (He, 2020). These two studies illustrate broadly common strategies: dramatic reductions in the CO_2 intensity of electricity, significant but somewhat lower reductions in the CO_2 intensity of fuels, a doubling or tripling of electrification rates, and some amount of geological CO_2 sequestration.

Differences in metric values reflect different policy strategies, resource endowments, and, in the case of per capita energy consumption, different levels of economic development between the United States and China. For instance, higher electrification in the China study may be a

[14] See, for instance, Williams et al. (2021) and Larson et al. (2020).

[15] U.S. data are from Form EIA-860 Data. China estimate is based on Carbon Tracker data.

[16] Urbanization rate data are from the World Bank's World Development Indicators, https://databank.worldbank.org/.

Table 4 | Pillar Metric Values in 2018 and Illustrative Values in 2050, Based on Two Recent Studies

PILLAR	METRIC	UNITED STATES		CHINA	
		2018	2050[A]	2018	2050[B]
Energy demand reduction (FEC shown in parentheses)	GJ/person (EJ)	203 (66)	130 (50)	60 (86)	60 (85)
Electricity decarbonization	tCO_2/TJ	131	5	224	10
Fuels decarbonization	tCO_2/TJ	54	25	67	35
Electrification	%	21%	50%	25%	70%
Non-energy CO_2 reduction	$MtCO_2/yr$	258	/	1,320	250
CO_2 sequestration	$GtCO_2/yr$	/	0.8	/	1.7

Notes: FEC is final energy consumption. All 2050 estimates are rounded to the nearest five, except for CO_2 sequestration. All 2018 energy and emissions data is based on International Energy Agency (IEA) (2019a) and population data for the energy efficiency pillar metric is from the United Nations Department of Economic and Social Affairs (UN DESA) (2019). U.S. non-energy CO_2 emissions are from the Environmental Protection Agency (EPA) (2020); China non-energy CO_2 emissions is a 2020 estimate from He (2020).

[A] Based on the "Central" scenario from Williams et al. (2021). The study's CO_2 accounting did not include the U.S. terrestrial CO_2 sink. The Central scenario included 0.5 $GtCO_2$ of CO_2 utilized in products, which is included in CO_2 sequestration here, and 53 $MtCO_2$ of international bunker offsets, which are not separately accounted for in the table. The study used CCS, included in CO_2 sequestration, to reduce non-energy CO_2 emissions.

[B] Based on He (2020). The numbers here assume final energy consumption of 83 EJ (rounded to 85 EJ in the table) in 2050 (LBNL, 2020), a population of 1,402 billion in 2050 (UN medium variant estimates), and that 40%/60% of energy-related CO_2 emissions in 2050 are from electricity/fuels (based on the figure in p. 20). Non-energy CO_2 emission reductions in this study may have used CCS, which means that the non-energy CO_2 reduction metric may not be comparable with the Williams et al. (2021) study.

consequence of lower natural gas use in industry. Table 4 also illustrates the relationships among different pillars. Higher emission factors (tCO_2/TJ) for electricity and fuels in the China study require larger CO_2 sinks to reach net zero CO_2 emissions. However, while these metrics can be a useful basis for comparing high-level strategies, they are less meaningful for goal setting because policy strategies — for instance, the level of electrification — may reasonably differ across geographies and over time.

An important metric that is implied, but not explicitly reported, in Table 4 is total remaining fossil fuel consumption in 2050 and the percentage reduction in fossil fuel consumption in 2050 relative to current consumption. Across the U.S. studies reviewed for this report, remaining fossil fuel combustion in 2050 ranges from zero to around 30 EJ (60-100% reduction below 2020 levels).[17] In the China studies, remaining fossil fuel combustion in 2050 ranges from around 5 to 25 EJ (approximately 200 to 800 million tons of coal equivalent (Mtce), 80-95% reduction below 2020 levels).[18] Higher fossil fuel use in 2050 implies a larger reliance on geological CO_2 sequestration, assuming that there are practical limits to expanding the terrestrial CO_2 sink.

Higher remaining non-energy CO_2 emissions also imply higher levels of geological CO_2 sequestration. Non-energy CO_2 emissions in both countries are both diverse and significant. In the United States, the Environmental Protection Agency (EPA) estimated that annual non-energy CO_2 emissions

[17] This range is based on the Larson et al. (2020) E+ RE+ and E+ RE- scenarios, which encompasses the ranges in all other studies reviewed in Loken et al. (2021).

[18] This range is based on model results reviewed in Sha et al. (2020), which appears to encompass the ranges in other studies. The percentage reduction here assumes fossil fuel consumption of around 4,100 Mtce in 2020, based on He (2020).

were 258 $MtCO_2$ in 2018, covering industrial processes as diverse as cement production to soda ash manufacturing.[19] Strategies for mitigating non-energy CO_2, and non-CO_2 GHG emissions more broadly, have traditionally not been a focus of deep decarbonization and carbon neutrality studies, and will need to be given more attention over the next decade.

3.3 Sectoral Strategies

Most sectors have a "dominant" mitigation strategy, or a main technology or set of similar technologies that is expected to account for most CO_2 emission reductions. In many sectors, expectations of what these dominant strategies will be are similar across United States and China studies, though in some instances expectations reflect different assumptions and structural differences (Table 5).

- In the **electricity** sector, solar and wind energy are expected to be the dominant scalable non-fossil energy resources over the next three decades. Differences between the assumed shares of solar and wind generation in 2050 reflect China's larger hydropower resources and differences in assumptions about the scalability of nuclear power in China.[20]
- The two dominant strategies for low-carbon **fuels** across U.S. and China studies include a significant expansion of biofuel and, to a lesser extent, hydrogen supply. The large ranges in Table 5 illustrate the uncertainty and differences of opinion around the highest value uses of scarce bioenergy supplies and the scalability and economics of hydrogen produced through electrolysis. In both countries, bioenergy is expected to play a much larger role in energy systems than it does today.
- Differences in sectoral **electrification** rates may reflect differences in industry structure and technologies, but also differences in assumptions that may ultimately converge over time as technologies and markets mature. For instance, higher building electrification in the United States may be due to China's larger district heating network. The lower range of electrification rates in industry in U.S. studies and the lower range in China studies suggests that industry does not yet have a clear dominant strategy.
- In both countries, the dominant strategy for **terrestrial CO_2 sequestration** is likely to be afforestation and reforestation, though there is still debate over the size of the existing forest carbon sink and the potential for expanding it by 2050.

Technological innovation will mean that the dominant strategies in Table 5 will evolve over time. However, the pathway to 2030 is relatively clear in both countries: using renewable generation to decarbonize the electricity sector, electrification in the building and transportation sectors, land use policies that encourage CO_2 sequestration, and initial efforts to decarbonize fuels and achieve larger CO_2 emission reductions in industry.

The comparison in Table 5 illustrates again that, while the United States and China may differ in the specifics of sectoral strategies, to a significant extent their technology pathways to carbon neutrality will likely be similar.

3.4 Milestones

The shared nature of technology pathways suggests that the United States and China could have a common set of milestones by 2030, 2040, and 2050-2060. We identify seven milestones metrics that are impactful, will be common to both countries, and are reasonably straightforward to measure and monitor. Table 6 shows these milestones, their 2018 baseline values, and proposed target values for 2030, 2040, and 2050-2060.

---

[19] EPA (2020).

[20] See Khanna et al. (2021) for a range of estimates.

Table 5 | Dominant Strategies and 2050 Metric Values by Sector, Based on Recent Studies

SECTOR	DOMINANT STRATEGY	2050 METRIC	U.S.	CHINA
Electricity	Scale up solar and wind generation	Solar and wind share of electricity generation (%)	70-90%	40-70%
Fuels	Increase biofuel supply	Primary biofuel supply (EJ)	10-15 EJ	2-10 EJ
	Increase hydrogen supply	Delivered hydrogen (EJ)	2-20 EJ	5-15 EJ
Buildings	Electrification	Electrification rate (%)	70-90%	55-75%
Transportation	Electrification	Electrification rate (%)	45-55%	35-55%
Industry	Electrification	Electrification rate (%)	20-50%	50-70%
Terrestrial CO_2 sequestration	Afforestation and reforestation	Annual forest sequestration ($GtCO_2$/yr)	0.3-1.5	0.7-0.8

Units: EJ is exajoules and GtCO2 is gigatons of carbon dioxide.

Notes: All values except for afforestation and reforestation are rounded to the nearest five but not to zero. All values are from Loken et al. (2021) and the 1.5°C scenarios in Khanna et al. (2021) except for fuels and terrestrial CO2 sequestration. Primary biofuel ranges in the U.S. are based on Williams et al. (2021) (lower range) and Larson et al. (2020) (B+ scenario) (higher range). Larsen et al. (2020) allow for up to 23 EJ of primary bioenergy supply in 2050 in their B+ scenario, but around 500 TWh is used for bioenergy with CCS (BECCS) power generation and is not included in this total. Primary biofuel ranges in China are from Jiang et al. (2018) (lower range), which assumes most bioenergy is used in BECCS power generation, and from Sha et al. (2020) (higher range). Delivered hydrogen ranges in the U.S. are based on Williams et al. (2021) (lower range) and Larson et al. (2020) (higher range). Delivered hydrogen ranges in China are from Sha et al. (2020). Afforestation and reforestation ranges are from Larson et al. (2020) and He (2020).

Table 6 | Carbon Neutrality Milestones for the United States and China

Sectors		Milestone Metric	2018 Baselines		Milestones		
			China	U.S.	2030	2040	2050-2060
Energy supply	Electricity	Share of non-fossil generation in total electricity generation	30%	36%	50%	70%	90-100%
	Fuels	Share of low-carbon fuels in total fuels	0%	2%	5%	30%	60-100%
Transport	On-Road Passenger	ZEV sales share of total on-road passenger vehicle sales	5%	3%	50%	100%	100%
	On-Road Freight	ZEV sales share of total on-road freight vehicle sales	~0%	~0%	30%	70%	90-100%
Buildings	Electrification	Share of electricity in building final energy consumption	33%	53%	45% (CN) 65% (US)	60% (CN) 80% (US)	70-80% (CN) 90-100% (US)
Industry	Industry-wide CO_2 reductions	Percent reduction in year 2019 industrial CO_2 emissions	/	/	15%	40%	80-90%
Forestry	Terrestrial CO_2 sink	Net increase in forest volume (Bm^3)	/	/	4	8	12

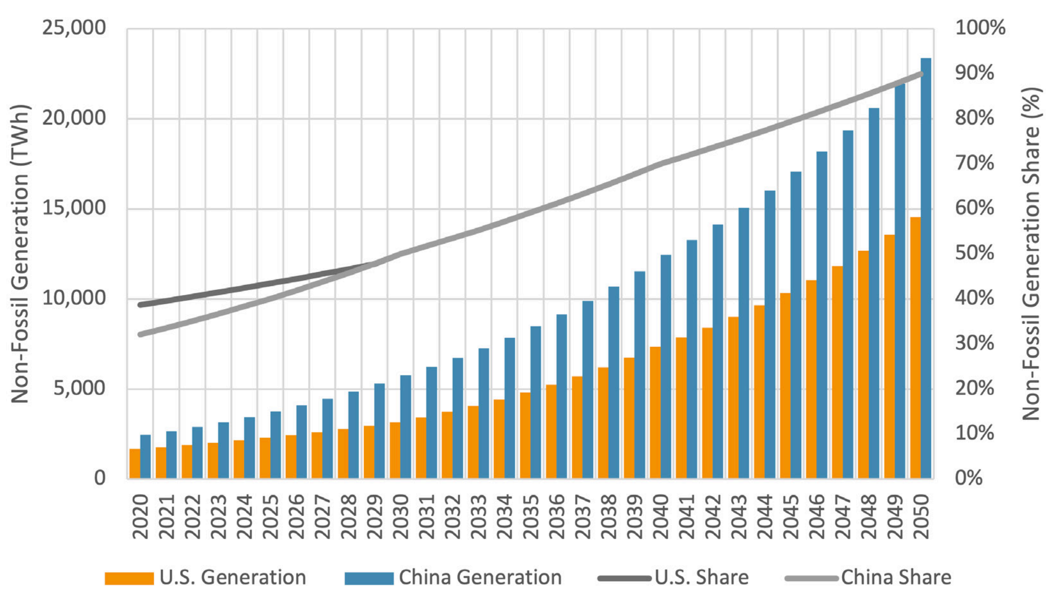
Notes: ZEV refers to zero emission vehicles, which, with current technologies, would primarily be full electric vehicles (EVs) and fuel cell vehicles (FCVs). Baseline values are from IEA (2019a) except for ZEV sales, which are from IEA (2019b). For "on-road passenger," the emphasis is on cars but could include buses as well; for "on-road freight," the emphasis is on lighter and heavier trucks. "Total sales" includes new vehicle sales and leases. China had an electric light commercial vehicle fleet of around 140,000 vehicles in 2018 (IEA, 2019b), but in terms of total annual freight vehicle sales ZEV sales are negligible. Baseline (2019) industrial CO2 emissions would include primary fuel consumption and energy feedstocks. We propose 2019 as a baseline year due to the distortionary effects of the COVID-19 pandemic on 2020 industrial emissions. As described later in the text, we recommend that these values be expanded to include industrial process CO2 emissions as well.

The target values in Table 6 are intended to be common points on a transition pathway to 2050 and 2060 carbon neutrality goals. Either country could exceed these target values;[21] they offer a common floor of ambition for both countries.

Share of non-fossil generation in total electricity generation

Proposed milestones for the share of non-fossil electricity generation in total generation increase approximately linearly (1-2 percentage points per year) from 2018 to 2050. Because the actual amount (TWh energy) of non-fossil generation depends on several other factors — total final energy consumption, the electrification rate, and the amount of fuels produced with electricity — a linear increase in the share of non-fossil generation will likely translate into a non-linear increase in the total amount of non-fossil generation.[22] Figure 9 illustrates this effect for both countries, based on the milestones in Table 6 and assuming the share of non-fossil generation reaches 90% by 2050.

Figure 9 | Illustration of a Linear Change in the Share of Non-Fossil Generation and a Non-Linear Increase in Total Non-Fossil Generation



Notes: See Appendix A for more detail on the calculations behind this figure.

In the United States, a 50% non-fossil generation share by 2030 would imply around a doubling (1,600 TWh increase) of non-fossil generation between 2020 and 2030.[23] If solar and wind generation account for most of this increase, generation from these resources would need to increase four-fold between 2019 and 2030.[24] A 50% share of non-fossil generation in China by 2030 also implies around a doubling (3,300 TWh increase) of non-fossil generation by 2030 and around a four-fold (2,900 TWh) increase in solar and wind generation.[25] The latter would require roughly 1.6 TW of new solar and wind generation capacity (2.1 TW total) by 2030, an increase of around 900 GW above the Chinese government's recent (2020) pledge to increase

---

[21] For instance, a recent U.S. National Academies study recommended increasing the share of non-fossil generation to 75% in the United States by 2030 (NASEM, 2021).

[22] Lower final energy consumption will lead to lower non-fossil generation, but a higher electrification rate and more electric fuels will lead to higher non-fossil generation. The dynamics among these variables — declining or flattening final energy consumption, an increasing electrification rate, and slow but then rapid increases in the share of non-fossil energy in fuels — will likely translate into a non-linear expansion of non-fossil fuel generation.

[23] See Appendix A.

[24] In the United States, solar (including distributed PV) and wind generated 402 TWh in 2019 (EIA, 2021).

[25] See Appendix A. In China, solar and wind generated 728 TWh in 2020 (CEC, 2021).

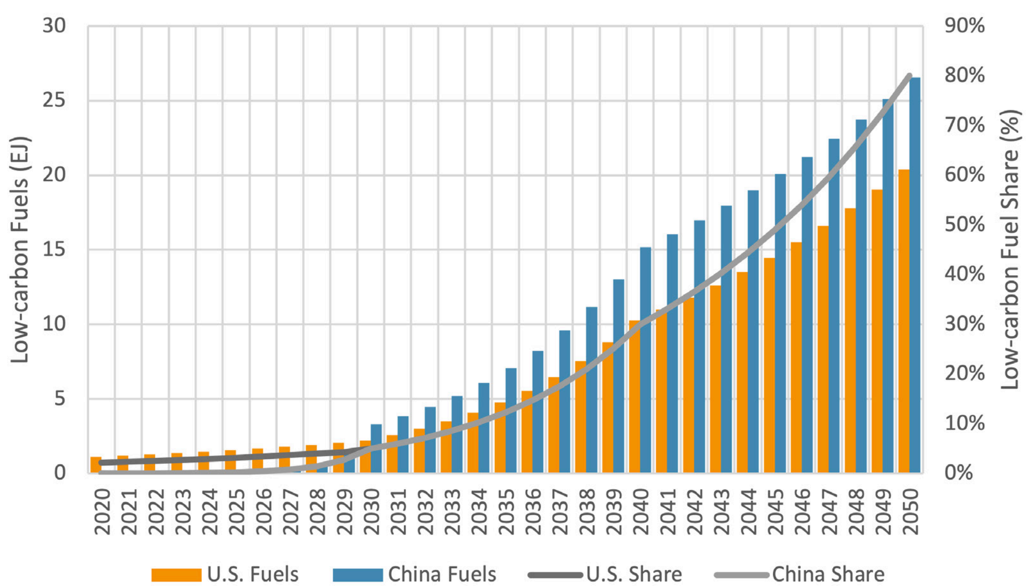
solar and wind generation capacity to 1.2 TW by 2030.[26]

For the two countries together, meeting a 50% non-fossil generation goal by 2030 implies a total of around 2 TW of new solar and wind generation capacity, or 200 GW per year increases in installed capacity between 2020 and 2030.[27] This amount is roughly equivalent to existing *global* solar and wind manufacturing capacity.[28]

Share of low-carbon fuels in total fuels

Proposed milestones for the share of low-carbon fuels in total fuels begin at low levels and increase rapidly in 2040 and 2050. This approach reflects two considerations: (a) fuels currently account for around 80-85% of final energy consumption in both the United States and China but the share and amount of fuel consumption is expected to decline due to electrification, which means that a linear increase in the share of non-fossil energy will lead to a non-linear increase in total non-fossil energy; and (b) significant uncertainty in the availability of bioenergy supplies and business models for low carbon fuels. Figure 10 illustrates the first consideration for both countries, based on the milestones in Table 6 and assuming the share of low-carbon fuels reaches 80% by 2050.

Figure 10 | Illustration of a Non-Linear Change in the Share of Low-Carbon Fuels and a Non-Linear Increase in Total Low-carbon Fuels



Notes: See Appendix A for more detail on the calculations behind this figure.

In each country, a 5% milestone for the share of low-carbon fuels would translate into roughly 2-3 EJ of low-carbon fuels by 2030. If half of these fuels are biomass-based and half are derived from electricity, the primary biomass supply requirements would be around 2-3 EJ per year and the required increase in electricity generation would be around 900-1,500 TWh per year. This more gradual scaling up of low-carbon fuels would allow time for supply chain development, to address concerns over sustainability for bioenergy and to develop regulatory frameworks that facilitate business models.

A 30% milestone in 2040 would require around 10-15 EJ of low-carbon fuels in each country,

[26] See Appendix A. Generation capacity requirements depend on capacity factors for solar and wind, which in turn depend on energy conversion efficiency and resource quality. At U.S. average capacity factors for wind (0.35) and solar (0.25) in 2019, for instance, China's total wind and solar capacity requirements in 2030 would be around 1.4 TW rather than 2.1 TW. Ultimately, the main reason that installed capacity is important is due to land use implications.

[27] See Appendix A.

[28] IEA (2020a) estimates that global solar manufacturing capacity in 2020 was 165 GW; the IEA (2020b) projects that net wind capacity additions in 2020 were 65 GW.

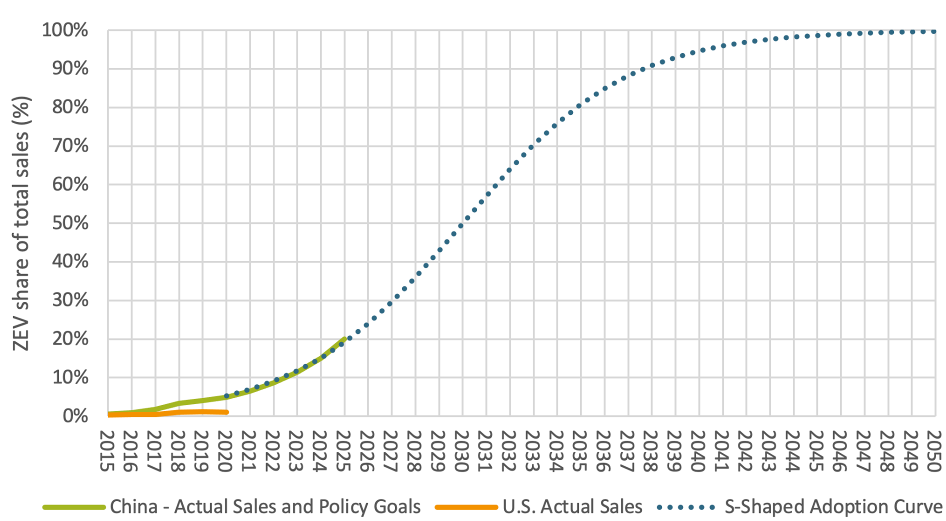
increasing to 20-27 EJ by 2050.[29] For reference, in the United States biomass accounts for around 1 EJ of fuels, mostly ethanol that is blended with gasoline, with the remainder (98%) being fossil fuels.[30] In China, outside of traditional biomass use in rural areas, biomass use in fuels is negligible and fossil fuels account for nearly 100% of fuels.[31] It is not clear the extent to which current biomass fuel production in either country could be considered to have net zero CO_2 emissions, which underscores the need for rigorous and effective regulatory frameworks to ensure that bioenergy contributes to mitigation, rather than exacerbation, of climate change.

In the near term, absolute energy-based (EJ) milestones might be more meaningful than relative share-based ones, for encouraging the development of a low-carbon fuels industry. However, over the longer term share-based targets are more flexible and meaningful. In the longer term, the balance between fuels versus electricity and strategies for decarbonizing fuels should be driven by economic fundamentals and a robust regulatory framework, rather than energy-based targets.

ZEV sales share of on-road passenger and freight vehicle sales

Proposed milestones for zero emission vehicle (ZEV) sales of both passenger and freight on-road vehicles imply a significant increase in sales of these vehicles by 2030 and 2040. Milestones are in terms of sales (a flow) rather than total vehicles (a stock), so if passenger and freight vehicles have roughly 10-15-year and 15-20-year lifetimes, respectively, these milestones would imply that most internal combustion engine (ICE) passenger vehicles will have been retired by 2050 and remaining ICE freight vehicles retire between 2050 and 2060.

Figure 11 | Actual ZEV Sales (U.S., China) and Policy Goals (China) Relative to a Generic S-Shaped Adoption Curve that Meets Milestones



Notes: ZEV sales in this figure do not include plug-in hybrids. ZEV sales data are from DOE (2020) and the Chinese Association of Automobile Manufacturers (CAAM). Total vehicle sales for the United States are from the Bureau of Transportation Statistics (BTS) (2020) and for China are from CAAM. U.S. sales total sales data include both sales and leases. China total passenger vehicle forecasts to 2025 are based on annual average growth consistent with 30 million passenger vehicle sales by 2030. China ZEV and total sales data are limited to passenger vehicles.

[29] See Appendix A.

[30] Williams et al. (2021).

[31] USDA (2020) estimates that ethanol and biodiesel production in China were 3 and 0.8 billion liters in 2020, equivalent to around 0.09 EJ of energy (21 MJ/L ethanol, 33 MJ/L biodiesel). Most of the approximately 1 EJ of bioenergy consumption in China is either consumed in solid form or converted to electricity (Pan et al., 2018).

China's current policies target a 20% share of "new energy vehicles" in new passenger vehicle sales by 2025, which could be consistent with a 50% ZEV target by 2030 and 100% by 2040 assuming S-shaped adoption (Figure 11).[32] The United States does not have federal targets, policies, or regulations that are consistent with this level of passenger ZEV adoption, but some states have set or proposed ZEV targets that are aligned with or exceed these milestones and these milestones were proposed in Congressional legislation in 2019.[33] Meeting the 2030 milestone would imply total annual ZEV sales of between 20 and 25 million vehicles in both two countries by 2030, a more than 20-fold increase relative to 2020 ZEV sales.[34]

Neither the United States nor China have developed national targets for zero-emissions freight vehicles and sales of these vehicles are still low. A 30% milestone would thus be ambitious but is consistent with U.S. state-level policies. For instance, in 2020 a coalition of 15 U.S. states signed a memorandum of understanding setting a target of 30% ZEV sales for medium- and heavy-duty vehicles by 2030.[35]

Share of electricity in building final energy consumption

Proposed milestones for residential and commercial buildings are based on the total electricity consumed in buildings as a share of final energy consumption. This metric has the advantage of being relatively easy to measure and regularly published in government energy statistics. Its downside is that the United States and China are starting at very different base year values (33% in China versus 53% in the United States) and have historically taken different approaches to heating systems (district heating in China, natural gas distribution in the United States), which makes it difficult to use the same target values.

The share of electricity in building final energy consumption can increase as new all-electric or mostly electric buildings are built, as existing buildings are electrified, and through reductions in the amount of final energy consumed in buildings. Given the relatively slow pace of new construction relative to existing buildings and an S-shaped adoption curve for retrofits, the share of electricity in building final energy consumption will likely change slowly at first. The proposed milestone values work backward from the 2050 electrification rates in Table 5 and assume that increases in electrification rates from 2020 to 2030 and 2030 to 2040 will be slower.

Even with slower increases from 2020 to 2030, these milestone values imply either that a significant fraction of new buildings would be all-electric or that a significant number of existing buildings would replace fossil fuel-based heating systems with electric heat pumps. For China, they assume that it will be more cost-effective in many cases to reduce CO_2 emissions from buildings through electrification than with district heating. If this proves not to be the case, the milestone values in 2050-2060 and in the intermediate years would be lower.

Two alternative metrics would be (1) the share of electric heating, the share of all-electric, or the share of zero emission new buildings, but these are more difficult to measure and do not capture the importance of retrofitting existing buildings, or (2) building CO_2 intensity (kgCO_2 per m^2 per year), which is difficult to measure and interpret because it is an aggregate measure (the m^2 in the denominator is total building floor area), it overlaps with electricity and low-carbon fuel milestones (mixes energy supply and end-use), and neither country regularly estimates and reports total building area.

---

[32] The Ministry of Industry and Information Technology's (MIIT's) definition of "new energy vehicles" currently includes full EVs, plug-in hybrid EVs, and FCVs, but would need to be narrowed to include only full EVs and FCVs by 2030 to be consistent with this milestone.

[33] For instance, California's Executive Order N-79-20 requires 100% of new vehicle sales to be ZEVs by 2035. Washington's proposed HB 1204/SB 5256 would require all 2030-model and later passenger cars and light duty trucks registered in the state to be electric. At a national level, the 2030 milestone is consistent with National Academies recommendations (NASEM, 2021). The 2030 and 2040 milestones are consistent with the Zero-Emission Vehicles Act, which was proposed in 2019.

[34] This estimate assumes total annual passenger vehicle sales of around 20 million in the United States and 30 million in China in 2030, consistent with industry forecasts (Schiller et al., 2020), but does not include vehicle leases. Passenger ZEV sales (excluding hybrids) in the United States were 0.24 million in 2019 (Department of Energy (DOE), 2020) and in China were 1.00 million in 2020 (Chinese Association of Automobile Manufacturers (CAAM), 2021).

[35] California's Advanced Clean Truck Program requires 30% of all new medium- and heavy-duty vehicles sold in California to be a ZEV by 2030 and 100% by 2045. NASEM (2021) also recommends a 30% ZEV target for heavy-duty vehicles in the United States.

Percent reduction in year 2019 industrial CO_2 emissions

The milestone for industry is cross-sector and measured in absolute reductions rather than intensity. Industrial CO_2 emissions cover multiple economic sectors that often have very different production processes and emissions sources, but industrial CO_2 emissions can be reasonably well measured and monitored in the aggregate. The milestone is also based on CO_2 emissions from final energy consumption (not including electricity emissions) and industrial process CO_2 emissions, which focuses on the emissions that industry has a more direct ability to manage.

This approach to defining an industry milestone would allow the United States and China to use a range of different strategies — structural economic change (reducing the share of industry in GDP), end-use efficiency, electrification, fuel switching, and CCS — to reduce industrial CO_2 emissions.

The proposed target values assume a significantly larger decline in absolute CO_2 emissions from industry in China from 2020 to 2030 because China's industrial emissions are around five times larger than industrial emissions in the United States.[36] However, in terms of percentage reductions in industrial CO_2 intensity (CO_2 emissions per unit industrial value added), the 2030 values have similar implications for both countries. Both would need to reduce industrial CO_2 intensity by around 35% by 2030 to meet the 2030 milestone of a 15% reduction in year 2019 emissions.[37]

Net increase in forest volume

In both countries, the current terrestrial CO_2 sink is mainly due to reforestation and afforestation over the past two decades.[38] Expanding, or even maintaining, existing levels of this sink (0.7-0.8 $GtCO_2$/yr in each country) over the next 30 years would require a significant level of forest policy effort. The milestones aim to capture a level of CO_2 sequestration in forests, in volumetric terms, that is equivalent to maintaining the current annual forestry sink for the next three decades.[39]

3.5 Key Technology Strategies, Policy Focus, and Policy and Technology Gaps

As suggested by the milestones, key technology strategies within different sectors are at different stages of the policy focus categories introduced in the *Framework Building Blocks* section. As a result, different technology strategies have different policy or technology gaps. The United States and China face similar challenges for each technology strategy, as discussed below, but at the level of more detailed policy their different challenges reflect different social, economic, and regulatory contexts.

Table 7 shows key technology strategies for each sector, policy focus for each strategy, and policy and technology gaps for the strategy. Key technology strategies are based on the dominant strategies in Table 5 but the end-use sectors in Table 7 provide more granularity.

---

36 This estimate is based on an estimate of 7,087 MtCO2 of industrial sector (including agriculture) emissions in 2019, from LBNL, and the EIA's estimate (EIA, 2020) of 1,423 MtCO2 for the United States in 2019. These estimates include electricity sector emissions. The ratio of industrial process CO2 emissions for both countries is comparable to the ratio of their energy-related industrial CO2 emissions: 1,320 MtCO2 in China in 2020 (He, 2020) and 258 MtCO2 in the United States in 2019 (EPA, 2020).

37 See Appendix A.

38 The U.S. EPA estimates that the net flux for "forest land remaining forest land" and "land converted to forest land" was -773 MtCO2 in 2019, which was equivalent to the total net amount of CO2 sequestered in that year (EPA, 2020). Estimates of China's terrestrial CO2 sink vary widely. He (2020) reports a 0.7 GtCO2/yr sink in 2020, but Wang et al. (2020) estimate China's land sink at 3-4 GtCO2/yr between 2010 and 2016.

39 The milestones assume 800 MtCO2/yr over 30 years, a carbon fraction of dry wood of 0.5 tC/t, and a biomass conversion expansion factor of 1 t/m3. This translates to 425 Mm3/yr (= 800 MtCO2 / (44 tCO2/ 12 tC) / (0.5 tC/t × 1 t/m3) of new forest, or roughly 4 Bm3 every 10 years.

Table 7 | Key Technology Strategies, Policy Focus, and Policy and Technology Gaps

DP = Deployment | MT = Market Transformation | RD&D = Research, Development & Deployment

SECTOR	KEY TECHNOLOGY STRATEGIES	POLICY FOCUS			POLICY AND TECHNOLOGY GAPS
		DP	MT	RD&D	
Electricity	Scale up wind and solar generation	● (primary)		○ (secondary)	Land use tradeoffs, integration obstacles Lack of cost-effective reliable energy and long-duration storage technologies
Fuels	Increase biofuel and hydrogen supply		● (primary)	○ (secondary)	High cost, lack of regulatory frameworks Lack of cost-effective advanced (land efficient) biofuel technologies
On-road passenger transport	Electrification	● (primary)			Adoption barriers and new charging and electricity distribution infrastructure requirements
On-road freight transport	Electrification and fuel switching		● (primary)		Adoption barriers and new charging and electricity distribution infrastructure requirements
Buildings	Electrification for new buildings	● (primary)		○ (secondary)	Adoption barriers and new electricity distribution infrastructure requirements
	Electrification for existing buildings		● (primary)	○ (secondary)	High cost, adoption barriers, and new electricity distribution infrastructure requirements
Industry	Electrification and fuel switching		○ (secondary)	● (primary)	High cost and lack of business models Lack of cost-effective alternative energy technologies for some industrial processes
	Technologies to reduce industrial CO_2 process emissions			● (primary)	Lack of cost-effective technologies for reducing process emissions
Forestry / agriculture	Afforestation, reforestation, and soil carbon sequestration		● (primary)		Lack of funding, monitoring, verification, and compliance mechanisms
Geological sink	Power and industry CCS			● (primary)	Lack of funding, monitoring, verification, and compliance mechanisms

KEY	● Primary policy focus	○ Secondary policy focus

Electricity. In both countries, the shares in Table 5 imply TW-scale development of solar and wind resources over the next two decades, which may create land use conflicts and would require a significant expansion of electric transmission systems. For instance, in their "Central" scenario Williams et al. (2021) project that the expansion of wind and solar required to meet a 2050 carbon neutrality goal for the United States would require 36 million hectares of land and would entail a near-doubling of interstate transmission capacity. To provide a sense of scale, the United States has a total land area of 915 million hectares and 152 million hectares of arable land.[41]

[40] Loken et al. (2021); Khanna et al. (2021).

[41] Data are from the World Bank World Development Indicators, https://databank.worldbank.org/.

Neither country has national policies that would encourage solar and wind development on this scale, though some U.S. states have set binding intermediate and longer-term clean energy goals that could do so.[42] In addition, both countries face institutional barriers to generators. In the United States, electric utility regulation is a more important barrier to the rapid deployment of solar and wind generation, because utilities procure power on behalf of most electricity customers but may also own fossil fuel generation.

Recent studies in the United States suggest that electricity systems may be able to cost-effectively and reliability operate with non-fossil penetrations approaching 80-90% of total generation, but beyond that their costs would rise significantly to maintain existing levels of reliability.[43] Although this challenge could be resolved with existing technologies,[44] developing new low-cost zero emission sources of reliable electricity generation, such as advanced nuclear or biogas, and long-duration electricity storage technologies would greatly reduce the required level of effort and complexity needed to meet carbon neutrality goals.

Fuels. Biofuels are expected to play an important role in low-carbon energy systems in both countries, but there are questions around whether biofuels can be produced at the 5-10 EJ scale shown in Table 5 in either country without negative land use impacts and competition with food and other uses of biomass. Advanced biofuels that are more land efficient are thus a key common RD&D area, though even with innovations in biofuel technologies new regulatory frameworks will still be needed to ensure that sustainability concerns can be addressed. Costs for liquid biofuels, biogas, hydrogen, and synthetic fuels remain too high to be competitive and it is not yet clear where their highest value applications will be. Policies and regulatory and business models that would support either biofuels or electricity-derived fuels at multi-EJ scale do not exist in either country.

On-road passenger and freight transport. Electrification is likely to be the dominant technology for reducing CO_2 from passenger transport, while technology strategies for freight are likely to be more mixed. Although EVs are now closer to lifecycle cost parity with ICE vehicles, cost and convenience concerns and the lack of a more extensive charging network still hamper more widespread adoption of EVs. Some form of additional policy push is needed in both countries to reach a 50% ZEV milestone by 2030, though innovation and increases in manufacturing scale needed to meet this milestone would significantly drive down EV costs. The United States does not yet have national policies or regulations for encouraging the manufacturing and deployment of freight ZEVs, though California's Advanced Clean Truck Program is an example of a state-level initiative that could serve as a model for national policy. China's Ministry of Finance has offered subsidies for heavy-duty "new energy vehicles" since 2015, but the scale of policy and regulation in China would need to increase dramatically to meet a 30% ZEV sales milestone for on-road freight transport by 2030.[45]

Buildings. Electrification and improvements in building shell efficiency are likely to be dominant strategies for reducing CO_2 emission from buildings. Implementing these strategies in new and existing buildings will pose different challenges. In new buildings, electric space and water heating may be cost-effective in some climates but RD&D is needed to address the heat pump performance challenges and electric distribution requirements in colder weather climates. For existing buildings, innovations in policy, diagnostic tools, and retrofit strategies are needed to reduce costs. In China, an additional challenge will be the role of electrification versus district heating systems. Greater electrification and buildings and transportation in both countries will

---

[42] For instance, California's electricity generation policies target 60% clean energy by 2030 and 100% by 2045 an New York's target 70% renewables by 2030 and 100% zero emissions electricity by 2040. Both of these targets are backed by existing an existing regulatory framework, though New York's is not binding. For an overview, see the National Conference of State Legislatures, "State Renewable Portfolio Standards and Goals," https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx. China has national goals for TW-scale solar and wind development but does not yet have a policy or regulatory framework to implement these goals.

[43] See, for instance, E3 (2018) and Sepulveda et al. (2018).

[44] See, for instance, Williams et al. (2021) and Larson et al. (2020).

[45] See Ministry of Finance, 2015, Notice on Financial Support for Encouraging Adoption of New Energy Vehicles 2016-2020 (关于2016-2020 年新能源汽车推广应用财政支持政策的通知), http://fgk.mof.gov.cn/law/getOneLawInfoAction.do?law_id=83837.

require thoughtful consideration of how to manage the reliability, resilience, and security needs of more electric energy systems.

Industry. Industrial CO_2 emissions are heterogeneous but are dominated by a few key sectors. In the United States, refining, chemicals, and iron and steel production account for about 65% of energy-related CO_2 emissions from industry.[46] In China, iron and steel, non-metallic products (mostly cement), and chemicals account for about 75% of energy-related CO_2 emissions from industry.[47] This suggests that, while technology strategies for reducing CO_2 emissions in industry may be sector specific, key sectors of focus that are common to the United States and China would include the steel, chemicals, and cement industries. These sectors do not yet have clear pathways for reducing GHG emissions and require RD&D. In addition to a more sector-specific focus, there may also be cross-cutting strategies, such as efficiency improvements for motors, process heating systems, and steam systems, that warrant attention and RD&D. Across sectors, it is still unclear what the right mix of incentives and regulation will be for encouraging the development and adoption of new technologies. For internationally traded products, this challenge is compounded by the desire of governments to avoid reducing the competitiveness of domestic manufacturing.

Forestry and agriculture. There are broadly two strategies for increasing CO_2 sequestration in forestry and agriculture: (1) national programs, which often pay landowners for conservation, and (2) offsets in cap-and-trade programs, which pay landowners for sequestering CO_2 permanently or at least over long periods of time. The former is typically taxpayer funded and is subject to the availability of funding, though both countries have historically had large national conservation programs. The latter may have a ready source of funding, through cap-and-trade systems, but requires monitoring, verification, and enforcement mechanisms to ensure that payments lead to CO_2 sequestration. Neither the United States nor China have the methodologies or institutions to run rigorous offset programs at million megaton to gigaton CO_2 per year scale.

Geological sink. Technologies for capturing and geologically sequestering CO_2 are increasingly mature, but geological CO_2 sequestration lacks both a business model and a model for international governance of the CO_2 sink. While other measures for mitigating CO_2 can be justified in terms of domestic benefits — air quality improvements, public health, technology innovation, land conservation — the only benefit of geological CO_2 sequestration is lower global CO_2 emissions, which means that an effective system of international governance will be needed to verify and monitor sequestered amounts, with mechanisms to encourage compliance.

3.6 Areas for U.S.-China Coordination

The above sections illustrate that many of the high-level technology and policy strategies for achieving carbon neutrality will be common to both the United States and China. What does this imply for U.S.-China coordination on carbon neutrality?

We identify four main forms of coordination:

1) **Common milestones,** which would seek to develop common measures of progress toward mid-century carbon neutrality goals, with the goal of creating larger markets that spur innovation and reduce technology costs.

2) **Dialogue and technical exchange,** which would establish regular dialogue and technical exchange on topics where the two countries face similar challenges and where discussion could help to promote convergence in technology strategies.

---

[46] Data are from EIA (2020).

[47] Based on Wang et al. (2019).

3) **RD&D prioritization,** which would seek to identify common or complementary priority areas for RD&D, to focus and increase the scale of RD&D efforts, encourage healthy competition, and enhance the chances of breakthrough technologies.

4) **International leadership,** which focuses on advancing U.S.-China global leadership on technology and governance issues.

For each of these four forms, Table 8 describes potential focus areas. For dialogue and technical exchange, these focus areas are key questions; for RD&D prioritization, they are key technology areas; for international leadership, they are areas where the United States and China can exert coordinated leadership.

Coordination around these four areas could occur through a U.S.-China Carbon Neutrality Working Group, which would be a natural successor to the U.S.-China Climate Change Working Group. This Carbon Neutrality Working Group could have national and subnational tracks, in recognition of the comparative strengths of U.S. and Chinese climate policy: China's national climate policy initiative has been earlier and stronger than the United States', whereas, because of a lack of national leadership, U.S. subnational goal setting, planning, and policy development for meeting long-term GHG emission reduction targets have been stronger than in China. Creating space for subnational dialogue and technical exchange under a Working Group would enable U.S. states and cities to support the development of subnational planning and policymaking capacity in China and would provide a forum for sharing implementation experience.

A subnational component to U.S.-China coordination around carbon neutrality also recognizes that, for the United States and China to achieve mid-century goals, some states-provinces and cities will need to lead by achieving carbon neutrality ahead of national targets. Subnational initiatives under a U.S.-China Carbon Neutrality Working Group could thus focus on setting goals and milestones that may exceed those at a national level.

Table 8 | Potential Focus Areas for U.S.-China Coordination on Carbon Neutrality

COLLABORATION FORMS	FOCUS AREAS
Common Milestones	Developing **common and specific milestones** for 2030, 2040, and 2050-2060, along the lines of the milestones proposed in this report, and sharing information on effective policies and programs for achieving milestones
Dialogue and Technical Exchange	**Medium- and long-term planning.** What are potential technology pathways to achieving carbon neutrality goals and what are the key policy and technology pathways along different pathways?
	Finance. How can the financial industry support the transition to lower carbon energy systems and more sustainable agriculture, forestry, and waste management systems?
	Just transition. How can governments support the transition to carbon neutral economies while at the same time reducing inequality?
	Renewable electricity systems. How can electricity systems be operated cost-effectively and reliably with much higher penetrations of solar and wind generation?
	Low-carbon fuels. What are potential regulatory and business models that can support an industry for low-carbon fuels — biofuels, hydrogen, and synthetic fuels? How can the sustainability and food security concerns around biofuels be addressed?
	Zero emission vehicles. What policy and regulatory measures can support the scaling up in manufacturing and adoption needed to electrify passenger transport? What are potential regulatory models for encouraging zero emission vehicles in freight transport?
	Zero emission buildings. What policy and regulatory measures can support electrification and building shell efficiency improvements for new and existing buildings?
	Industry decarbonization. What are the technologies and potential policy and regulatory measures to encourage CO_2 reductions in industry, focusing on the steel, cement, and chemicals sectors and cross-cutting technologies in other sectors?
	Forestry and agricultural extension. What management and extension practices can promote forest and agricultural soil carbon sequestration on a large scale, and how can sequestration be funded, monitored, and verified?
	Non-CO_2 GHG mitigation. What technologies and regulatory approaches can reduce methane emissions in energy systems and methane and nitrous oxide emissions in agriculture? What regulatory approaches can support alternatives to hydrofluorocarbons (HFCs)?
RD&D Prioritization	**Reliable zero emission energy and long-duration storage technologies,** which would facilitate low-cost, reliable 100% renewable electricity systems
	Advanced biofuels, which would reduce the land use impacts and food security concerns with biofuels
	Scalable building retrofit technologies and tools, which would reduce the costs of electrifying or improving building shell efficiency in existing buildings
	Low emissions technologies for industry, which would provide low-cost technology options for reducing CO_2 emissions in the steel, cement, and chemical sectors and for other cross-cutting technologies
International Leadership	**International shipping and aviation.** Leadership in international organizations that creates a path to zero emissions ships and planes
	Technology transfer. Incorporating CO_2 emissions standards into guidelines for international development aid
	CO_2 sink governance. Development of international institutions to monitor, verify, and enforce CO_2 sequestration

CHAPTER FOUR
CONCLUSIONS

Momentum from recent national carbon neutrality commitments is creating a window of opportunity for making meaningful progress against the temperature targets ratified in the Paris Agreement. The United States and China will be prime movers in efforts to get to net zero emissions globally by around mid-century, but their bilateral relationship will be equally critical. Given the scale and scope of the transition challenge, neither country will be able to achieve these goals in isolation.

Although recent attention has focused on differences between the United States and China, the three reports in this series highlight that there is a significant amount of convergence in technology pathways to achieve carbon neutrality between the two countries. Overall, strategies for achieving carbon neutrality are expected to be similar. This convergence is the result of common technologies, a fundamentally interconnected world, and physical resource limits.

Convergence suggests that, though challenges in the U.S.-China bilateral relationship may limit the depth of their collaboration, there is high value to coordination. Coordination does not require joint and verifiable commitments or resolving differences as a precondition. At its simplest, coordination only requires a shared understanding of the pace and direction of technology transition.

An important form of U.S.-China coordination will be around setting intermediate and long-term sectoral milestones for achieving carbon neutrality. Unlike national commitments, milestones are non-binding measures of progress toward longer-term goals. They can be designed to capture key sector transitions — such as the shift toward non-fossil generation in the electricity sector or the shift to non-internal combustion engine vehicles in transportation sector — in ways that are readily measurable and provide a meaningful reference for policymaking.

If the United States and China can develop common and credible milestones, as proposed in this report, this would provide a simple, powerful signal on the pace and direction of expected technology change, both domestically and internationally. Coordinated milestones could spur the technological innovation and cost reductions that will be practically needed for success.

Milestones would also fill an important gap between long-term goals and the nearer-term transitions required to achieve them. Although there has recently been a growing focus in both countries on the changes in technologies required to meet mid-century carbon neutrality goals, there has been less focus on what long-term studies imply for needed actions over the next decade. This is an important oversight. In many ways, the challenges of building momentum and re-orienting capital and political economy across the energy, buildings, industrial, and transportation sectors will be larger over the next decade than they will in subsequent decades.

In setting 2030 and 2040 milestones, it is important to work backward from mid-century goals rather than focusing on incremental change from 2020, in terms of thinking about feasibility. The scale of 2030 milestones may seem daunting, but lower effort in the next decade (a 2030 milestone) will mean significantly more effort in the following decade (a 2040 milestone). In essence, working backward from a 2050-2060 goal of net zero emissions will raise the trajectory of required intermediate milestones.

Milestones can be adapted over time as technologies change. Indeed, the technologies of 2050 — energy, vehicle, building, industrial, waste management, agricultural, forestry — will likely be very different than those of today. The necessary steps forward over the next decade to meet mid-century emissions targets, however, are relatively clear. They include a significant scaling-up of renewable energy to decarbonize electricity systems, rapid growth in EV and heat pump adoption, land use policies that support CO_2 sequestration, methane controls in energy systems, and initial efforts to develop low-carbon fuels and reduce CO_2 emissions in industry.

More ambitious efforts over the next decade could reduce the need for expensive or institutionally challenging solutions, such as direct air capture and sequestration of CO_2, in the longer term. This suggests new ways of considering the insurance value provided by policy-driven efforts to lower energy demand through conservation and end-use efficiency. Greater nearer-term ambition would also help to buy down the costs of reducing GHG emissions in middle-income countries, which will account for most global emissions growth over the coming decades.

Although most of the deep decarbonization and carbon neutrality studies we reviewed in this series are based on existing technologies, RD&D that improves upon existing technologies or enables new technologies will be critical for reducing costs or addressing physical challenges. For both countries, the most critical RD&D problem is in developing additional low-cost reliable generation and long-duration storage technologies for firming renewable electricity systems. By developing a shared understanding of RD&D priorities, focusing on common or complementary problems, and at least publishing results, the United States and China will be able to achieve far more than either country could in so in isolation. The remarkable cost reductions and global growth of solar PV technologies over the past decade underscore the upside of parallel, coordinated RD&D and the fact that a global RD&D effort does not require centralized management.

The focus in this report was more narrowly on CO_2 emissions, but there are ample reasons to extend U.S.-China coordination to GHG emissions more broadly, particularly for dialogue, technical exchange, and RD&D. Reductions in methane, nitrous oxide, and hydrofluorocarbon (HFC) emissions could reduce the need for negative emissions technologies over the next four decades.

To coordinate effectively, the United States and China will need to reconstitute but also reimagine the Climate Change Working Group that facilitated their climate-related dialogue and negotiations from 2013 to 2017. The successor proposed here, a U.S.-China Carbon Neutrality Working Group, would include participation of subnational governments in recognition of the two countries' comparative strengths of the United States and China. Inclusion of a subnational focus in the Working Group would also provide space for leading states-provinces and cities to develop commitments and milestones that exceed national ambition.

CHAPTER FIVE

APPENDIX A: DOCUMENTATION OF CALCULATIONS

5.1 General Calculations

The estimates in the milestone section rely on a high-level model that draws on inputs from the U.S. and China reviews. This appendix provides a detailed description of the model and calculations in the main text.

The model separates final energy consumption into electricity and fuels. Final electricity consumption in year y (EF_y) is calculated as final energy consumption in year y (FE_y) multiplied by the economywide electrification rate (α_y)

$$EF_y = FE_y \times \alpha_y$$

Fuels are non-electric solid, liquid, and gaseous forms of final energy consumption. Final fuels consumption in year y (FF_y) is calculated as final energy consumption in year y (FE_y) multiplied by one minus the economywide electrification rate in year y (α_y)

$$FF_y = FE_y \times (1 - \alpha_y)$$

Some portion of fuels consumption will be in the form of electricity derived fuels. The amount of electricity consumed in final fuels consumption in year y (EFL_y) will be final fuels consumption in year y, multiplied by the share of zero emission fuels in that year (β_y), multiplied by the share of electricity in zero emission fuels (θ_y)

$$EFL_y = FF_y \times \beta_y \times \theta_y$$

The portion of zero emission fuels that are not electric fuels are assumed to be final biofuels (BFL_y)

$$BFL_y = FF_y \times \beta_y \times (1 - \theta_y)$$

Primary biofuels consumption in year y (PB_y) is final biofuels consumption in year y (BFL_y) divided by a conversion rate (ρ)

$$PB_y = \frac{BFL_y}{\rho}$$

The model calculates total electricity generation in year y (EG_y) as the sum of final electricity consumption in year y (EF_y) and final electric fuels in year y (EFL_y) divided by an electricity-to-fuel conversion rate (μ), divided by one minus transmission and distribution (T&D) losses (γ). EG_y in EJ units is converted to TWh by dividing by 3.6 and multiplying by 1,000.

$$EG_y = \frac{EF_y + \frac{EFL_y}{\mu}}{(1 - \gamma)} \times \frac{PWh}{3.6\ EJ} \times \frac{10^3\ TWh}{PWh}$$

This approach assumes that electric fuels have the same T&D losses as direct electricity consumption, which likely overestimates electricity generation as electric fuel production may be interconnected at sub-transmission and transmission voltages.

Total non-fossil generation in year y (NFG_y) is calculated as total generation multiplied by the share of non-fossil generation in year y (σ_y)

$$NFG_y = EG_y \times \sigma_y$$

Table 9 shows the input values used for calculations in the main text and Table 10 shows calculated parameter values.

Table 9 | Input Values Used for Calculations in the Main Text

VARIABLE	SYMBOL	VALUES					
		UNITED STATES			CHINA		
		2030	2040	2050	2030	2040	2050
Final energy consumption (EJ)	FE_y	63	57	51	101	92	83
Electrification rate	α_y	30%	40%	50%	35%	45%	60%
Share of zero emission fuels	β_y	5%	30%	80%	5%	30%	80%
Share of electric fuels	θ_y	50%	60%	70%	50%	60%	70%
Electric fuels conversion rate	ρ	50%	50%	50%	50%	50%	50%
Biofuels conversion rate	μ	50%	50%	50%	50%	50%	50%
T&D losses	γ	7%	7%	7%	7%	7%	7%
Share of non-fossil generation	σ_y	50%	70%	100%	50%	70%	100%

Notes and sources: U.S. final energy consumption and electrification rate values for 2050 are from Williams et al. (2021); 2030 and 2040 values are linear interpolations between the 2020 and 2050 values in Williams et al. (2021). China final energy consumption values for 2030 and 2050 are from LBNL (2020); the 2040 value is a linear interpolation between the LBNL 2030 and 2050 values. Electrification rate for China in 2050 is based on the range of estimates in Khanna et al. (2021); 2030 and 2040 values are interpolated using a 25% electrification rate in 2020, based on IEA (2019a). The share of electric fuels in 2030 is based on Williams et al. (2021) and increases over time assuming limits to biofuel supplies. Electric fuels and biofuels conversion rates are middle-of-the-road approximations based on Williams et al. (2021). T&D losses are based on rule-of-thumb values in the United States. Shares of zero emission fuels and non-fossil fuel generation are based on milestones.

Table 10 | Calculated Parameter Values

PARAMETER	SYMBOL	VALUES					
		UNITED STATES			CHINA		
		2030	2040	2050	2030	2040	2050
Final electricity consumption (EJ)	FE_y	19	23	26	35	41	50
Final fuels consumption (EJ)	FF_y	44	34	26	66	51	33
Electric fuels consumption (EJ)	EFL_y	1	6	14	2	9	19
Biofuels consumption (EJ)	BFL_y	1	4	6	2	6	8
Primary biofuel supply (EJ)	PB_y	2	8	12	3	12	16
Net electricity generation (TWh)	EG_y	6,304	10,487	16,147	11,539	17,806	25,981
Non-fossil generation (TWh)	NFG_y	3,152	7,341	16,147	5,769	12,465	25,981

5.2 Wind and Solar Generation Calculations

We use different assumptions to calculate the amount of wind and solar generation for the United States and China that would result from a 50% non-fossil generation milestone in 2030 (Table 11). For the United States, we assume that all incremental non-fossil generation comes from solar and wind generation, due to the limited availability of new hydropower resources and limits on the scalability of nuclear power in the United States. For China, we assume that hydropower can provide an additional 100 TWh (25-30 GW) from 2020 to 2030, consistent with 2030 forecasts in IEA (2019a) and 2050 hydropower generation in He (2020) and taking China's total hydropower generation capacity close to 400 GW by 2030.[48] We assume that nuclear can provide an additional 300 TWh (~40 GW) from 2020 to 2030, which is consistent with 2050 projections by He (2020) and equivalent to building approximately 80% of China's current nuclear generation capacity (49 GW) over the next decade.[49]

Table 11 | Assumptions and Projections for 2030 Solar and Wind Generation and Installed

	UNITED STATES	CHINA
Non-fossil generation in 2019/2020 (TWh)	1,572	2,449
Non-fossil generation in 2030 (TWh)	3,152	5,769
New hydro and nuclear generation, 2020-2030 (TWh)	0	400
New wind and solar generation, 2020-2030 (TWh)	1,653	2,920
Wind generation / (wind + solar generation)	60%	60%
Wind capacity factor (%)	0.35	0.25
Solar capacity factor (%)	0.25	0.15
Wind generation capacity in 2030 (GW)	402	999
Solar generation capacity in 2030 (GW)	375	1,111
Total wind and solar capacity in 2030 (GW)	777	2,110
Total wind and solar capacity in 2020 (GW)	165	535

Notes and sources: Non-fossil generation and capacity in the United States (2019) and China (2020) are from EIA (2021) and China Electricity Council (CEC) (2021), respectively. Wind share of wind and solar generation is a rough estimate, based on its share in China in 2020 (64%) (CEC, 2021) and the 69% 2050 share in Williams et al. (2021). Solar and wind capacity factors for the United States are based on EIA (2021) and for China are based on CEC (2021).

5.3 Industrial CO_2 Intensity Calculations

We estimate the percentage reduction in industrial CO_2 intensity to meet a 15% industrial CO_2 emission reduction milestone by 2030 using

$$CI = \frac{\frac{CE_1}{VA_1} - \frac{CE_0}{VA_0}}{\frac{CE_0}{VA_0}} = \frac{\frac{CE_0 \times (1-\alpha)}{GDP_0 \times (1+r)^{(T-t)} \times \beta_1}}{\frac{CE_0}{GDP_0 \times \beta_0}} - 1 = \frac{(1-\alpha)}{(1+r)^{(T-t)}} \times \frac{\beta_0}{\beta_1} - 1$$

[48] The hydropower data and capacity factors used in these estimates are based on CEC (2021) data.

[49] *Ibid.*

Where CI is the percentage change in industrial CO_2 intensity, CE is CO_2 emissions, VA is industrial value added, α is the industrial CO_2 emission reduction milestone, r is the annual average rate of real GDP growth, T and t are the initial and final periods, and β is the share of industrial value added in total value added (GDP).

For China, we use an annual average real growth rate of 5% per year from 2020 to 2030. Based on World Bank data, the share of real industrial value added in real GDP in 2019 in China was 0.45; if this value were to fall to 0.35 by 2030, comparable to what it was in the early 1990s, the percentage reduction in industrial CO_2 intensity would be 33%.[50]

$$\frac{(1-0.15)}{(1+0.05)^{10}} \times \frac{0.45}{0.35} - 1 = -0.33$$

If this value were to fall to 0.40 by 2040, the percentage reduction would be 41%. This illustrates the role of structural change in reducing industrial CO_2 emissions in China.

For the United States, we use an annual average real growth rate of 2.5% per year from 2020 to 2030. Based on World Bank data, the share of real industrial value added in real GDP in 2019 in the United States was 0.19; if this value were to hold steady to 2030, the percentage reduction in industrial CO_2 intensity would be 34%.[51]

$$\frac{(1-0.15)}{(1+0.025)^{10}} \times 1 - 1 = -0.34$$

[50] Data are from World Bank World Development Indicators, https://databank.worldbank.org/. The share of industrial value added here is real industrial value added (2010$) divided by real GDP.

[51] *Ibid.*

CHAPTER SIX
REFERENCES

China Association of Automotive Manufacturers (CAAM). (Multiple Years). Vehicle Industry Economic Overview（汽车工业经济运行情况), China Association of Automotive Manufacturers, http://www.caam.org.cn/chn/21.html.

China Electricity Council (CEC). (2021). National Electricity Statistics Brief for 2020 (2020国电力工业统计快报一览表), China Electricity Council, https://www.cec.org.cn/upload/1/editor/1611623903447.pdf.

Energy and Environmental Economics (E3). (2018). *Deep Decarbonization in a High Renewables Future*. California Energy Commission Report, CEC-500-2018-012, https://efiling.energy.ca.gov/GetDocument.aspx?tn=223785.

Fu, S., Du X., Clarke, L., and Yu, S. (2020). *China's New Growth Pathway: From the 14th Five Year Plan to Carbon Neutrality*. Beijing: Energy Foundation China, https://www.efchina.org/Reports-en/report-lceg-20201210-en.

He, J. (2020). China Low-carbon Development and Transition Pathways Research: Overview of Project Results. (中国低碳发展战略与转型路径介绍：项目成果介绍).

Jiang, K., He, C., Dai, H., Liu, J., Xu, X. (2018), "Emission scenario analysis for China under the global 1.5°C target," *Carbon Management* 9 (5): 481-491, https://doi.org/10.1080/17583004.2018.1477835.

International Energy Agency. (2019a). *World Energy Outlook 2019*, International Energy Agency, https://www.iea.org/reports/world-energy-outlook-2019.

International Energy Agency. (2019b). *Global EV Outlook 2019*, International Energy Agency, https://www.iea.org/reports/global-ev-outlook-2019.

International Energy Agency (IEA). (2020a). *Solar PV module manufacturing and demand, 2014-2020*, International Energy Agency, https://www.iea.org/data-and-statistics/charts/solar-pv-module-manufacturing-and-demand-2014-2020.

International Energy Agency (IEA). (2020b). *Renewables 2020: Analysis and Forecasts to 2025*, International Energy Agency, https://www.iea.org/reports/renewables-2020/wind.

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.*

Khanna, N., Zhou, N. and Price, L. (2021). *Getting to Net Zero: A Review of Recent Studies on Mid-century Carbon Neutrality Pathways for China*. California-China Climate Institute, *Forthcoming*.

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K., and Swan, A. (2020). *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*. Interim Report, Princeton, https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.

Lawrence Berkeley National Laboratory (LBNL). (2020). *China Energy Outlook: Understanding China's Energy and Emission Trends*. Lawrence Berkeley National Laboratory-20011326, https://china.lbl.gov/china-energy-outlook-2020.

Loken, R., Mahone, A., and Kahrl, F. (2021). *Getting to Net Zero: A Review of Recent Studies on Mid-century Carbon Neutrality Pathways for the United States*. California-China Climate Institute. *Forthcoming.*

Mahone, A., Kahn-Lang, J., Li, V., Ryan, N., Subin, Z., Allen, D., De Moor, G., and Price, S. (2018). *Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model*. California Energy Commission, CEC-500-2018-012, https://efiling.energy.ca.gov/GetDocument.aspx?tn=223785.

Ministry of Foreign Affairs of the People's Republic of China (MOFA). (2020). *Statement by H.E. Xi Jinping President of the People's Republic of China At the General Debate of the 75th Session of The United Nations General Assembly*, https://www.fmprc.gov.cn/mfa_eng/zxxx_662805/t1817098.shtml.

National Academies of Sciences, Engineering, and Medicine (NASEM). (2021). *Accelerating the Decarbonization of the U.S. Energy System*, National Academies of Sciences, Engineering, and Medicine, https://www.nap.edu/resource/25932/interactive/index.html.

Pan, X., Chen, W., Wang, L., Lin, L., and Li, N. (2018). "The role of biomass in China's long-term mitigation toward the Paris climate goals." *Environmental Research Letters* 13: 1-9, https://iopscience.iop.org/article/10.1088/1748-9326/aaf06c/pdf

Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K. and Hare, W. (2015). "Zero emission targets as long-term global goals for climate protection." *Environmental Research Letters* 10: 1-11, https://iopscience.iop.org/article/10.1088/1748-9326/10/10/105007/pdf

Schiller, T., Kummer, P., Berdichevskiy, A., Weidenbach, M., and Sadoun, J. *Future of Automotive Sales and Aftersales.* Deloitte, https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Consumer-Business/gx-deloitte-future-of-automotive-sales-aftersales.pdf.

Sepulveda, N.A., Jenkins, J.D., de Sisternes, F.J., and Lester, R.K., "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation." *Joule* 2: 2403-2420, https://doi.org/10.1016/j.joule.2018.08.006.

The White House. (2021, January 27). *Executive Order on Tackling the Climate Crisis at Home and Abroad*, The White House Briefing Room, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/.

United States Bureau of Transportation Statistics (BTS). (2020). *National Transportation Statistics*, United States Bureau of Transportation Statistics, https://www.bts.gov/.

United States Department of Agriculture (USDA). (2020). *China Biofuels Annual*. United States Department of Agriculture, https://www.fas.usda.gov/data/china-biofuels-annual-6.

United Nations Department of Economic and Social Affairs (UN DESA). (2019). *World Population Prospects 2019*. United Nations Department of Economic and Social Affairs, https://population.un.org/wpp/.

United States Department of Energy (DOE). (2020). *Transportation Energy Data Book*. Oak Ridge National Lab, https://cms.bts.gov/content/gasoline-hybrid-and-electric-vehicle-sales.

United States Energy Information Administration (EIA). (2020). *Annual Energy Outlook*, United States Energy Information Administration, https://www.eia.gov/outlooks/aeo/.

United States Environmental Protection Agency (EPA). (2020). *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2018*, United States Environmental Protection Agency, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018

United States Energy Information Administration (EIA). (2021). *Electric Power Monthly*, United States Energy Information Administration, https://www.eia.gov/electricity/monthly/.

Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W.R. 3rd, Price, S., and Torn, M.S. (2012). The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. *Science* 335: 53-59, https://doi.org/10.1126/science.1208365

Wang, J., Feng, L., Palmer, P.I., Liu, Y., Fang, S., Bösch, H., O'Dell, C.W., Tang, X., Yang, D., Liu L., and Xia, C. (2020). Large Chinese land carbon sink estimated from atmospheric carbon dioxide data. *Nature* 586: 720-723, https://doi.org/10.1038/s41586-020-2849-9.

Williams, J.H., Haley, B., Kahrl, F., Moore, J., Jones, A.D., Torn, M.S., and McJeon, H. (2014). Pathways to Deep Decarbonization in the United States. *New York: SDSN/IDDRI*, https://usddpp.org/downloads/2014-technical-report.pdf.

Williams, J.H., Jones, R.A, Haley, B., Kwok, G., Hargreaves, J., Farbes, J., and Torn, M.S., (2021). Carbon Neutral Pathways for the United States. *AGU Advances* 2, https://doi.org/10.1029/2020AV000284.

Wang, J., Rodrigues, J.F.D., Hu, M., Behrens, B., Tukker, A. (2019). The evolution of Chinese industrial CO2 emissions 2000–2050: A review and meta-analysis of historical drivers, projections and policy goals. *Renewable and Sustainable Energy Reviews* 116: 1-11. https://doi.org/10.1016/j.rser.2019.109433.