TRACKING SUBNATIONAL

PROGRESS

TOWARD CARBON NEUTRALITY IN THE U.S. AND CHINA

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Acronym and Abbreviation List	
BEA	Bureau of Economic Analysis
CEC	California Energy Commission
CEC	China Electricity Council
CES	Clean Energy Standards
CEYEB	China Energy Yearbook Editorial Board
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DOE	Department of Energy
EIA	Energy Information Agency
EPA	Environmental Protection Agency
ETS	Emissions Trading System
EV	Electric Vehicle
FHA	Federal Highway Administration
FIA	Food Inventory and Analysis
GDP	Gross Domestic Product
GSP	Gross State Product
GW	Gigawatt
ha	Hectare
ICCT	International Council for Clean Transportation
IEA	International Energy Agency
IRA	Inflation Reduction Act
LDV	Light-duty Vehicle
LPG	Liquified Petroleum Gas
MIIT	Ministry of Industry and Information Technology
MOHURD	Ministry of Housing and Urban Rural Development
MOU	Memorandum of Understanding
NBS	National Bureau of Statistics
NEA	National Energy Administration
NEV	New Energy Vehicle
NDRC	National Development and Reform Commission

Acronym and Abbreviation List (cont'd)	
NREL	National Renewable Energy Laboratory
PJ	Petajoules
PHEV	Plug-in Hybrid Electric Vehicle
RFS	Renewable Fuel Standard
RPS	Renewable Portfolio Standard
SEPS	State Energy Data Systems
SFA	State Forest Administration of China
tce	Tons Coal Equivalent
U.S.	United States
USDA	United States Department of Agriculture
USFS	United States Forest Service
ZEV	Zero Emissions Vehicle
m^3/ha-y	Cubic Meters per Hectare per Year

EXECUTIVE SUMMARY

The United States (U.S.) and China have set ambitious targets for carbon neutrality – reducing carbon dioxide (CO_2) emissions to net zero levels by 2050 and 2060, respectively. Implementation of policies to meet these targets will take place at a subnational level, within U.S. states and Chinese provinces. How can governments and non-governmental organizations track subnational progress toward carbon neutrality?

This report develops indicators and 2035 milestones for each indicator to track progress by U.S. states and Chinese provinces toward mid-century carbon neutrality goals. It builds on a 2021 report, Getting to Net Zero, which developed a framework for supporting coordination on carbon neutrality between the U.S. and China, including technology pathways, common milestones, and priority areas for dialogue, research and development, and international leadership.

The indicators in this report (Table 1, pg. vi) aim to balance simplicity and completeness, with publicly available data that can be regularly updated over time. They focus on two core transitions: (1) the transition from fossil fuel-dominant to non-fossil fuel energy systems, and (2) the transition to more carbon-intensive land use.

Table 1 includes two kinds of indicators: flow (adoption) and stock (fleet) indicators. Flow indicators track the flow of new infrastructure and equipment and may change relatively quickly. Stock indicators track changes in total energy mix and land use and will tend to change relatively slowly. In tandem, flow and stock indicators can provide a useful lens on the impacts of policy and the pace of nearer-term and long-term change. For most flow indicators, standardized, publicly available data are not yet available at a subnational level. National governments can play an important role in addressing this data gap.

The 2035 milestones in Table 1 are national milestones, consistent with either current national policy or studies of longer-term carbon neutrality pathways.[1] Indicator values for each state and province will likely change at different rates, but changes should be directionally consistent with the 2035 milestones, and over time there should be greater convergence in indicator values among states and provinces. A key goal of tracking subnational progress is to identify the regions and sectors that may need more targeted support from national governments, in order to inform and adapt national policy.

The U.S. and China have very different economies, geographies, and energy systems. So why develop a common set of indicators for both countries? By developing common indicators, we can identify sectors and regions where each country is making faster or slower progress, as the basis for dialogue and coordination between national and subnational governments. A common set of indicators also can help to build confidence that states or provinces in the other country are making progress in energy and land use transitions.

Over the past two decades, the U.S. and China have both made significant progress in the initial stages of a transition to non-fossil fuel energy systems, though thus far the most visible changes have been in the electricity sector. In both countries, non-fossil fuel generation – renewables,

1 Of these milestones, only “share of non-fossil fuel electricity generation in total generation” in the U.S. is explicitly tied to a specific national policy goal. The remaining milestone values are consistent with the results of longer-term decarbonization studies. See Appendix A for an overview of milestone calculations.

Table 1 | Indicators, Recent Indicator Values, and 2035 Milestones

SECTOR	INDICATOR	2020 VALUE		2035
		U.S.	CHINA	U.S.
ENERGY SUPPLY				
Electricity Generation	Share of new non-fossil fuel capacity in total new generation capacity (3-year moving average)	79% (2019-2021)	67% (2018-2020)	>90%
	Share of non-fossil fuel electricity generation in total generation	40%	32%	>95%
Centralized Heat Supply	Share of non-fossil fuel energy in total centralized heat supply	N/A	2%	N/A
ENERGY CONSUMPTION				
Buildings	Share of heat pump sales in total water heater and furnace sales	N/A	N/A	80%
	Share of non-fossil fuel energy in residential and commercial final energy consumption	51%	61%	70%
Industry	Share of non-fossil fuel energy in industrial final energy consumption	22%	32%	45%
Transportation	Share of zero-emissions vehicle (ZEV) sales in light-duty or passenger vehicle sales	8% (2022)	22% (2022)	80%
	Share of ZEV sales in heavy-duty or freight truck sales	< 1% (2022)	7% (2022)	60%
	Share of non-fossil fuel energy in transportation final energy consumption	5%	7%	20%
LAND USE				
Forest Area	Annual increase in forest area as a share of total land area (percentage points per year, %/yr)	0.1%/yr (2007-2017)	0.3%/yr (2010-2020)	0.1%/yr
	Annual increase in forest volume per forest area (cubic meters per hectare per year, m^3/ha-yr)	1.1 m^3/ ha-yr (2010-2020s)	1.7 m^3/ ha-yr (2010-2020)	1.0 m^3/ ha-yr
ECONOMY-WIDE				
Energy Intensity	Reduction in energy consumption per unit real gross domestic product (GDP)	33% (2000-2020)	36% (2000-2020)	43% (relative to 2020)
CO_2 Intensity	Reduction in energy-related CO_2 emissions per unit real GDP	44% (2000-2020)	38% (2000-2019)	70% (relative to 2020)

Flow indicator	
Stock indicator	

Sources and notes: See Appendix A for a detailed description of how milestone values were calculated. Sources for most historical values can be found in corresponding sections of the report. ZEV sales shares are shares of electric vehicle sales from the International Energy Administration (IEA) (2023). These data include plug-in hybrid electric vehicles (PHEVs), which are not zero emitting, not other zero emitting vehicles, such as fuel cell vehicles. The U.S. does not have a significant centralized heat supply, and thus we do not report this indicator for the U.S. Several flow indicator values are "N/A" because data are not publicly available. We report the forestry metrics in total, rather than per year, later in the report; use of the per year values here enables comparison with historical values large hydropower, and nuclear – now accounts for about 70% to 80% of new generation capacity. Between 2010 and 2020, the share of electricity generated from non-fossil fuel energy resources rose from 30% to 40% in the U.S. and from 19% to 32% in China. Regionally, the largest increases in the share of non-fossil generation between 2000 and 2020 were in areas with higher quality wind resources: the midwestern U.S. and northern China. More recently, however, large declines in the cost of solar generation have led to greater regional convergence in the share of new non-fossil generation capacity in China, a trend that is likely emerging in the U.S. as well.

The energy consuming sectors – buildings, industry, and transportation – present a more nuanced story. In China, the share of non-fossil fuel energy use in buildings and industry grew rapidly over the last decade, driven by a combination of environmental policy and technological change. In the U.S., non-fossil energy shares in buildings and industry were relatively flat; likely a consequence of low natural gas prices and limited federal and state policies to encourage fuel switching. Neither country has made significant progress in reducing the share of fossil fuel consumption in transportation, despite more than a decade of national biofuel policies, more stringent national vehicle emissions standards, and state and provincial efforts to support alternative transportation fuels.

The geography of changes in state and provincial fossil fuel consumption, energy intensity, and CO_2 intensity reflects the different social, technology, and resource challenges that the U.S. and China face in transitioning their energy systems to non-fossil fuel energy sources. In the buildings sector, for instance, northern urban areas in China have extensive district heating networks, whereas southern urban areas and most rural areas lack centralized heat supply. China's challenges for increasing the share of non-fossil energy use in buildings will be to (1) develop non-fossil heating solutions for rural and southern urban areas and (2) decide whether to develop non-fossil energy sources for district heating or to electrify building heating in northern urban areas. In the U.S., by contrast, there is very little district heating, and most fossil fuel heating in urban and rural areas is supplied by natural gas and oil products. The largest challenge for increasing the share of non-fossil energy use in U.S. buildings will be to develop reliable and low-cost ways to electrify heating in colder northern regions.

Sustained progress over the next 15 years will be critical for putting the U.S. and China on a trajectory to meet their mid-century carbon neutrality goals. In the transportation sector, for instance, will emissions standards, government programs, and incentives be enough to drive rapid adoption of electric vehicles (EVs) and growth in the share of non-fossil fuel energy in transportation? Will the growth of non-fossil fuel generation be enough to ensure that transportation electrification actually leads to significant reductions in CO_2 emissions? The indicators in this report provide a comprehensive, yet still tractable, means of gauging subnational progress over the next decade.

The value of tracking progress toward carbon neutrality in the U.S. and China together, rather than doing so separately, will increase over time as both countries face and overcome a range of regional challenges: land constraints on renewable energy development; renewable integration challenges in regional electric grids; technology, political, and economic challenges in industry; building electrification in colder areas and electrification of heavier industries; adoption of non-fossil fueled transportation modes in logistical hubs; and difficulties in reconciling economic development and land conservation. By monitoring the U.S. and China in tandem, cooperation between the two can focus on regions that face comparable challenges – for instance, land constraints in the northeast U.S. and China's coastal provinces may mean that both take a more distributed approach to renewable energy development. Regionally targeted bilateral cooperation can help to promote convergence in indicators among states and provinces over time.

CHAPTER ONE
BACKGROUND

The U.S. and China both have set ambitious national goals for achieving carbon neutrality by around mid-century. Changes in energy systems and land use to meet those goals will occur at a state or provincial level, which means it will be important to track state and provincial progress toward these longer-term goals through nearer-term indicators and milestones.

This report develops indicators and milestones for tracking U.S. states' and Chinese provinces' progress toward national mid-century climate neutrality goals. It builds on a previous report, Getting to Net Zero: U.S.-China Framework and Milestones for Carbon Neutrality,[2] which focused on national-level U.S.-China coordination and milestones. In contrast, this report develops indicators and milestones for tracking progress toward carbon neutrality at a subnational level.

This report is organized into five main sections:

1. **Carbon Neutrality Indicators and Milestones** provides an overview of the indicators and 2035 milestones developed for this report.

2. **Tracking Progress: 2000-2021** illustrates, for each indicator, how U.S. states and Chinese provinces have progressed over the last two decades.

3. **Conclusions** confirms the importance of indicators, highlights key takeaways from the analysis of historical trends, and outlines challenges going forward.

4. **Appendix A: Milestone Calculations** explains how 2035 milestones were calculated for each indicator.

5. **Appendix B: Data Sources and Preparation** describes data sources and data preparation methods for indicator values.

Although most of the indicators in this report can be tracked using publicly available data, there are several data gaps and issues for subnational indicators in both the U.S. and China. Throughout the report, we identify where these gaps and issues are and how national governments can play a role in resolving them.

The indicators developed for this report will continue to be updated regularly, as data availability allows.

2 Dai et al. (2021).

CHAPTER TWO

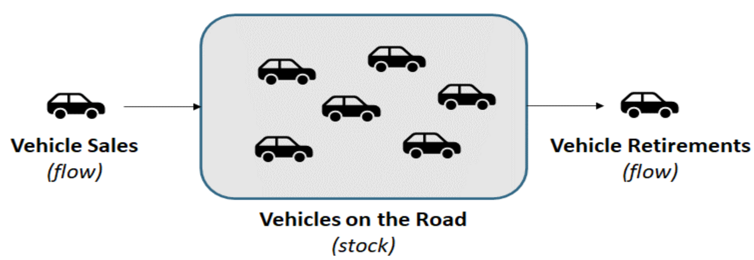
CARBON NEUTRALITY INDICATORS AND MILESTONES

Carbon neutrality indicators are measures to track progress against carbon neutrality goals. Indicators should be succinct and impactful: they should track important changes in energy systems and land use that are expected to be necessary to meet longer-term goals. In practice, this means focusing on a relatively small set of indicators that capture the most critical changes in the flow and stock of energy infrastructure and end-use equipment (see Box) and in land use. At the same time, at least some indicators should be policy relevant, meaning that they can be directly shaped by policy and regulation.

Flow and Stock Indicators

Flow indicators capture more rapid changes in the adoption and retirement of new energy infrastructure and equipment and marginal changes in land use. **Stock indicators** capture slower changes in the total stock of energy infrastructure and equipment.

The figure below illustrates the distinction between flow and stock indicators using a vehicle example. Every year, some new vehicles are added to and retired from the total stock of vehicles. Flow indicators track changes in vehicle additions (sales) and retirements or in the attributes and performance of these vehicles. Stock indicators track changes in the total stock of vehicles or in the attributes or performance of the entire fleet of vehicles on the road.



Changes in flow variables can occur relatively quickly. For instance, in California sales of light-duty ZEVs increased from 4% to 18% of total light-duty vehicle sales from 2017 to 2022.[A] However, changes in stock variables tend to occur more slowly. Despite increases in ZEV sales, through the end of 2020 California's transportation sector was still 98% reliant on petroleum products.[B] Changes in total transportation sector energy use happen more slowly because sales of new cars (in California, about 2 million per year) tend to be small relative to the stock of vehicles (in California, about 14 million registered in 2020).[C]

A Data are from the California Energy Commission (CEC), https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/new-zev-sales

B Data are from the U.S. Energy Information Administration's (EIA's) State Energy Data System (SEDS).

C Vehicle sales data are from the CEC link above; total registered vehicles data are from the U.S. Federal Highway Administration's (FHA's) Highway Statistics Series, https://www.fhwa.dot.gov/policyinformation/statistics/2020/mv1.cfm

By definition, achieving carbon neutrality means that a country reduces its net CO_2 emissions — annual CO_2 emissions minus any carbon that is terrestrially or geologically sequestered — to zero.[3] Because fossil fuel combustion is the main source of CO_2 emissions in the U.S. and China, reducing the share of fossil fuels in the total supply of energy will be the cornerstone of efforts to achieve net zero CO_2 emissions in both countries.

Almost all non-fossil fuel energy resources — biomass, geothermal, hydropower, nuclear fission, solar, waves, and wind — are currently used to generate electricity.[4] This implies that, at least in the near term, the two most important strategies for reducing CO_2 emissions will be to increase the amount of electricity generated from non-emitting sources of energy and to electrify sources of energy demand. These two strategies correspond to two kinds of stock indicators: (1) the share of non-fossil fuel energy in electricity generation, and (2) the share of non-fossil fuel energy, including electricity, consumption in the buildings, industry, and transportation sectors.5 For China, we also include a non-fossil share indicator for heat supply that captures the country's large district heating network.

In addition to these stock indicators, we propose four nearer-term flow indicators that more accurately gauge changes in the sales and adoption of new equipment and infrastructure. These include the share of non-fossil fuel generating capacity in total new generating capacity, the share of heat pump sales in total water heater and furnace sales, the share of ZEV sales in light-duty vehicle sales, and the share of ZEV sales in heavy-duty vehicle sales. As described in the next section, the last three of these indicators have data availability issues that can hopefully be addressed over time.

Four additional indicators are useful for tracking changes in land use and economy over time. These include increases in the share of forest area in total land area and increases in forest volume per forest area, which are are proxies for changes in the amount of carbon stored in forests, and reductions in energy intensity and reductions in CO_2 intensity, which track changes in energy consumption and CO_2 emissions per unit of gross state or provincial product.

Interim milestones can be created for each of these indicators. An interim milestone reflects either a policy goal or an interpolated value between the indicator's present value and a future (2050 or 2060) value that would be consistent with achieving carbon neutrality goals. This report uses 2035 as an interim milestone year, consistent with policymaking targets in both the U.S. and China. It uses national milestones, based on government policy targets, independent studies, and interpolated values (see Appendix A). States and provinces will differ in the extent to which they meet these milestones due to resource endowments and policy, but national milestones nevertheless provide a useful gauge of subnational progress toward interim and longer-term policy goals. Table 2 shows base year values and 2035 milestones values for each indicator examined in this report.

For energy consuming sectors, the energy accounting framework for our indicators treats energy carriers, such as electricity and steam, as non-fossil energy resources. Therefore, we have separate indicators for the primary energy supply for these carriers: electricity generation and, for China, heat supply.[6] This means that it is important to track energy supply and consumption indicators in tandem. Transportation electrification with a fossil fuel intensive electricity supply, for instance, will not necessarily lead to reductions in CO_2 emissions.

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3 Net CO_2 emissions in any given year do not need to be zero for a country to be carbon neutral; net emissions should be zero over some time horizon – a decade, for instance.

4 The exception in this list is biomass, which is often blended into gasoline and diesel to create biofuels.

5 Higher consumption of non-fossil fuel primary energy resources, such as biomass, will also increase the share of non-fossil fuel energy in final energy consumption in the buildings, industry, and transportation sectors, but in the near term most of the increase will likely come from electrification.

6 We follow reporting conventions in accounting for conversion losses in electricity generation and heat supply indicators. For electricity generation, shares are of total generation and do not include energy conversion losses. For heat supply, shares are of primary energy supply.

Table 2 | Indicators, Recent Indicator Values, and 2035 Milestones

SECTOR	INDICATOR	2020 VALUE		2035 MILESTONES	
		U.S.	CHINA	U.S.	CHINA
ENERGY SUPPLY					
Electricity Generation	Share of new non-fossil fuel capacity in total new generation capacity (3-year moving average)	79% (2019-2021)	67% (2018-2020)	>90%	>90%
	Share of non-fossil fuel electricity generation in total generation	40%	32%	>95%	>55%
Centralized Heat Supply	Share of non-fossil fuel energy in total centralized heat supply	N/A	2%	N/A	10%
ENERGY CONSUMPTION					
Buildings	Share of heat pump sales in total water heater and furnace sales	N/A	N/A	80%	80%
	Share of non-fossil fuel energy in residential and commercial final energy consumption	51%	61%	70%	75%
Industry	Share of non-fossil fuel energy in industrial final energy consumption	22%	32%	45%	45%
Transportation	Share of ZEV sales in light-duty or passenger vehicle sales	8% (2022)	22% (2022)	80%	80%
	Share of ZEV sales in heavy-duty or freight truck sales	< 1% (2022)	7% (2022)	60%	60%
	Share of non-fossil fuel energy in transportation final energy consumption	5%	7%	20%	20%
LAND USE					
Forest Area	Annual increase in forest area as a share of total land area (percentage points per year, %/yr)	0.1%/yr (2007-2017)	0.3%/yr (2010-2020)	0.1%/yr	0.2%/yr
	Annual increase in forest volume per forest area (cubic meters per hectare per year, m^3/ha-yr)	1.1 m3/ ha-yr (2010s-2020s)	1.7 m3/ ha-yr (2010-2020)	1.0 m3/ ha-yr	1.4 m3/ha-yr
ECONOMY-WIDE					
Energy Intensity	Reduction in energy consumption per unit real GDP	33% (2000-2020)	36% (2000-2020)	43% (relative to 2020)	43% (relative to 2020)
CO_2 Intensity	Reduction in energy-related CO_2 emissions per unit real GDP	44% (2000-2020)	38% (2000-2019)	70% (relative to 2020)	60% (relative to 2020)

Flow indicator	(green)
Stock indicator	(beige)

Sources and notes: See Appendix A for a detailed description of how milestone values were calculated. Sources for most historical values can be found in corresponding sections of the report. ZEV sales shares are shares of electric vehicle sales, from IEA (2023). These data include plug-in hybrid electric vehicles (PHEVs), which are not zero emitting, not other zero emitting vehicles, such as fuel cell vehicles. The U.S. does not have a significant centralized heat supply, and thus we do not report this indicator for the U.S. Several flow indicator values are "N/A" because data are not publicly available. We report the forestry metrics in total, rather than per year, later in the report; use of the per year values here enables comparison with historical values..

Table 3 | Kinds of Policies that May Affect Different Indicators

SECTOR OR AREA	POLICIES	INDICATORS
Electricity Generation	Renewable portfolio standards (RPS), clean energy standards (CES), emissions standards, regional emissions caps, cap and trade programs, carbon tax, regulatory and market reforms	Share of new non-fossil fuel capacity in total new generation capacity (3-year moving average)
		Share of non-fossil fuel electricity generation in total generation
Centralized Heat Supply		Share of non-fossil fuel energy in total centralized heat supply
Buildings	Building standards and codes, tax incentives, utility programs, consumer education programs, workforce training, carbon tax, building certification, net zero energy building policies, government building policies, regulatory and market reforms	Share of heat pump sales in total water heater and furnace sales
		Share of non-fossil fuel energy in residential and commercial final energy consumption
Industry	Industry programs, product labeling, tax incentives, energy efficiency standards, emissions standards, regional emissions caps, cap and trade, carbon tax, government procurement	Share of non-fossil fuel energy in industrial final energy consumption
Transportation	ZEV mandates, emissions standards, tax incentives, utility programs, charging infrastructure investment, government procurement	Share of ZEV sales in light-duty and heavy-duty vehicle sales
		Share of non-fossil fuel energy in transportation final energy consumption
Land Use	National conservation programs, reforestation programs, ecosystem restoration programs, incentives for private landowners, extension support, cap and trade offsets	Annual increase in forest area as a share of total land area (percentage points per year, %/yr)
		Annual increase in forest volume per forest area (cubic meters per hectare per year, m3/ha-yr)
Economy-Wide	All energy, fiscal, and monetary policies that encourage changes in economic structure, end-use energy efficiency, and switching from fossil fuel to non-fossil fuel energy supply and consumption	Reduction in energy intensity
		Reduction in energy-related CO_2 intensity

Over time, two additional indicators will become more important and can be added to the list in Table 2. The first of these is the share of non-fossil fuel energy sources in annual consumption of solid, liquid, and gaseous fuels. This category might include biofuels, green hydrogen, and other future fuels. The second indicator is geological CO_2 sequestration. Both indicators are likely to be relatively small over the next decade and would require data that are not yet readily available.[7]

The list of indicators in Table 2 does not include explicit metrics for energy consumption efficiency. Absolute efficiency metrics, such as energy consumption per unit area in buildings, are often difficult to compare across subnational entities because of differences in local climate, demographics, and economy, and due to data limitations. Metrics that are relative to a base year, such as the change in per capita energy consumption relative to year 2000 levels, may facilitate more meaningful comparisons. The list of indicators in Table 2 does not yet include relative efficiency metrics, though we may explore adding them in the future. Energy consumption

7 In our current metrics, the share of non-fossil energy in fuels is captured through final energy consumption rather than energy supply. Increases in non-electric energy carriers, such as hydrogen, would thus leave a gap in our metrics, because a decrease in the share of primary fossil fuels in final energy consumption would not be covered by our supply metrics (electricity, heat). Neither the U.S. nor China currently reports data on the composition of non-electric and, in China's case, non-heat energy carriers.

efficiency is also implicitly included in indicators for the share of non-fossil energy consumption. For instance, end-use efficiency reduces final energy consumption and thus tends to lower the effort required to reduce fossil fuel energy consumption.[8]

For most of the indicators in Table 2, there are relatively direct links between policy and changes in indicator values (Table 3). For instance, tax credits that encourage EV adoption should increase the share of ZEV sales and the share of non-fossil fuel energy in transportation. Different levels of government have different policy levers. In the U.S., for instance, building energy policies are typically managed at the state and local level, often supported by federal incentives. Throughout the report, we describe how different levels of policy have historically shaped indicator values across states and provinces, and how they may do so going forward.

8 For instance, consider a state where building energy consumption is 200 petajoules (PJ) and non-fossil energy accounts for 50% of consumption (100 PJ fossil fuel, 100 PJ non-fossil fuel). Ignoring growth in demand for simplicity, if the state can reduce building natural gas consumption by 5% through a weatherization program, the state's share of non-fossil fuel energy would increase to 51% (= 100 PJ / [95 PJ + 100 PJ]).

CHAPTER THREE

TRACKING PROGRESS: 2000–2021

This section examines changes in indicator values for U.S. states and Chinese provinces over the last two decades. The U.S. has 50 states and China has 31 provinces, provincial-level municipalities, and autonomous regions (collectively referred to as "provinces" in this report), making it difficult to visualize indicators and changes in indicators over time. To address this issue, the report uses regional aggregations and maps to summarize trends.

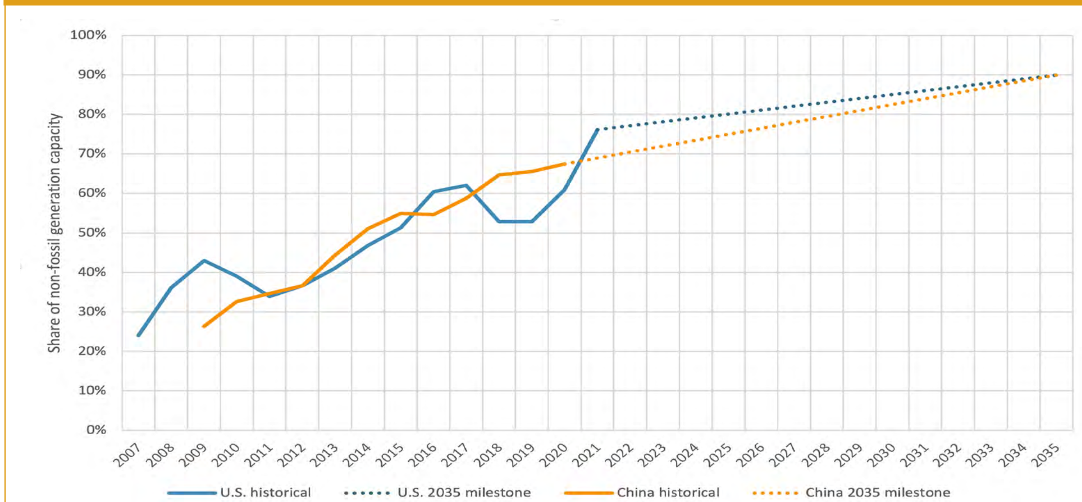
States and provinces will make progress toward national carbon neutrality milestones at different rates. For electricity generation, buildings, industry, forestry, and energy and CO_2 intensity, indicator values reflect different starting points and levels of difficulty that are tied to local climate, natural resources, demographics, and economics. For instance, reducing the share of fossil fuel energy in buildings may be easier in states or provinces that have milder climates than in those that need space heating for several months a year. For this reason, changes in indicator values, rather than current indicator values, are often more important measures of progress.

3.1 Electricity Generation

A region's mix of electricity generation resources will be driven by resource availability and economics, in addition to local and national policy. Historically, U.S. states and Chinese provinces with higher shares of non-fossil electricity generation have been concentrated in hydropower-rich areas and in resource-poor coastal regions where large nuclear power plants have often been seen as an attractive supply option. Going forward, regional and local differences in non-fossil generation shares will similarly reflect resource endowments and economics.

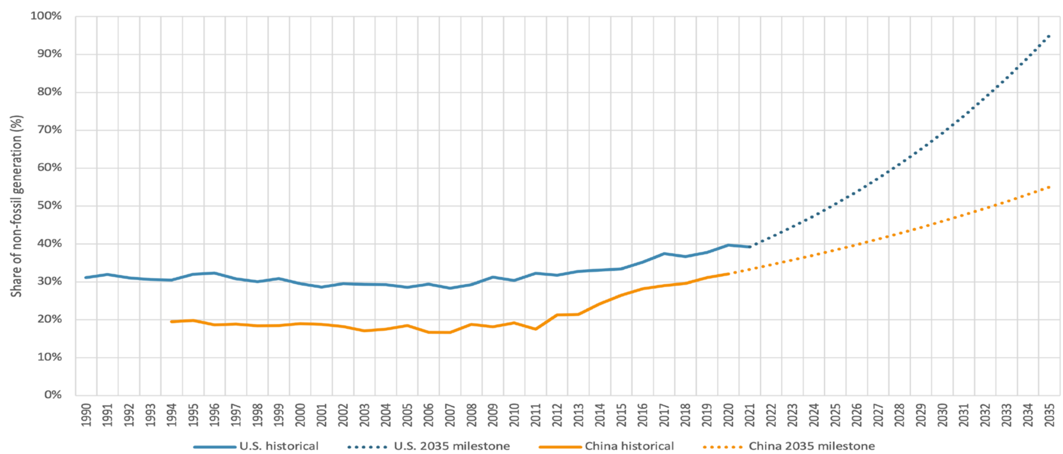
At a national level, non-fossil fuel electricity generation capacity in both the U.S. and China grew rapidly after 2010. In the U.S., the share of new non-fossil generation capacity in total new

Figure 1 | Share of New Non-Fossil Generation Capacity (Three-Year Moving Average) in the U.S. and China, Historical and Trajectories to 2035 Milestones



Sources and notes: U.S. data are from EIA (multiple years (a)). China data are from CEC (multiple years) and the China Energy Yearbook Editorial Board (CEYEB) (multiple years). The three-year moving average dampens annual volatility.

Figure 2 | Share of Non-Fossil Generation in the U.S. and China, Historical and Trajectories to 2035 Milestones



Sources and notes: Data for the U.S. are from EIA (multiple years (b)). Data for China are from China Electricity Council (multiple years) and CEYEB (multiple years). Data for China do not include biomass generation, which is within "thermal generation" (火电) and was not reported separately before 2009. In 2020, including biomass generation would have increased the share of non-fossil generation from 32% to 34%.

capacity (three-year moving average) rose from 39% in 2010 to 76% in 2021 (Figure 1), with wind and solar accounting for 95% of new non-fossil generation capacity added between 2005 and 2021.[9] In China, the share of non-fossil generation capacity rose from 33% in 2010 to 67% in 2020, with wind (Figure 1), solar, and hydro accounting for 35%, 30%, and 27%, respectively, of all new non-fossil generation capacity added between 2007 and 2020.[10] Rapid increases in new non-fossil generation capacity (gigawatts, GW) led to an increase in the share of non-fossil generation (gigawatt-hours, GWh). Between 2010 and 2020, the share of non-fossil generation rose from 30% to 40% in the U.S. and from 19% to 32% in China (Figure 2).[11]

3.1.1 U.S. States

In most U.S. states, wind, solar, and electricity storage now account for almost all new generation capacity, with some residual natural gas-fired generation. Over the last two decades, the most rapid increases in the share of new non-fossil generation capacity have been in the resource-rich West and Midwest, and more recently in the South (Figure 3). In these regions, falling costs have made wind and solar generation increasingly economic. The share of new non-fossil generation has grown more unevenly in the Northeast, which, despite strong clean energy goals, is more resource constrained and has yet to develop policy and business models to sustainably scale up new non-fossil generation over the past two decades.[12]

Growth in wind and solar generation capacity has translated into increases in the share of non-fossil generation at a state level. Figure 4 shows the shares of non-fossil generation for each state in 2020 and Figure 5 shows the change in shares of non-fossil generation from 2010 to 2020. These shares reflect complex dynamics among electricity demand growth, non-fossil generation growth, annual variability in hydropower generation, and retirement of existing generation. For instance, despite rapid growth in renewable generation, California's share of non-fossil generation has remained at about 50% over the past two decades, due to electricity demand growth and the

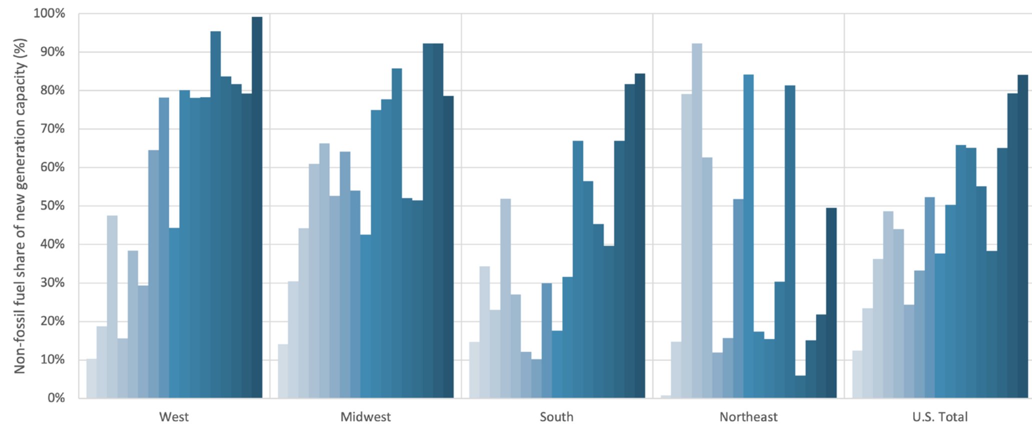
9 EIA (multiple years (a)).

10 CEC (multiple years).

11 Ibid.

12 In fairness, the Northeast had a slightly larger share of non-fossil generation (43%) than the Midwest (40%) or South (43%) regions in 2021, due to investments in nuclear and, in New York, hydropower generation in the twentieth century. Data are from EIA (multiple years (a)).

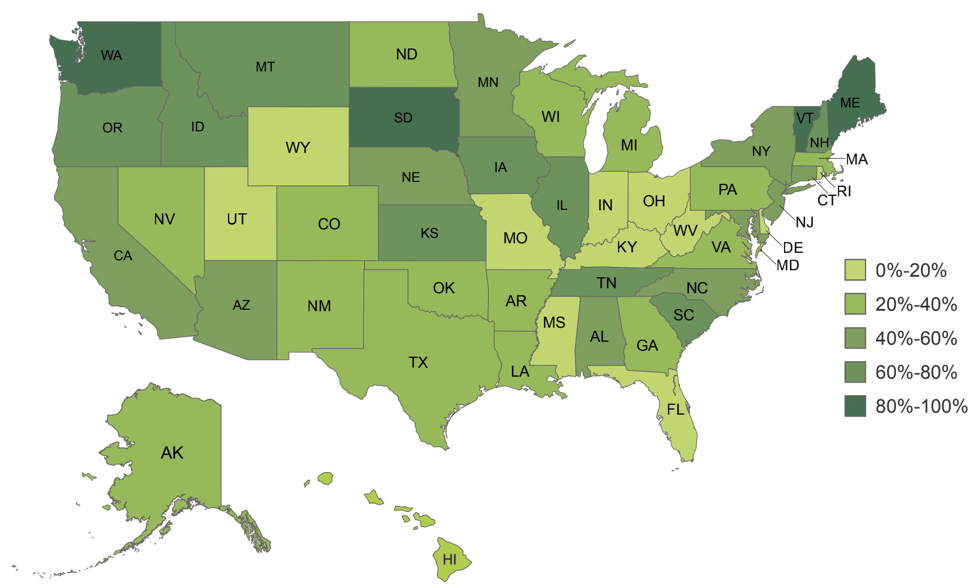
Figure 3 | Share of New Non-Fossil Fuel Generation Capacity in Total Generation Capacity by U.S. Census Region, 2005-2021



Sources and notes: Data are from EIA (multiple years (a)). Columns are individual years, from left (2005) to right (2021).

retirement of a large nuclear power plant. From the perspective of longer-term carbon neutrality goals, however, these kinds of dynamics are nearer-term bottlenecks that must eventually be overcome to reach higher shares of non-fossil generation.

Figure 4 | Share of Non-Fossil Generation by State, 2020



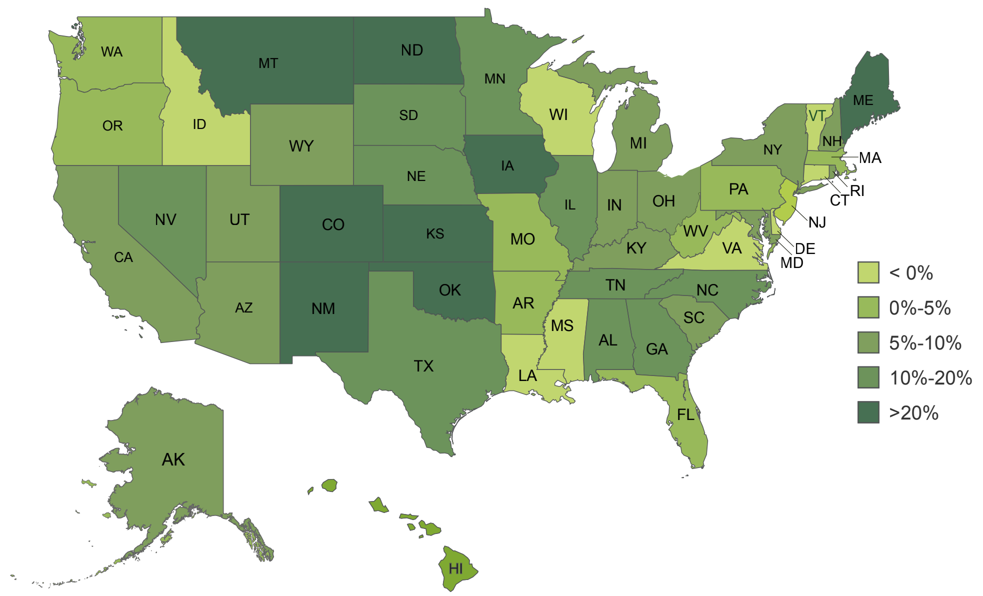
Sources: Data are from EIA (multiple years (a)).

Figure 4 and Figure 5 also illustrate the increasing role of economics in driving higher shares of non-fossil generation. Many of the most rapid increases in the share of non-fossil generation have been in Western and Midwestern wind-rich states that do not have strong renewable energy policies, such as the Dakotas, Kansas, Iowa, Montana, and Oklahoma. In many of these states, wind generation is now cost competitive with fossil fuel generation.[13]

Many states already have relatively high shares of non-fossil generation. More than half (26) of all states now have shares of non-fossil generation that exceed 40%, 17 exceed 50%, and 10 exceed

13 DOE (2022a).

Figure 5 | Change in the Share of Non-Fossil Generation by State, 2010 to 2020



Sources and notes: Data are from EIA (multiple years (a)). Change is percentage point change rather than percent change. For instance, a 20% percentage point change from 2010 to 2020 implies that a state that had a 10% share of non-fossil generation in 2010 would have a 30% share in 2020.

60% (Figure 4). In addition, 90% of the more than 750 GW of generation waiting to connect to the U.S. electricity grid at the end of 2020 was non-fossil generation,14 implying that states' non-fossil generation shares will continue to increase over the next decade. The U.S. Congress' 2022 Inflation Reduction Act will drive additional increases in non-fossil generation shares, but a range of obstacles – from human resources to transmission cost allocation methods – will need to be overcome to meet the U.S. government's goal of 100% clean energy by 2035.15 Tracking progress over the next decade can help to identify states and regions that may require targeted policy or regulatory support.

3.1.2 Chinese Provinces

New non-fossil fuel generation capacity has grown rapidly across provinces in China and now accounts for most new generation capacity. In about half (15) of Chinese provinces non-fossil generation capacity now accounts for more than 70% of new generation capacity and is greater than 50% in nearly all (27) provinces.[16] Increases in non-fossil generation capacity during the 2010s have been more evenly distributed in China than in the U.S. Before rapid growth in solar and wind generation in the 2010s, most non-fossil generation was in the form of hydropower, concentrated in the Southwest, and nuclear power, concentrated in eastern coastal provinces.[17] By contrast, and partly as a result of national policy, wind and particularly solar development has been less regionally concentrated (Figure 6).[18] This has enabled growth in non-fossil fuel generation capacity in the Eastern and South-Central regions to catch up to the resource-rich northern and western regions.

14 Rand et al. (2021).

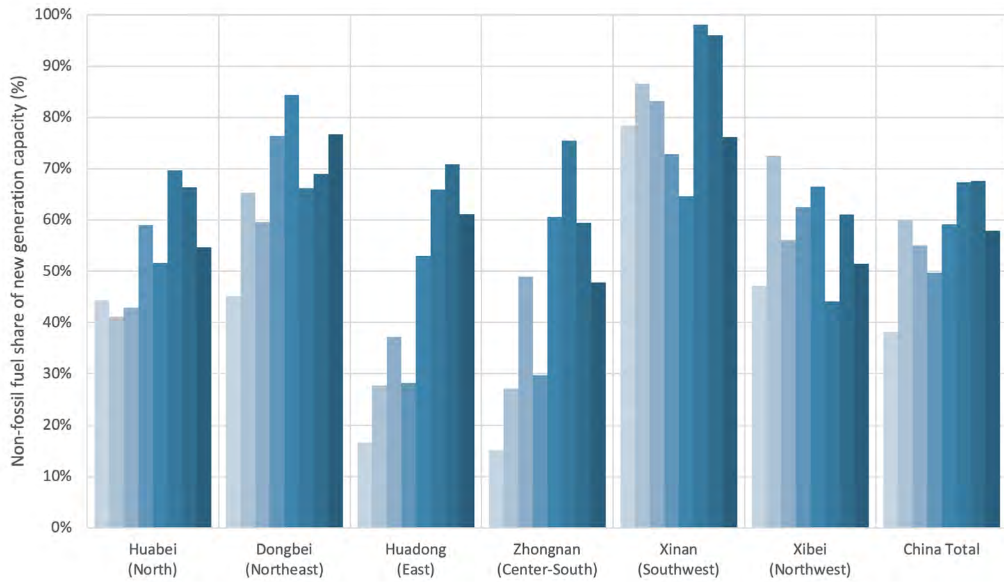
15 Denholm et al. (2022).

16 Based on three-year rolling averages of the shares of non-fossil generation capacity.

17 Southwest provinces (Chongqing, Sichuan, Guizhou, Yunnan, Tibet) generated 57% of China's hydropower in 2020; the three South-Central provinces of Hubei, Guangxi, and Hunan generated 20%. The top five nuclear generating provinces accounted for nearly 90% of nuclear generation in 2020: Guangdong (32% in 2020), Zhejiang (19%), Fujian (18%), Jiangsu (10%), and Liaoning (9%). All nuclear power in China is generated in provinces along the eastern coast.

18 In the 13th Five-Year Plan (2016-2020), the National Development and Reform Commission (NDRC) changed its renewable energy development strategy, shifting from a policy that encouraged renewable resource development in areas with the highest quality resources to one that encouraged development in areas that have lower quality resources but are closer to electricity demand and require less transmission investment.

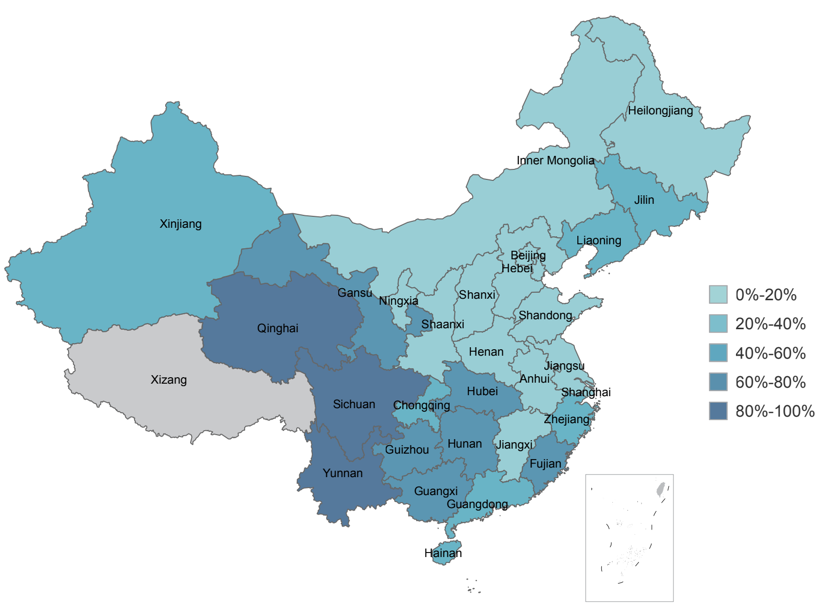
Figure 6 | Share of New Non-Fossil Fuel Generation Capacity in Total Generation Capacity by Chinese Statistical Region, 2012-2019



Sources and notes: Data are from CEYEB (multiple years). Columns are individual years, from left (2012) to right (2019). At the time of writing, data for 2020 were not yet available.

Although provinces with higher shares of non-fossil generation remain concentrated in China's hydropower-rich Southwest and Center-South (Figure 7), increases in the share of non-fossil generation have been relatively even across provinces (Figure 8), mirroring changes in new generation capacity. More than half of provinces (17) increased the share of non-fossil generation by more than 10 percentage points from 2010 to 2020. However, average non-fossil shares remain relatively low; in just under half (15) of provinces the share of non-fossil generation was less than 25% in 2020.[19]

Figure 7 | Shares of Non-Fossil Generation by Province, 2020



Sources: Data are from CEYEB (multiple years).

19 CEYEB (multiple years).

Figure 8 | Change in the Share of Non-Fossil Generation by Province, 2010 to 2020

Sources: Data are from CEYEB (multiple years). Change is percentage point change rather than percentage change.

National and provincial policy will drive continued growth in non-fossil generation in Chinese provinces over the 2020s. At a national level, the 14th Five-Year Plan (2021-2025) set a target of installing 1,200 GW of wind and solar generation by 2030, an increase from 535 GW of total wind and solar generation capacity in 2020. Barring major changes to national policy, the more even distribution of new non-fossil generation capacity and increases in the share of non-fossil generation would likely continue.[20]

3.2 Centralized Heat Supply

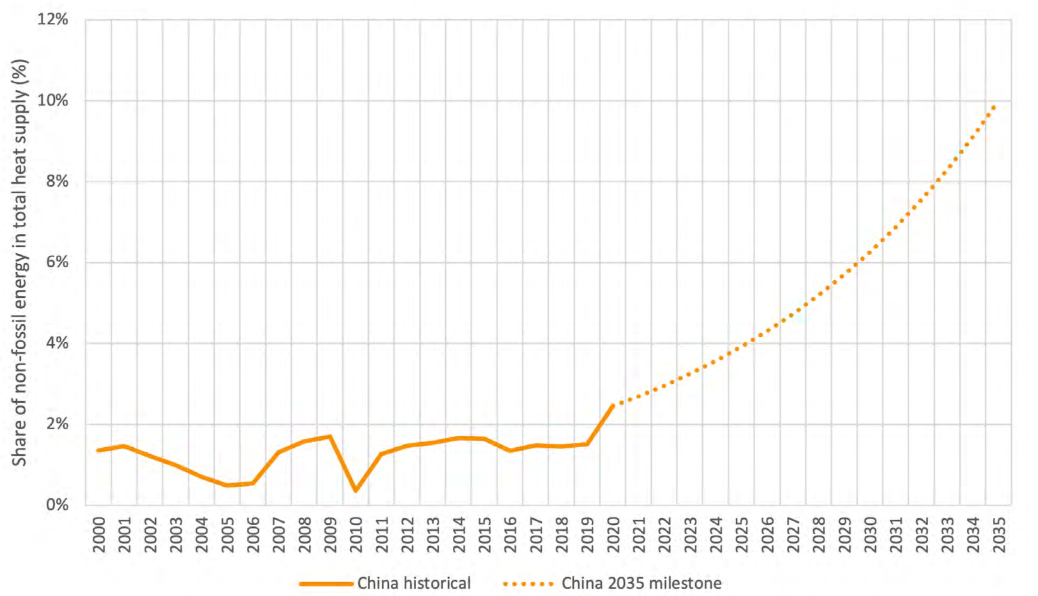
The U.S. and China have very different building and industrial heating systems. Space and water heating in U.S. buildings, both urban and rural, tends to be decentralized, with most heating energy consumed onsite in furnaces and water heaters. Many parts of urban China, by contrast, have centralized heating systems, in which heat plants or combined heat and power (CHP) plants supply heat to buildings through district heating networks. In rural China, biomass remains a large source of energy for building heating. In China, industrial heat is also more likely to be produced in central-scale CHP plants than in the U.S. To capture these differences in heating energy, we include a heat supply metric for China but not for the U.S.

At a national level in China, the majority of heat energy is produced from fossil fuels (Figure 9). Historically about 80%-90% of China's heat supply has been generated with coal, though following stricter air quality regulations heat from coal has been increasingly replaced with natural gas.[21] Given the relatively low levels of non-fossil energy in heating supply, we do not report this metric for individual provinces here but will track it going forward. Increasing this share will be an important challenge for China's provinces, for reducing both CO_2 emissions and air pollution.

20 The NDRC's 2023 Workplan seems to signal a return to the construction of large wind and solar bases in remote areas, which would lead to a more geographic concentration in new non-fossil generation capacity and generation (NDRC 2023).

21 Data are from CEYEB (multiple years).

Figure 9 | Share of New Non-Fossil Fuel Energy in Total Heating Supply in China, Historical and Trajectories to 2035 Milestones



Sources and notes: Data are from CEYEB (multiple years). Data for 2010 are anomalous. The uptick in 2020 was the result of an increase in "other energy," which includes such primary non-fossil fuel energy resources as biomass, solar thermal, and geothermal. It is unclear whether this is also anomalous or represents the beginnings of a sustained increase in the share of non-fossil energy.

3.3 Buildings

The mix of building energy sources is driven by a range of factors. Electric appliance adoption can increase the share of electricity in building energy. Climate and climate change also can affect building energy mix; milder regions tend to have higher shares of electricity in building final energy consumption. Resources and regulation also affect building energy use. Hydropower-rich regions of the U.S. tend to have electric space heating, for example, and in some U.S. states utility regulators encouraged electrification of buildings and industry. In China, urbanization and national policy led to a shift from primary coal consumption (coal boilers) to district heating over the 2000s and 2010s. Energy policy is thus one among many factors that shape building energy use.

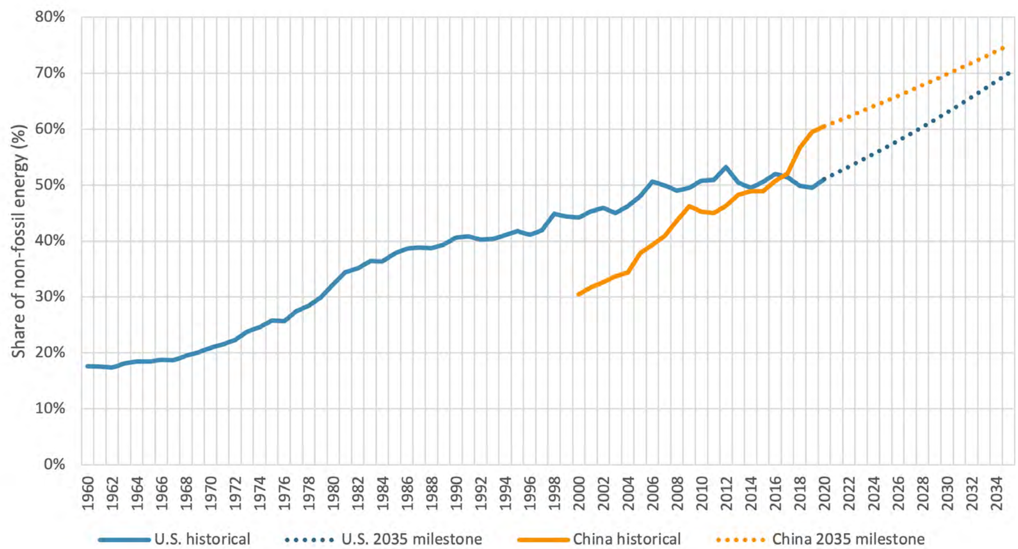
Differences between heating systems in the U.S. and China can be seen in their respective shares of non-fossil building energy consumption (Figure 10). In China, non-fossil shares are higher because of the country's extensive district heating network: less primary fossil fuel energy for building heating is consumed onsite. Our 2035 milestone for China is thus higher than for the U.S., consistent with China's more centralized building heating systems. The heating supply metric captures the share of non-fossil energy in centralized heat in China.

In the U.S. and China, the share of non-fossil energy – mainly electricity – in building final energy consumption has grown over the past three decades (Figure 10). In the U.S., growth in the share of non-fossil building energy has been steadier and began to flatten out after 2006 for reasons that are not yet clear.[22] In China, increases have been more rapid, driven by electricity demand growth in the residential sector and the shift from cvoal boilers to centralized heating systems beginning in the mid-2000s.[23]

22 Potential factors driving this flattening include lower natural gas prices, declining household size, and a decrease in average home sizes.

23 For more on the evolution of China's district heating network, see IEA and Tsinghua University (2017).

Figure 10 | Share of New Non-Fossil Fuel Energy Use in the U.S. and China, Historical and Trajectories to 2035 Milestones



Sources and notes: Data for the U.S. are from EIA (multiple years (b)). Data for China are from CEYEB (multiple years). China's energy accounting does not report "buildings" as a separate category within final energy consumption. See Appendix B for a description of how we defined building energy consumption..

3.3.1 U.S. States

For individual states, the share of non-fossil energy consumption in buildings depends on climate, resources, and state policies. Figure 11 shows non-fossil shares for each state for 2020; Figure 12 shows the change in shares between 2010 and 2020. Most states with lower shares of non-fossil energy are located in the colder Northeast and Upper Midwest regions. State and federal policy or alternative technologies for space and water heating have yet to be a major driver of non-fossil building energy use.

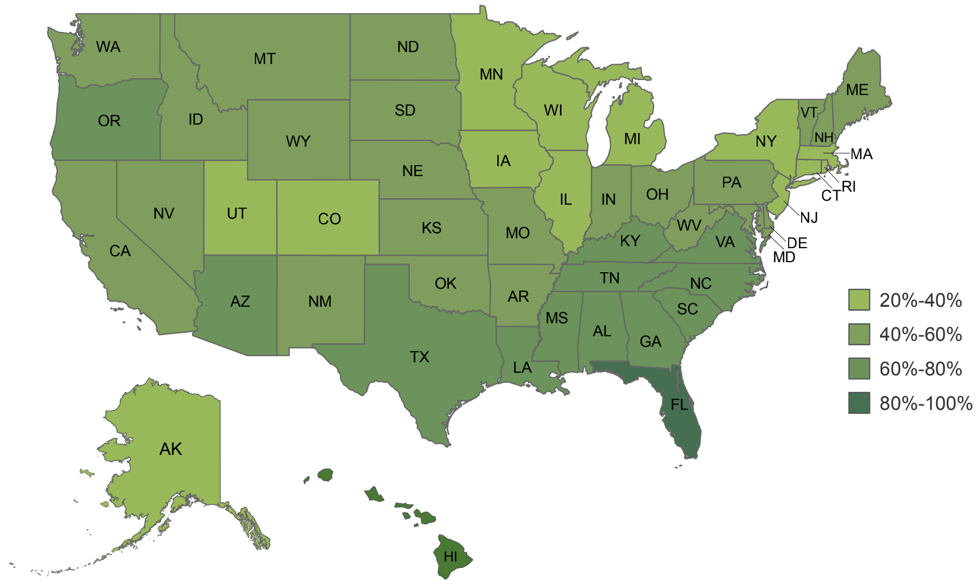
State, city, county, and federal policy is expected to significantly increase building electrification, and thus the share of non-fossil energy in building energy consumption, over the next 15 years.24 A small but growing number of states, cities, and counties are enacting building electrification policies through changes in building codes, building performance standards, consumer incentives, changes in utility regulation, and utility programs.[25] The most important regions for gauging national progress toward higher shares of non-fossil energy in buildings will be in the colder Northeast and Midwest regions.

The main expected technologies for replacing fossil fuel energy use in U.S. buildings are currently electric heat pumps and electric induction ovens. The U.S. does not currently collect data on water heater, furnace, and oven sales, and thus it is currently difficult to calculate a flow indicator for building energy use. The U.S. Department of Energy could consider a manufacturer survey that would collect these data at a state level, as a means to gauge trends in each state.

24 See, for instance, Denholm et al. (2022).

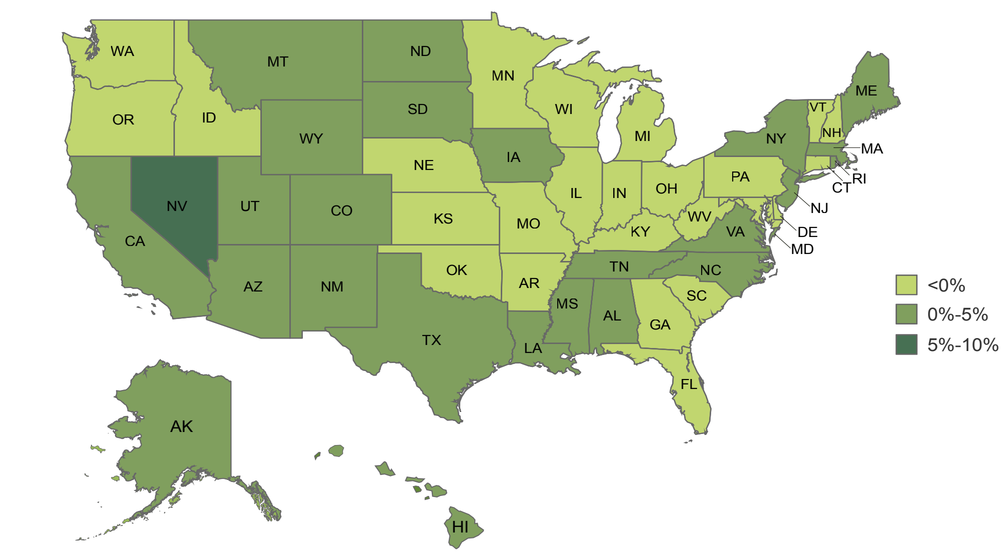
25 For an overview of state policies, see Berg (2022). For descriptions of municipal policies, see Louis-Prescott and Golden (2022).

Figure 11 | Share of Non-Fossil Energy Consumption in Buildings by State, 2020



Sources and notes: Data are from EIA (multiple years (b)).

Figure 12 | Change in the Share of Non-Fossil Energy Consumption in Buildings by State, 2010 to 2020



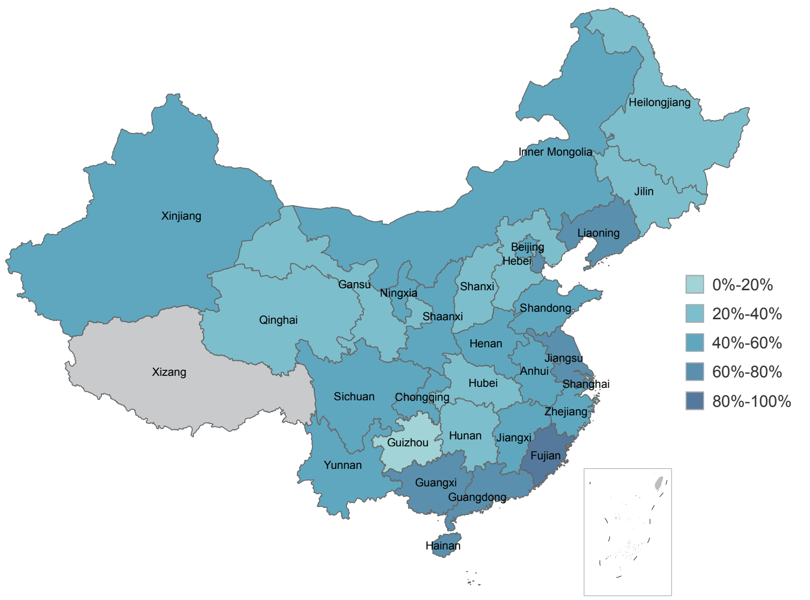
Sources and notes: Data are from EIA (multiple years (b)). Change is percentage point change rather than percentage change.

3.3.2 Chinese Provinces

Space heating in China has historically been divided along a north-south ("Qin-Huai") line, with urban areas in provinces north of the line having access to centralized heat supply and those south of the line having little to no access.[26] Provinces also have differed in the extent to which natural gas has been used as a heating fuel in buildings. As a result, shares of non-fossil energy in buildings tend to be less regionally concentrated than in the U.S.

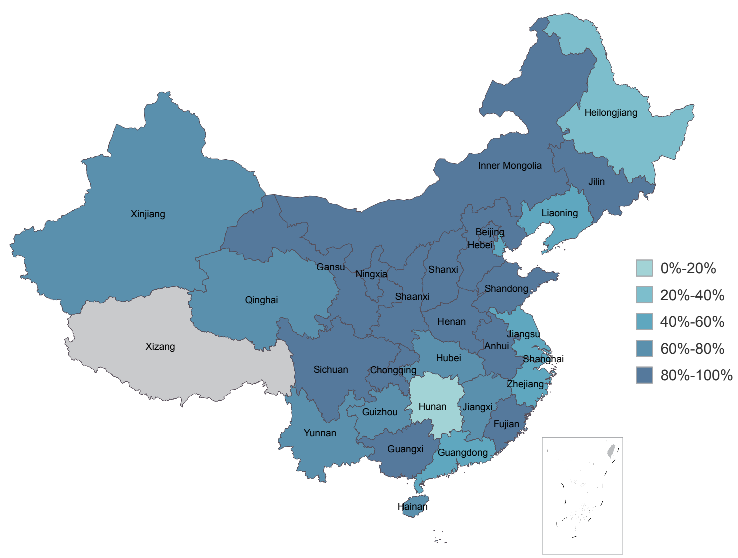
26 This policy was enacted in the 1950s, during a period of energy scarcity, but has continued into the present. The north-south line for heating is roughly, but not entirely, consistent with the Qin-Huai line (秦岭淮河线) that has historically been used by geographers to separate north and south China.

Figure 13 | Share of Non-Fossil Energy Consumption in Buildings by Province, 2020



Sources: Data are from CEYEB (multiple years).

Figure 14 | Change in the Share of Non-Fossil Energy Consumption in Buildings by Province, 2010 to 2020



Sources and notes: Data are from CEYEB (multiple years). Change is percentage point change rather than percentage change.

Increases in the provincial shares of non-fossil building energy over the last two decades were the indirect result of energy planning and policy. The expansion of district heating in urban areas over the 2000s and 2010s was aimed both at improving energy efficiency and reducing pollution.[27] The National Development and Reform Commission's (NDRC's) Winter Clean Heating Plan for Northern Regions (2017-2021) sought to expand district heating, natural gas furnaces, electric heating, and direct heating with geothermal, biomass, solar, and other renewable resources.[28] However, increases in the share of non-fossil building energy were slowed by rising natural gas consumption in buildings,

27 IEA and Tsinghua University (2017).

28 NDRC (2017).

which has grown faster than district heating in China's building sector over the past two decades.[29] Ultimately, reducing CO_2 emissions from building energy consumption to net zero levels will require replacing most natural gas energy and infrastructure with a centralized heat supply that has zero net CO_2 emissions or decentralized technologies such as heat pumps and solar thermal systems.

Despite recent growth in natural gas use in China's urban buildings, the trend toward higher provincial shares of non-fossil energy in buildings will likely continue over the next two decades, though it is not yet clear whether they would be mostly driven by an expansion of district heating or by electrification.[30] This question about decarbonization strategy intersects with two important questions for China's building energy policies. First, how should colder urban areas south of the Qin-Huai line, which have not historically had access to centralized heat supply, be heated in the winter, given that the rationale for the Qin-Huai line is obsolete and that heating demand in these areas is growing? Second, what is the right strategy for heating in rural areas across the country, which generally lack access to any heat energy infrastructure and have a much greater reliance on coal and biomass energy than urban areas? Both indicator values and China's emerging policy environment for building energy suggest that the most important provinces for measuring progress will be the 10 provinces that have low shares of non-fossil energy consumption due to higher shares of coal and natural gas use.[31]

Due to policy uncertainty and lack of available data, it is difficult to calculate flow indicators – for instance heat pump sales as a share of new end use heating equipment or the share of non-fossil energy in new heat supply – for building energy in China. The NDRC, NEA, and Ministry of Housing and Urban-Rural Development (MOHURD) could consider developing a long-term vision and strategy for building decarbonization. To fill the data gap, the NDRC, NEA, and Ministry of Industry and Information Technology (MIIT) could consider a manufacturer survey on end-use equipment for space and water heating in buildings.

3.4 Industry

Industry is a broad aggregation of different sectors that produce different goods – from paper products to steel – through different technologies and processes that have different kinds of energy requirements and will likely require different decarbonization strategies. For instance, lighter industry, such as computer or textiles production, may be more readily amenable to electrification than heavier industry, such as steel, chemicals, and cement. For states and provinces, the share of fossil fuel energy use in industry depends to a large extent on the manufacturing mix. Industry is a much larger energy consumer, and is a larger focus of policy, in China than in the U.S.[32]

In the U.S., the share of non-fossil energy in industrial energy consumption increased rapidly during the 1970s, mostly as a result of changing industry mix and higher electricity consumption, but has remained relatively flat at about 20% to 25% since the late 1980s (Figure 15). The share of non-fossil energy in China's industrial sector was on par with that in the U.S. in the early 2000s but increased rapidly in the 2010s due to growth in electricity consumption. Stricter air quality policies in the 2 al electrification.[33]

Because of the challenges of technological diversity across the industrial sector, we did not

29 Natural gas consumption in buildings grew 4.1-fold from 2000 to 2010 and 2.3-fold from 2010 to 2020, whereas centralized heat consumption grew by 1.7- and 2.2-fold, respectively. Data are from CEYEB (multiple years).

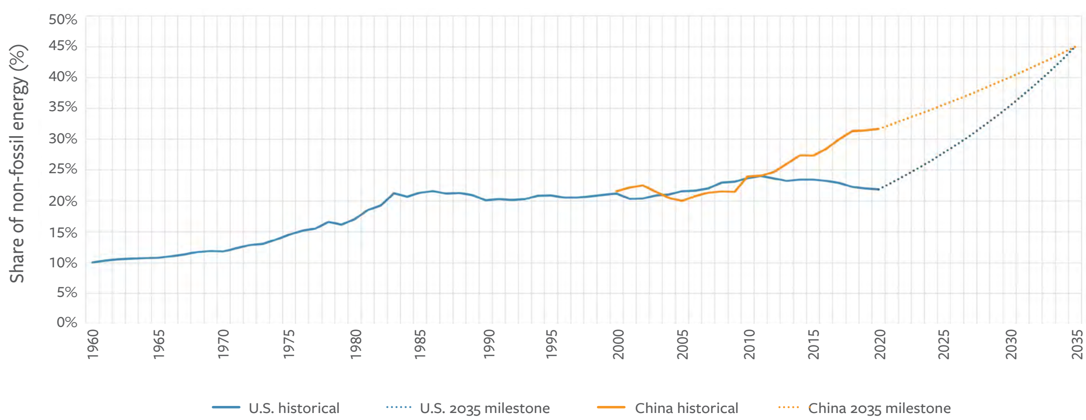
30 In more remote rural areas, the NDRC (2017) signaled a preference for heating with primary renewable energy, such as geothermal, solar thermal, and bioenergy, though these are likely to be deployed on a smaller scale than district and electric heating. Rural consumption of these energy sources is also often difficult to measure accurately.

31 Provinces where the share of non-fossil energy consumption in buildings was less than or equal to 40% in 2020 include Hebei, Shanxi, Jilin, Heilongjiang, Hubei, Hunan, Guizhou, Shaanxi, Gansu, and Qinghai.

32 Due to different definitions and accounting conventions, industrial energy use in the U.S. and China is not directly comparable. However, orders of magnitude are still illustrative. In the U.S., industry accounts for about 35% of total final energy consumption (EIA 2022). In China, based on data from CEYEB (multiple years) we estimate that industry accounts for 70% of the country's total final energy consumption.

33 These include the 2013 Air Pollution Prevention and Control Action Plan (大气污染防治行动计划), which for the first time set pollution concentration targets.

Figure 15 | Share of Non-Fossil Industry Energy Use in the U.S. and China, Historical and Trajectories to 2035 Milestones



Sources and notes: Data for the U.S. are from EIA (multiple years (b)). Data for China are from CEYEB (multiple years). See Appendix B for a description of how we defined industry energy consumption in China.

develop or track industry flow indicators or milestones for either country, though in the future it may be useful to track changes in technologies for the largest industrial energy using sectors. In the U.S., the largest industrial energy consuming sectors are refining, chemicals, and iron and steel.[34] In China, the largest consumers are the steel, cement, and chemicals sectors.[35]

3.4.1 U.S. States

For individual U.S. states, the share of non-fossil energy use in industry depends on resource endowments, state economic policy, and other factors shaping the structure of state economies. States with higher shares of refining and chemical sector value added in gross state product tend to have lower non-fossil fuel shares (Figure 16).[36] States that have higher (> 40%) non-fossil shares have a combination of higher wood energy and electricity consumption (Southeast, Maine, Northwest), higher biofuels consumption (Midwest), or high electricity consumption (Nevada). Recent changes in industrial non-fossil energy shares do not show a clear regional pattern (Figure 17).

The policy framework and technologies for reducing energy-related CO_2 emissions in U.S. industry remain uncertain. The U.S. federal government does not have a coherent policy or regulatory framework for reducing industrial CO_2 emissions; neither do most states.[37] Additionally, and unlike buildings and transportation, there are less well-characterized pathways for reducing CO_2 emissions in U.S. industry.[38] Although some more regular increases in the share of non-fossil energy in industry may occur over the next decade through continued changes in industry structure and improvements in end-use efficiency, progress is likely to be sporadic and uneven across states.

34 EIA (2022).

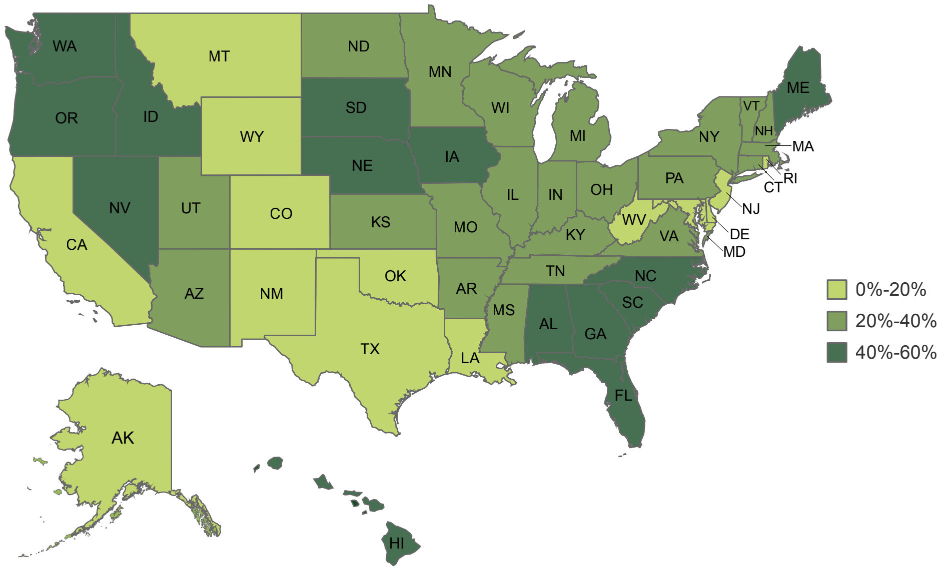
35 National Bureau of Statistics (NBS) (multiple years).

36 For instance, states with higher shares of heavy industry value added in gross state product (GSP) do not necessarily have lower shares of non-fossil energy. Gross state product data are from the U.S. Bureau of Economic Analysis (BEA), https://www.bea.gov/

37 At a federal level, EIA analysis of the Inflation Reduction Act found that the Act had limited to no impact on industrial sector CO_2 emissions, which were projected to increase due to higher natural gas consumption in manufacturing (EIA 2023). As far as we know, California is the only state with CO_2 regulations on industry.

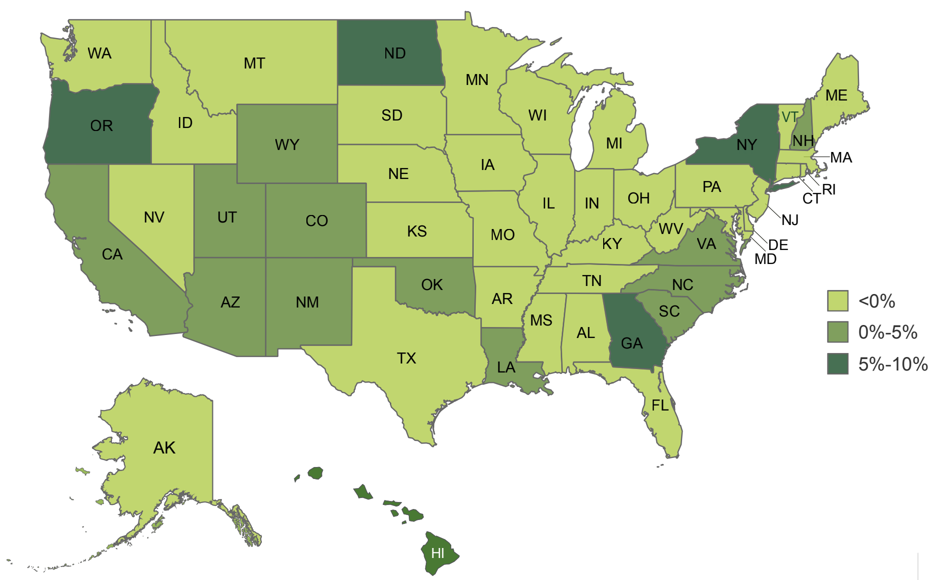
38 The U.S. Department of Energy's (DOE's) 2022 Industrial Decarbonization Roadmap (DOE 2022b) identified four strategies for reducing CO_2 emissions in industry (energy efficiency; electrification; low-carbon fuels, feedstocks, and energy sources; and carbon capture, utilization, and storage) across several key sectors (iron and steel; chemical manufacturing; food and beverage manufacturing; petroleum refining; and cement manufacturing). However, many of these technologies have not yet been deployed on a commercial scale in industry.

Figure 16 | Share of Non-Fossil Energy Consumption in Industry by State, 2020



Sources and notes: Data are from EIA (multiple years (b)).

Figure 17 | Change in the Shares of Non-Fossil Energy Consumption in Industry by State, 2010 to 2020



Sources and notes: Data are from EIA (multiple years (b)). Change is percentage point change rather than percentage change.

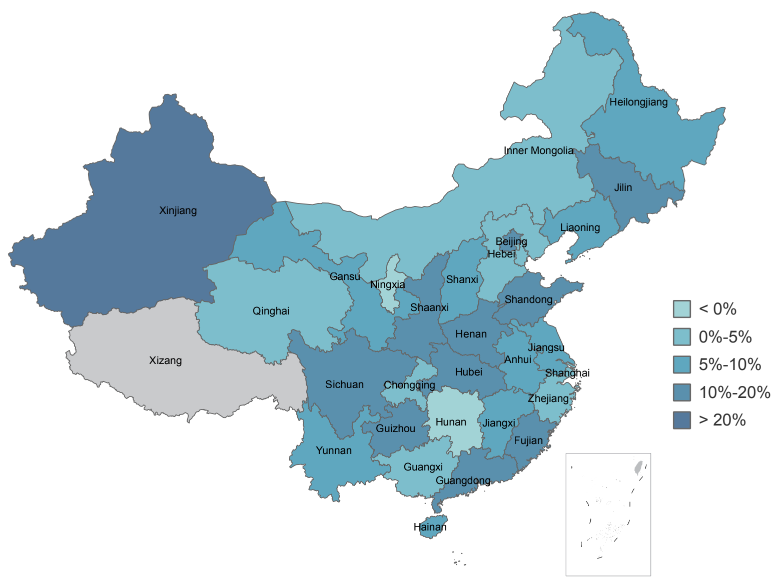
3.4.2 Chinese Provinces

China has more regional variation in industrial non-fossil shares than in the United States. Non-fossil shares are generally higher in the East and Northwest due to higher electricity consumption in industry, which may reflect a combination of industry mix and access to low-cost electricity (Figure 18), but changes in non-fossil shares do not reveal a clear pattern (Figure 19). The National Bureau of Statistics (NBS) does not publish data on industrial value added by sector, making it difficult to draw connections between energy consumption patterns and economic activity.

Figure 18 | Share of Non-Fossil Energy Consumption in Industry by Province, 2020

Sources: Data are from CEYEB (multiple years).

Figure 19 | Change in the Share of Non-Fossil Energy Consumption in Industry by Province, 2010 to 2020



Sources and notes: Data are from CEYEB (multiple years). Change is percentage point change rather than percentage change.

Like the U.S., the policy framework and technologies for reducing CO_2 emissions in China's industrial sector are uncertain.[39] Without supporting policies to reduce CO_2 emissions in industry, progress in increasing provincial shares of non-fossil energy in industry would likely be sporadic, and air quality policy and regulation could actually reduce the share of non-fossil energy in industry by encouraging growth in natural gas consumption. China's central government has more political space to use national tools for emissions regulation than the U.S. does; for instance, by including some industrial sectors in the country's national

39 For a detailed overview of potential decarbonization pathways in China, see Shao et al. (2022).

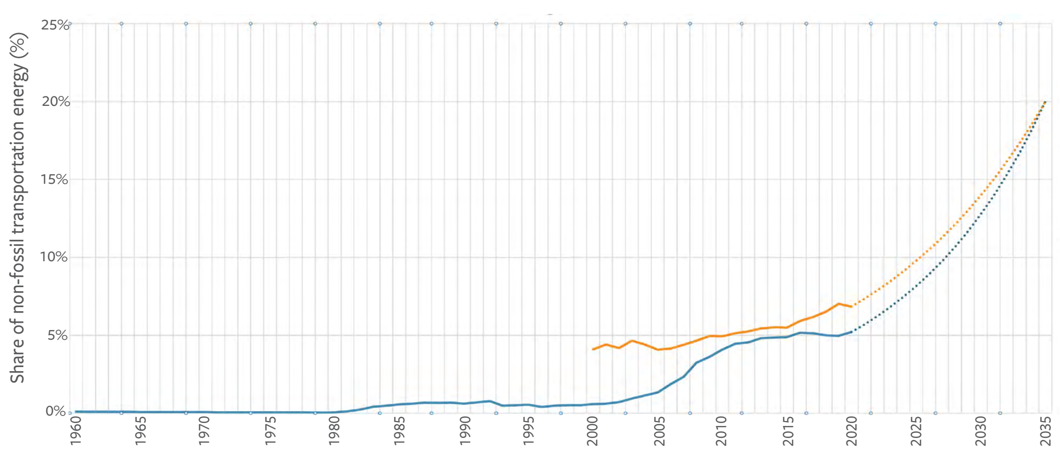
emissions trading system (ETS) or implementing a national carbon tax in industry. The greater potential for national CO_2 regulation in China's industrial sector implies that progress in increasing provincial shares of non-fossil energy in industry may be more uniform than among U.S. states.

3.5 Transportation

Oil products dominate the transportation sector. In the U.S., oil products made up 90% of transportation energy in 2020, with a smaller amount of natural gas (5%) and biofuels (5%) accounting for the remainder.[40] In China, oil products made up 85% of transportation sector energy in 2020, with natural gas (7%), electricity (4%), and biofuels (2%) accounting for most of the remainder.[41]

In the U.S., the transportation energy mix has changed little over the past two decades (Figure 20), despite increased focus by federal and state legislators and regulators. The 2005 Energy Policy Act created a national Renewable Fuel Standard (RFS) that required increasing amounts of renewable fuel – mostly ethanol and, to a lesser extent, biodiesel – to be blended into transportation fuels each year through 2022.[42] Since implementation in 2008 through 2020, the RFS had only displaced oil consumption in transportation by about 2%.[43] Over the next decade, state policy and federal incentives will likely play a larger role than federal regulations in the transition to ZEVs and higher shares of non-fossil energy in transportation.

Figure 20 | Share of Non-Fossil Transportation Energy Use in the U.S. and China, Historical and Trajectories to 2035 Milestones



Sources and notes: Data for the U.S. are from EIA (multiple years (b)). Data for China are from CEYEB (multiple years). See Appendix B for a description of how we defined transportation energy consumption in China.

In China, the transportation energy mix also has changed little over the past two decades (Figure 20). Central and local government policies encouraged adoption of electric fleet vehicles, and China developed an extensive electric rail system over the 2010s. During the 2010s, central government policy also encouraged the deployment of "new energy vehicles" (NEVs) through subsidies and, later, NEV sales requirements on car manufacturers.[44] Yet despite these efforts, the

40 EIA (2022).

41 CEYEB (multiple years).

42 For an overview of the RFS program, see U.S. Environmental Protection Agency (EPA), "Overview for Renewable Fuel Standard," https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard

43 We calculate percentage displacement as 2007 oil products consumption minus the increase in biofuel energy between 2007 and 2020, divided by 2007 oil products consumption, minus one. Most of the 20% reduction in oil energy consumption in transportation between 2007 and 2020 was the result of a 16% reduction in total transportation energy demand. Data are from EIA (multiple years (b)).

44 New energy vehicles include plug-in hybrid electric, battery electric, and fuel cell vehicles. See ICCT (2018) for an overview of China's initial NEV mandate.

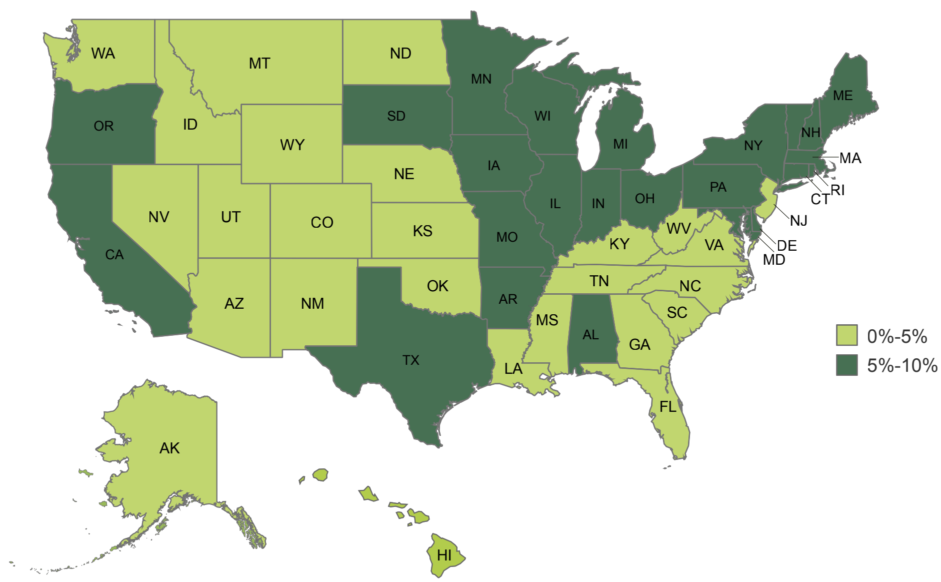
share of non-fossil energy in transportation was less than 7% in 2020. Because of the prevalence of fleet vehicles – buses, taxis, and municipal vehicles – in China's cities, local governments also play a significant role in shaping transportation energy use.

Electrification will likely complicate data collection for transportation energy in both the U.S. and China. Residential EV charging, as opposed to charging at commercially owned charging stations, will be difficult to distinguish from other building electricity consumption because EVs are often not separately metered. As a result, some portion of transportation energy may be absorbed by the building sector over time.

3.5.1 U.S. States

Non-fossil fuel resources, almost exclusively ethanol and biodiesel, make up about 4%-5% of transportation energy in most states, though there are a small number of states (Alaska, Hawaii, Louisiana, Wyoming) that are significantly below the national average of 5% (Figure 21).[45] Across most states, the share of non-fossil energy in transportation increased proportionally over the last two decades, driven by the RFS (Figure 22).

Figure 21 | Share of Non-Fossil Energy Consumption in Transportation by State, 2020



Sources and notes: Data are from EIA (multiple years (b)).

Going forward, biofuels may continue to play a role in transportation, but there are food security and environmental barriers to scaling them up to become a major net zero CO_2 transportation energy resource. Instead, most long-term decarbonization analyses for the U.S. project that electricity will be the dominant source of energy for light-duty and some heavy-duty vehicles in the U.S. by 2050, with any residual energy needs for the sector met by a combination of hydrogen and biofuels.[46]

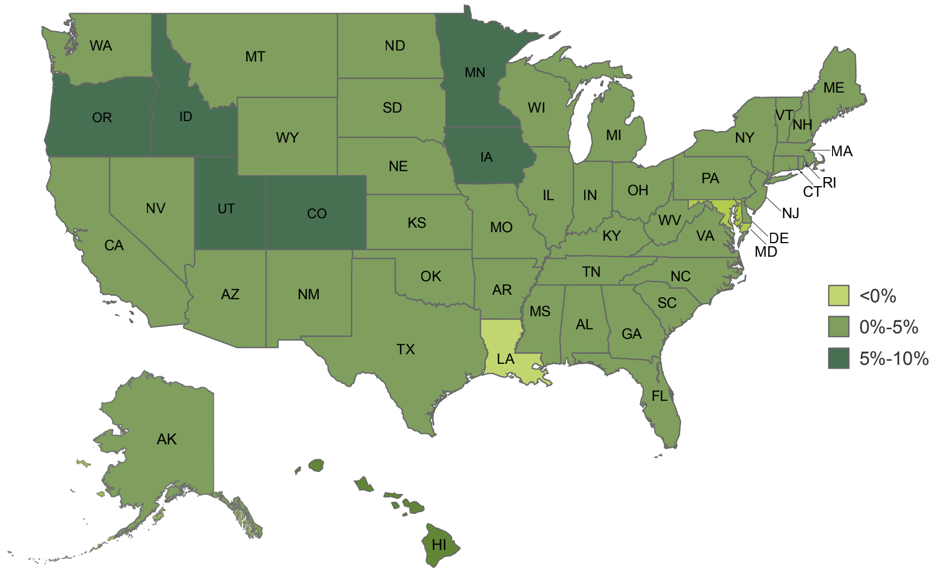
At a state level, the main two drivers of electrification over the next decade are likely to be state policy and federal tax incentives. As of mid-2022, 14 states had adopted California's ZEV program, which sets ZEV share requirements on light-duty vehicle sales in the state, and 15 states had signed on to a ZEV memorandum of understanding (MOU) to accelerate adoption of medium- and heavy-duty ZEVs.[47] State policy will be complemented by federal tax credits, most recently through the

45 We define "significantly below" as being more than 30% below. Two states (Minnesota, Oregon) are significantly above the national average.

46 See, for instance, Williams et al. (2021) and Larson et al. (2020).

47 For an overview, see the Center for Climate and Energy Solutions, "U.S. State Clean Vehicle Policies and Incentives," https://www.c2es.org/document/us-state-clean-vehicle-policies-and-incentives/

Figure 22 | Change in the Share of Non-Fossil Energy Consumption in Transportation by State, 2010 to 2020



Sources and notes: Data are from EIA (multiple years (b)). Change is percentage point change rather than percentage change.

2022 Inflation Reduction Act (IRA), for vehicles and charging infrastructure.[48] However, unlike the RFS, which is a national standard on fuel refiners and importers, the combination of state-level ZEV policies and federal incentives are likely to lead to greater divergence in the shares of non-fossil transportation energy across states over the next decade.

The share of ZEV sales in total vehicle sales can be a powerful flow indicator for tracking progress in ZEV adoption and impending changes in the transportation energy mix, as higher levels of ZEV sales will lead to changes in transportation energy use. However, to our knowledge, California is the only state that tracks and reports the share of ZEV sales.[49] The U.S. Department of Transportation could consider tracking and reporting ZEV sales and the share of ZEV sales by state, to measure outcomes from IRA funding. States, particularly those that have ZEV programs, could also consider reporting the share of ZEV sales to track progress against ZEV goals.

3.5.2 Chinese Provinces

The share of non-fossil energy in provincial transportation sectors in China varies widely, from a low of 2% to a high of 12%, and changes in shares over time appear to be somewhat random (Figure 23 and Figure 24). Some of the variance among provinces and over time is likely due to limitations in data (see Appendix B).

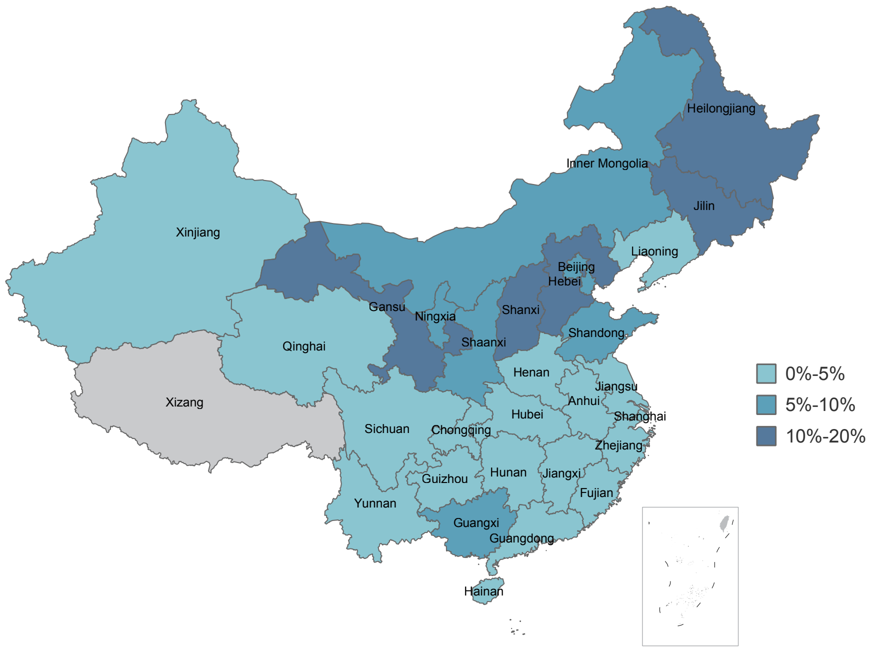
Electricity is also likely to be the dominant low carbon energy source in China's transportation sector going forward. For passenger vehicles, the main driver of NEV deployment will be the central government's dual credit policy, which sets NEV and fuel efficiency requirements on car manufacturers.[50] However, local government policies will also play an important complementary role. For instance, the central government's Blue Sky Protection initiative (蓝天保卫战) requires more than 150 cities to reach 50% NEV market share by 2030 but leaves policy design and implementation to individual cities. Some provinces and cities have set NEV goals that are more ambitious than

48 IRA incentives include tax credits for new and used vehicles and an extension of the tax credit for EV charging stations. See U.S. Congress (2022).

49 Some states, such as New York, track ZEV sales as part of their ZEV programs but do not appear to explicitly track and report the share of ZEV sales.

50 Chen and He (2022)

Figure 23 | Share of Non-Fossil Energy Consumption in Transportation by Province, 2020



Sources: Data are from CEYEB (multiple years).

Figure 24 | Change in the Share of Non-Fossil Energy Consumption in Transportation by Province, 2010 to 2020

Sources and notes: Data are from CEYEB (multiple years). Change is percentage point change rather than percentage change.

national policy. For instance, Hainan Province plans to increase NEV market share to 100% by 2030.[51] Shenzhen, China's third largest city, has electrified its bus fleet and most of its taxi fleet.[52] As a result of this interplay between national and local policy, the share of non-fossil energy in transportation in China is likely to undergo periods of divergence and convergence over the next decade and a half.

51 Wang et al. (2023).

52 World Bank Group (2021).

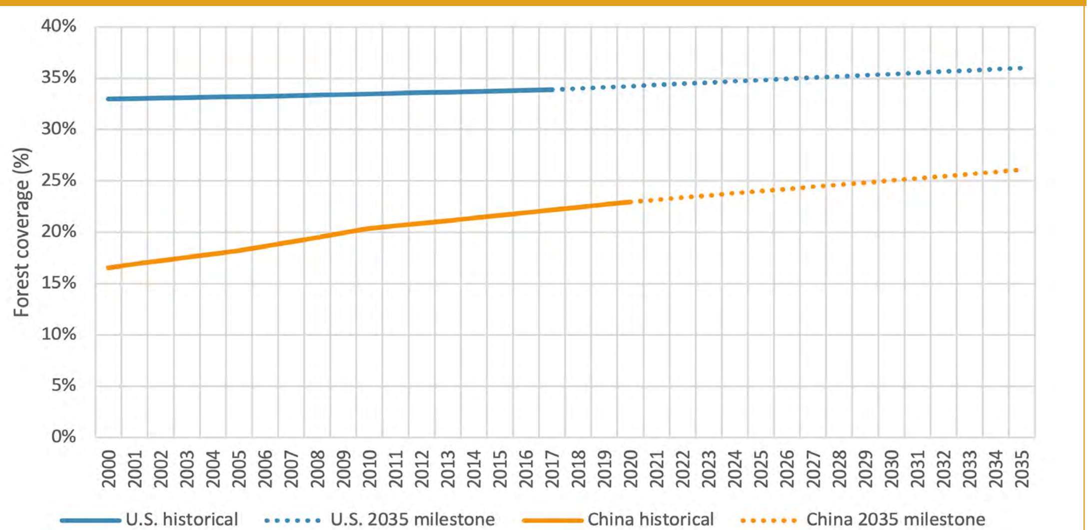
As in the U.S., the share of ZEV sales in total vehicle sales can be a powerful tracker in China. The MIIT could consider tracking and reporting ZEV sales and share by province, to measure compliance with national policy.

3.6 Forestry

Plant growth can reduce CO_2 concentration in the Earth's atmosphere by sequestering CO_2 in plant biomass through photosynthesis, a process referred to as "terrestrial sequestration." Converting land back into forest (reforestation) and planting new forests (afforestation) are generally the largest potential sources of terrestrial CO_2 sequestration and are the focus of our indicators.[53] In both the U.S. and China, forest growth has been the largest component of terrestrial carbon sinks over the past two decades.[54]

Both forest area and volume increased in the U.S. and China over the last 20 years. Each country has different definitions for forest area and volume, and so comparisons between the two countries require caution, but trends over time within each country are more meaningful. In the U.S., forest area increased from 33% to 34% of total land area between 1997 and 2017, an increase of 10 million hectares (Mha) (Figure 25). Forest volume per unit forest area (2017 forest area) grew from about 110 to 125 cubic meters per hectare (m^3/ha), and in total by about 5 billion m^3, from the early 2000s to the late 2010s (Figure 26). In China, forest area increased from 17% to 23% of total land area between 2000 and 2021, an increase of 62 Mha (Figure 25). Forest volume per hectare (2020 forest area) grew from about 50 to 80 m^3/ha and total volume grew by about 6 billion m^3 (Figure 26).

Figure 25 | Forest Area as a Share of Total Land Area in the U.S. and China, Historical and Trajectories to 2035 Milestones



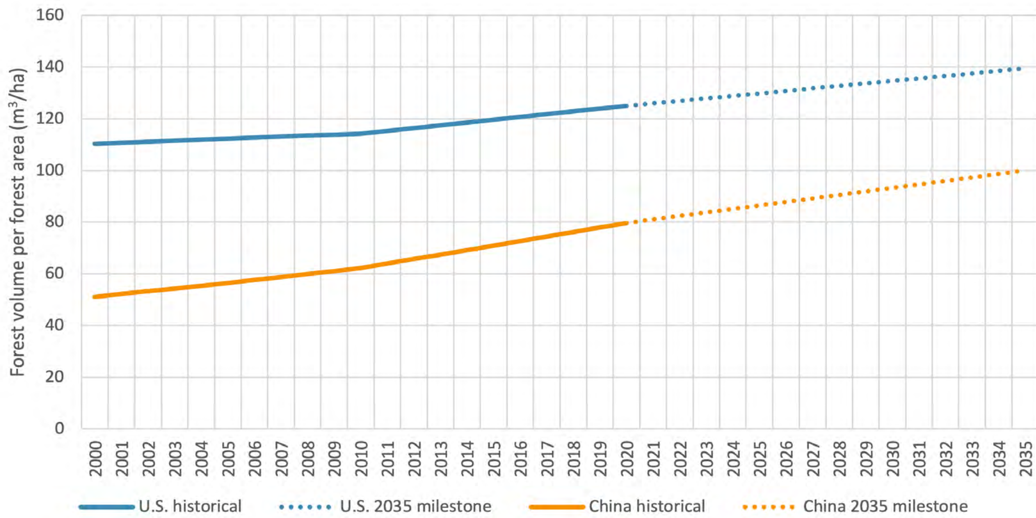
Sources and notes: U.S. forest and total land area data are from Oswalt et al. (2018). China data are from the National Bulletin of Statistics (multiple years).

It is challenging to set meaningful 2035 milestones for our forestry indicators. The U.S. does not have explicit goals for forest area, volume, or CO_2 sequestration, and there has been a long debate over whether these kinds of goals might favor quantity (m^3 volume or tons CO_2 of sequestered carbon) over quality (ecosystem health). China does have longer-term goals for forest area and

53 For instance, forests account for two-thirds of the 23.8 $GtCO_2$ per year in potential global natural mitigation solutions identified by Griscom et al. (2017).

54 EPA (2023); Yu et al. (2022).

Figure 26 | Forest Volume Per Forest Area in the U.S. and China, Historical and Trajectories to 2035 Milestones



Sources and notes: For U.S. forest volume, we use estimates of "Sound bole volume of live trees (at least 5 inches d.b.h./d.r.c.)" from the U.S. Department of Agriculture (USDA) Forest Service's EVALIDator 2.0.6 (https://apps.fs.usda.gov/fiadb-api/evalidator) to be consistent with state-level forest volume data published in the Forest Inventory and Analysis (FIA) state fact sheets. We calculate the U.S. total volume as the sum of state volumes. EVALIDator data are not available for all years, and for some states are not available for as long as a decade. In these cases, we use the previous or subsequent period's volume as a proxy. We use a base year for forest area (fix the denominator) to focus the indicator on forest volume. These national estimates are thus approximate. Bole volume is limited to the volume of larger trees from base to crown; it is a useful proxy for, but will significantly underestimate, forest carbon. U.S. forest area estimates are 2017 data from Oswalt et al. (2018). China data use "forest volume" (森林蓄积量) rather than total plant volume (活力木总蓄积量). All China data are from NBS (multiple years).

volume, but these appear to lack ambition and do not extend to 2035.[55] Our forest area milestones are instead based on reasoned extrapolations of historical trends (See Appendix A).

3.6.1 U.S. States

Over the past two decades, the largest increase in forest area and volume in the U.S. has been in the South (See Figure 27, Figure 28). Four (Texas, Oklahoma, Louisiana, Alabama) of the five states that had the largest percentage point increase in forest area and all of the five states with the largest increases in forest volume per forest area (Virginia, Mississippi, Alabama, North Carolina, South Carolina) are in the South. The reasons for the geographic distribution of results in Figure 27 and Figure 28 – the relative roles of federal, state, and local policy; conservation and restoration programs; or climate and ecosystem change – are not clear.

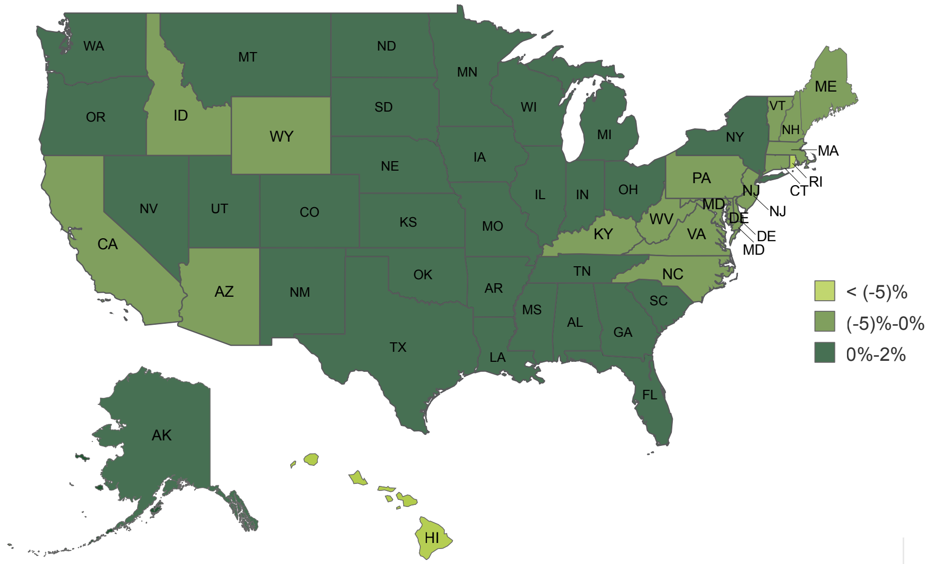
Forests are part of the Biden administration's suite of climate policies, though U.S. federal forestry policy has not had an explicit focus on CO_2 sequestration.[56] The Repairing Existing Public Land by Adding Necessary Trees (REPLANT) Act and U.S. Forest Service's National Reforestation Strategy provide a legal and planning framework for reforestation, with funding made available through the Bipartisan Infrastructure Law.[57] However, it remains uncertain how a combination of federal funding and strategy and state and local policy will affect either the magnitude or geographic distribution of forest area and volume over the coming decade.

55 China's National Forest Plan (2016-2050) sets a goal of increasing and maintaining forest area to more than 26% of land area by 2050 but gives no intermediate targets (SFA 2016). Achieving 26% forest cover by 2050 implies a rate of increase of 0.06% per year from 2020 (23%) to 2050, which is about one-fifth of the 2000 to 2020 average (0.3% per year). China's initial Nationally Determined Contribution (NDC) set a goal of increasing forest volume by 4.5 billion m3 by 2030, relative to 2005 (Government of China 2022), but forest volume had already increased by 5 billion m^3 by 2020. China's updated NDC increased the forest volume goal to 6 billion m3 by 2030, but this implies a rate of increase (0.1 billion m^3/yr) between 2020 and 2030 that is less than one third of the 2000-2020 average (0.3 billion m^3/yr). Data are from NBS (multiple years).

56 For an overview, see The White House (2022).

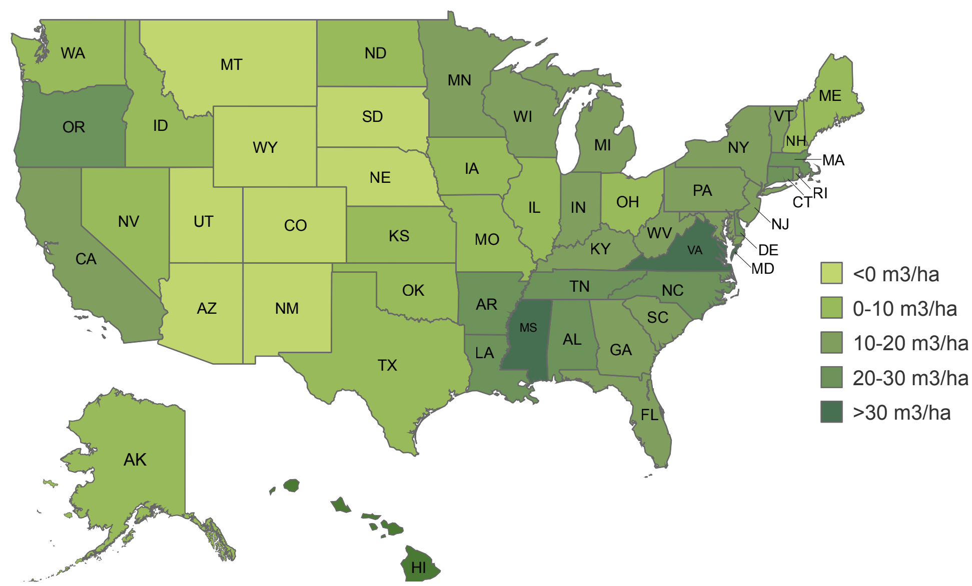
57 USFS (2022).

Figure 27 | Change in Forest Area as a Share of Total Land Area by State, 2007-2017



Sources: Oswalt et al. (2018). Change is percentage point change rather than percentage change.

Figure 28 | Change in Forest Volume Per Forest Area by State, 2000s to 2010s



Sources and notes: See the notes to Figure 26 for sources and notes for this figure.

3.6.2 Chinese Provinces

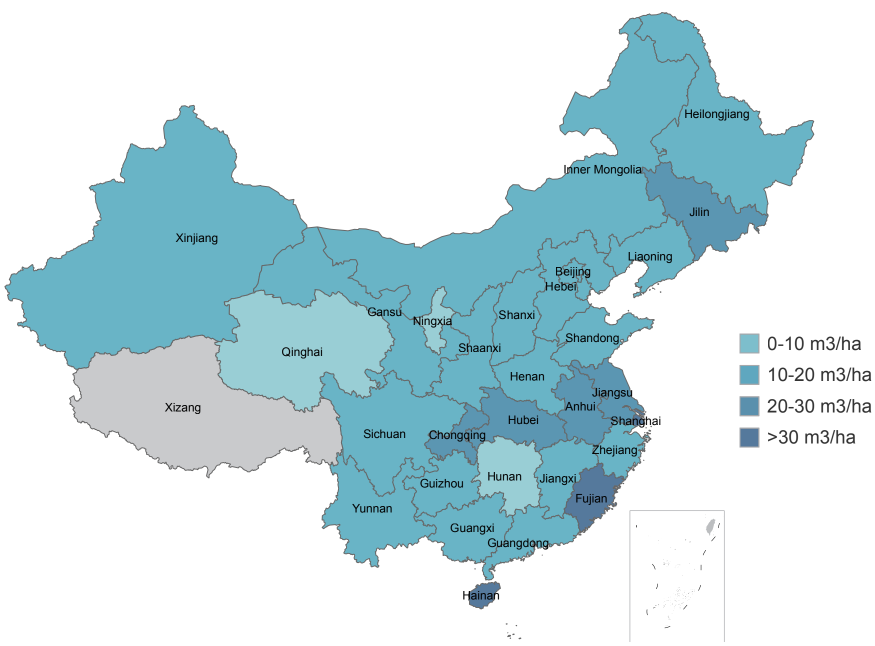
Over the past 25 years, China's key afforestation and reforestation programs have focused on watershed restoration.[58] This focus is visible in changes in forest area: non-municipal provinces with the largest increase in forest area – Chongqing, Guizhou, Guangxi, Yunnan, Hubei, Shaanxi – are all home to regionally important watersheds, and regionally the Southwest (Xinan) and Center-South (Huanan) regions saw the largest increase in forest area (Figure 29). Increases in forest volume over 2005 to 2020 were only moderately correlated with changes in forest area: the largest increase in forest volume was in the East (Huadong) region, which saw relatively smaller increases in forest area (Figure 30).

58 China initiated two major forest programs in response to disastrous floods in 1998: the National Forest Protection Program and Sloping Land Conversion Program (Green-to-Grain Program).

Figure 29 | Change in Forest Area as a Share of Total Land Area by Province, 2010-2020

Sources: NBS (multiple years). Change is percentage point change rather than percentage change.

Figure 30 | Change in Forest Volume Per Forest Area by Province, 2010 to 2020



Sources: NBS (multiple years).

Over the past two decades, China's national forest policies have adopted a broader set of goals, now including CO_2 sequestration and climate adaptation alongside traditional objectives for watershed protection and controlling desertification.[59] Additionally, there have been continued calls for China's national forest policy to shift from an overemphasis on expanding forest area to more holistic, ecosystem-based goals and metrics.[60] Both expanded goals and a greater focus on forest quality rather than quantity should lead to greater convergence in forestry indicators across provinces.

59 SFA (2016).

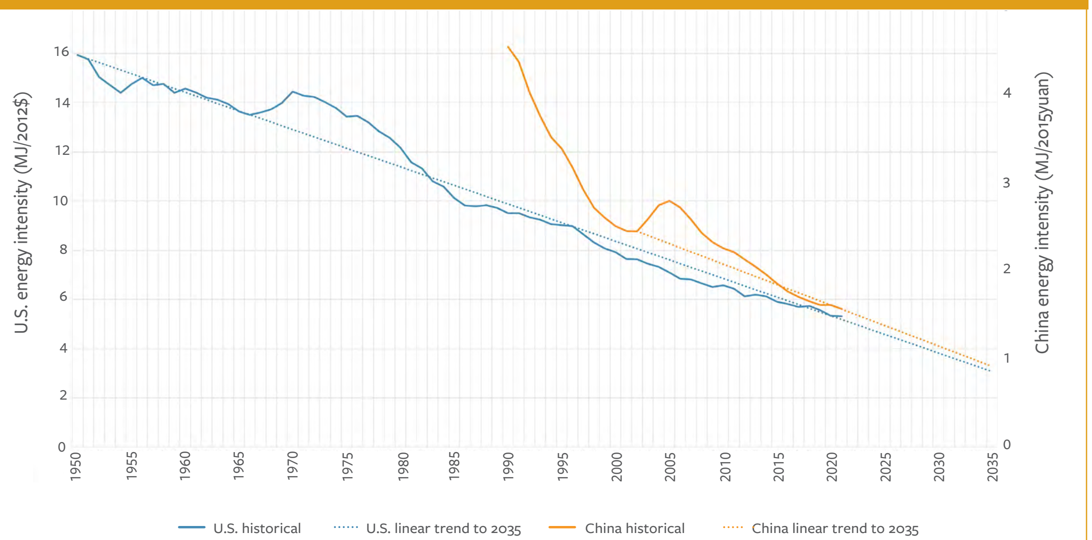
60 Lu et al. (2022); Niu (2023).

3.7 Energy Intensity

Energy intensity is typically defined as the total amount of energy consumed per dollar of real GDP. In most economies, energy intensity declines with economic development. However, declines in energy intensity are driven by a complex range of factors: demographics, de-industrialization, growth in service industries, natural resource depletion, economic and environmental regulation, changes in energy resources, increases in the energy efficiency of end-use equipment, transportation mode choices, and energy conservation. Many of these forces are beyond the direct control of policymakers, which means that energy intensity tends to be a passive, aggregate indicator. It does not directly link to specific policies but, as was the case in Japan in the 1970s, it can reflect the effects of a suite of individual policies and an overall prioritization of energy efficiency in public policy.[61]

In the U.S., energy intensity has declined almost linearly, at about 0.15 megajoules (MJ)/$ per year since energy data collection began in 1949 (Figure 31). In China, declines in energy intensity can be divided into two periods: 1990-2002 and 2002-present. Declines in each period have been approximately linear over time, aside from an anomalous increase from 2002 to 2004 (Figure 31).[62] In the more recent period (2002-present), energy intensity has declined by about 0.05 MJ/yuan per year. Our 2035 milestones assume that these linear trends continue to 2035, though for China we remove the effects of the 2002-2004 increase in energy intensity.

Figure 31 | Energy Intensity in the U.S. and China, Historical and Trajectories to 2035 stones



Sources and notes: U.S. data are from EIA (multiple years (b)). China nominal GDP and energy consumption data are from NBS (multiple years); nominal GDP was converted to 2015 real GDP using a GDP deflator for China from the World Bank's World Development Indicators, https://databank.worldbank.org/. See Appendix B for a discussion of methodological issues in calculating energy intensity in China.

Although linear declines in energy intensity will eventually saturate, two factors will likely drive higher declines in energy intensity in the nearer term. The first is the shift to non-fossil fuel generation resources. Fossil fuel generation resources have significant energy conversion losses, meaning that a large amount of the initial energy in coal, natural gas, or oil is lost as waste heat in the process of converting that energy into electricity. With exceptions, non-fossil generation resources do not have conversion losses. The result is that, for the same amount of final energy consumption, total primary energy consumption and energy intensity will decline as a result of shifting to non-fossil generation resources.[63]

61 Okajima and Okajima (2013).

62 Explanations for this anomalous increase range from declining investments in energy efficiency and low energy prices (Zhao et al. 2010) to data anomalies (Kahrl et al. 2013).

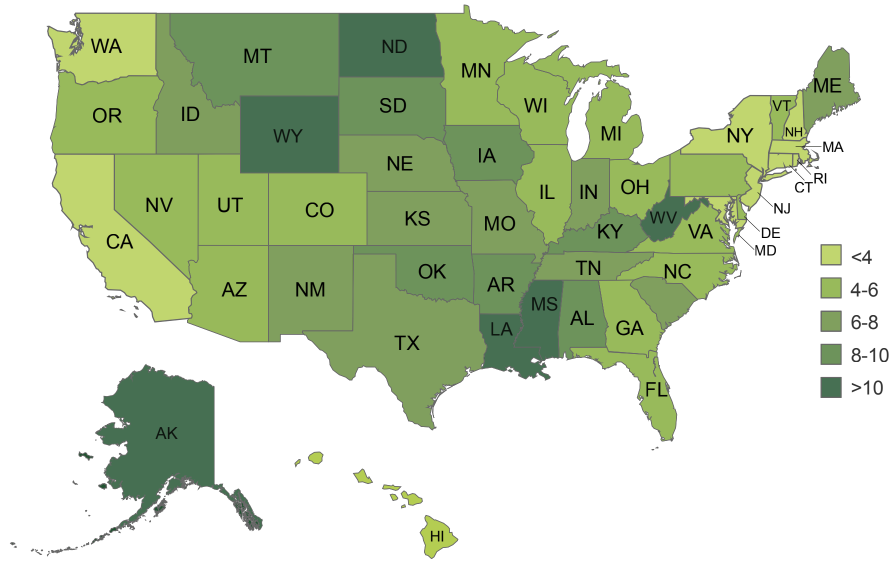
63 For instance, 1 kilowatt-hour (kWh) (3.6 MJ) of electrical energy from a natural gas power plant might require 7.2 MJ of energy from natural gas (50% conversion efficiency), whereas the wind energy required to supply 1 kWh (3.6 MJ) of wind energy is just 3.6 MJ.

The second factor is electrification, which generally results in large end-use efficiency improvements – a light-duty EV, for instance, will typically consume about one-third of the energy that an internal combustion engine vehicle consumes.[64] If the grid is primarily powered by fossil fuels, this higher end-use efficiency for electric equipment will be partially offset by higher energy conversion losses from generating electricity rather than using fossil fuels directly. As the generation mix increasingly shifts to non-fossil resources, however, electrification will also lead to significant declines in energy intensity.

3.7.1 U.S. States

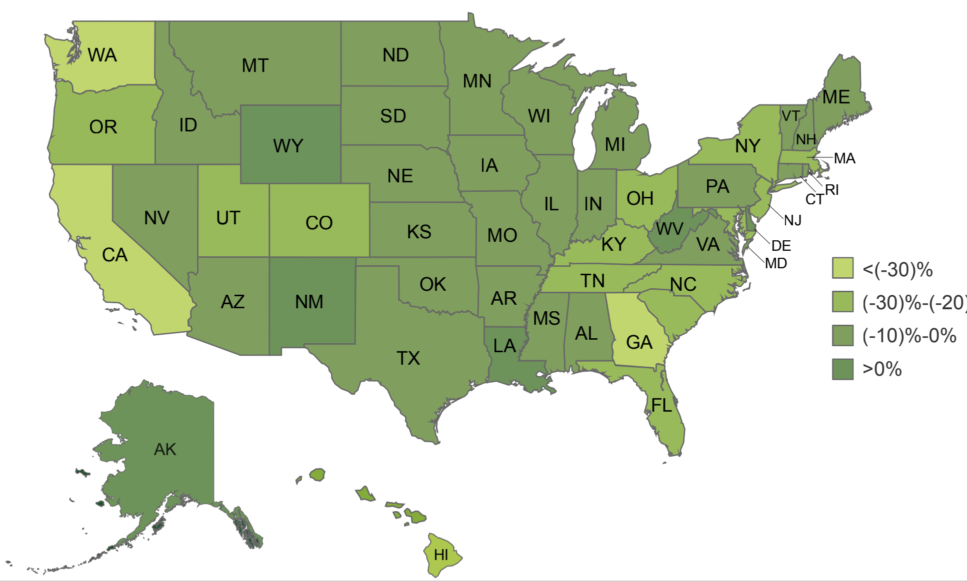
Both energy intensity and declines in energy intensity over the past two decades vary significantly across states (Figure 32 and Figure 33). The most energy intensive state

Figure 32 | Energy Intensity (MJ/2012$) by State, 2020



Sources: Data are from EIA (multiple years (b)).

Figure 33 | Change in Energy Intensity (%) by State, 2010 to 2020



Sources: Data are from EIA (multiple years (b)). Change is percentage change between 2010 and 2020.

64 For instance, an EV with a fuel efficiency of 0.25 kWh per mile will consume 0.9 MJ/mile, whereas an internal combustion engine vehicle with a fuel efficiency of 40 miles per gallon will consume 3.0 MJ/mile.

(Wyoming, 14.7 MJ/$) is nearly six times more energy intensive than the least intensive state (New York, 2.5 MJ/$). The state with the largest decline in energy intensity from 2010 to 2020 (Washington, -37%) was more than 40 percentage points lower than the state with the lowest decline (highest increase) (West Virginia, +6%). In general, states with more resource or manufacturing dependent economies tend to be more energy intensive than those that are more services dependent.[65] However, changes in energy intensity over time are only moderately correlated with the level of energy intensity, and declines in energy intensity in most (33) states were within 5 percentage points of the U.S. average (-19%). Regionally, the smallest decline in energy intensity from 2010 to 2020 was in the Midwest, whereas the three other census regions were more in line with the U.S. average (5.3 MJ/2012$).

3.7.2 Chinese Provinces

China has a clear regional distribution for energy intensity. The most energy intensive provinces are in the northern regions, whereas the least energy intensive provinces are in southern regions, particularly along China's coast (Figure 34). The reasons for this are at least partly historical:

Figure 34 | Energy Intensity (MJ/2015 yuan) by Province, 2020

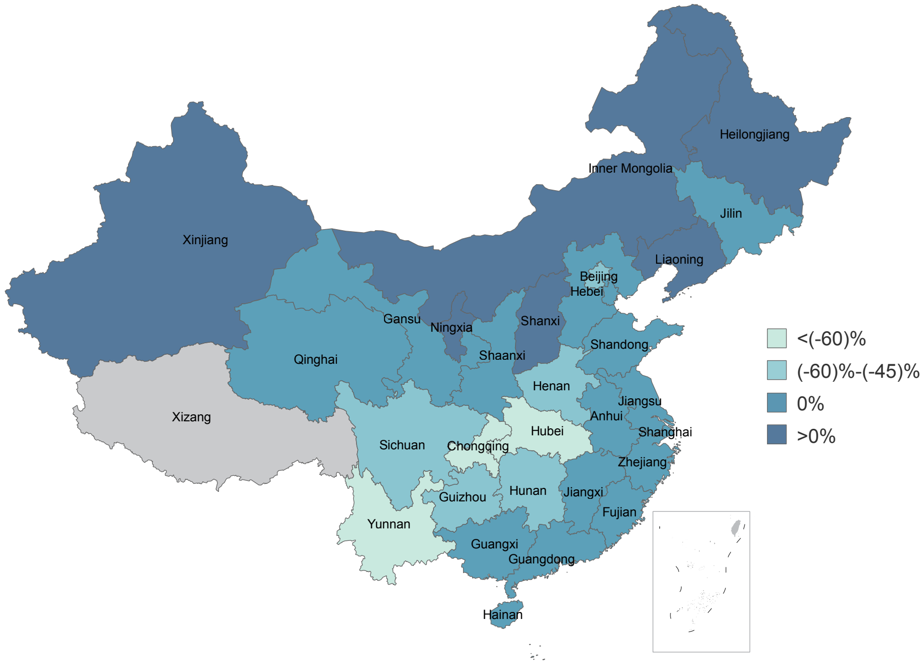
Sources and notes: Energy data are from CEYEB (multiple years). Provincial GDP data are from NBS (multiple years). We convert from nominal to real GDP using a national GDP deflator for China from the World Bank's World Development Indicator series.

northern provinces have traditionally been China's industrial heartland and resource bases, and the Western Development Strategy directed national investment into heavy industry in inland provinces in an attempt to narrow the wealth divide between inland and coastal provinces.[66] The gap between the most and least energy intensive provinces has been persistent. From

65 Resource and manufacturing dependent economies are those where the share of the mining, quarrying, and oil and gas extraction and manufacturing sectors significantly exceed U.S. averages. The 11 states in which energy intensity exceeds 9 MJ/$ all have resource or manufacturing intensive economies: Alabama, Alaska, Arkansas, Iowa, Louisiana, Mississippi, Montana, North Dakota, South Dakota, West Virginia, and Wyoming. State-level economic data are from the U.S. Bureau of Economic Analysis (BEA), www.bea.gov.

66 This is not to argue that heavy industry in China is regionally concentrated or concentrated in lower income provinces. Guangdong, China's richest province, is its largest cement producer; Jiangsu, the second richest province, is its second largest steel producer. For Northern and Western provinces, heavy industry and energy tends to be a larger share of provincial GDP.

Figure 35 | Change in Energy Intensity (%) by Province, 2010 to 2020



Sources and notes: Energy data are from CEYEB (multiple years). Provincial GDP data are from NBS (multiple years). We convert from nominal to real GDP using a national GDP deflator for China from the World Bank's World Development Indicator series. Change is percentage change between 2010 and 2020.

2015 to 2020, a period in which the Chinese economy saw continued structural change and declines in energy intensity, energy intensity actually increased in the six most energy intensive provinces (Figure 35).[67]

3.8 CO_2 Intensity

CO_2 intensity is typically measured as the amount of energy-related CO_2 emitted per unit of GDP.[68] It is the product of energy intensity (MJ/$) and the CO_2 intensity of energy supply (CO_2/MJ). This means that if the CO_2 intensity of energy supply is relatively constant, as was the case in both the U.S. and China before 2010, declines in CO_2 intensity will be driven mostly by declines in energy intensity.

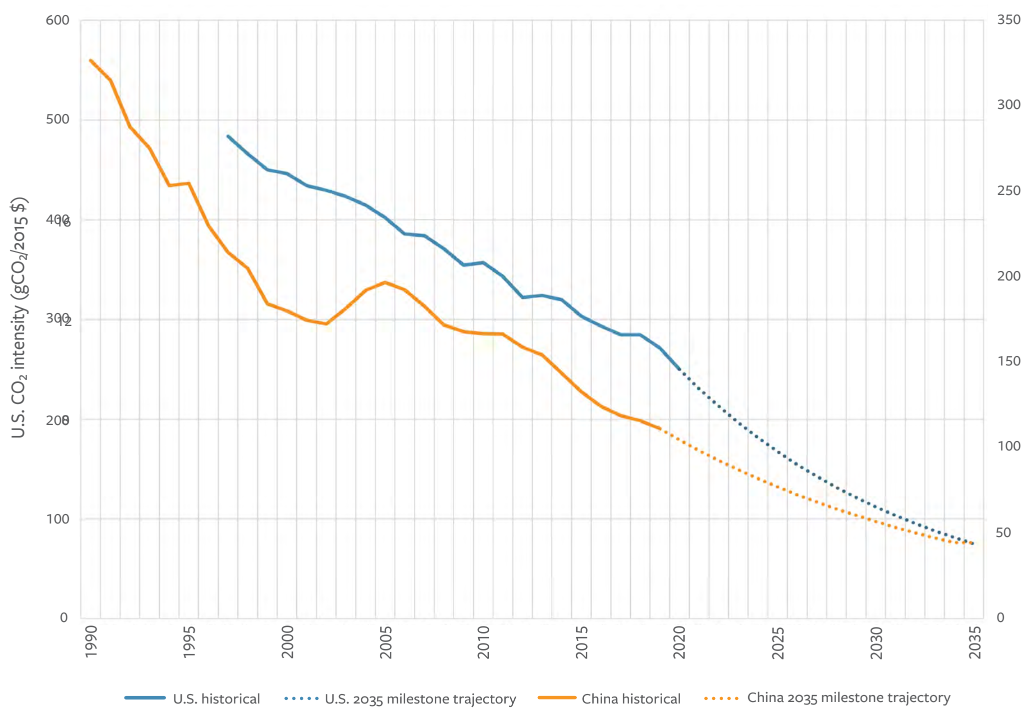
In the U.S. and China, declines in CO_2 intensity have been approximately linear over time (Figure 36). In the U.S., CO_2 intensity has been declining by about 10 grams of CO_2 (gCO_2) per dollar (2012$) per year since the late 1990s. In China, CO_2 intensity has also mirrored energy intensity, declining by about 4 gCO_2 per yuan per year since 2000. Declines in the CO_2 intensity of energy supply in the U.S. and China after 2010 were not large enough to change the linear path of CO_2 intensity between 2010 and 2020, but they may be large enough to do so in the future.

For the U.S., our 2035 milestone assumes that CO_2 intensity declines exponentially between 2020 and 2035, falling by about 70% (to 75 tons[t]CO_2/$, 2012$), consistent with linear declines in energy intensity and the CO_2 intensity of energy supply implied by our sector-specific milestones (see Milestones). For China, our 2035 milestone also assumes that CO_2 intensity declines exponentially between 2020 and 2035, falling by about 60% (to 44 tCO_2/yuan, 2015 yuan).

67 These six provinces include Ningxia, Shanxi, Inner Mongolia, Xinjiang, Heilongjiang, and Liaoning. Several of these provinces are also large energy producers. Inner Mongolia, Shanxi, and Xinjiang are China's largest coal producing regions. Heilongjiang is its largest oil producer. For more on China's economic structural change during the 2010s, see Kahrl (2022).

68 Energy-related CO_2 intensity only includes emissions from the combustion of fossil fuels: it does not include CO_2 process emissions in industry or non-energy-related CO_2 emissions from fossil fuels, nor does it include terrestrial or geological sequestration of CO_2. If the definition for "carbon neutrality" includes non-energy emissions and offsets from sequestration, CO_2 intensity does not necessarily need to fall to zero to reach carbon neutrality.

Figure 36 | Energy-related CO_2 Intensity in the U.S. and China, Historical and Trajectories to 2035 Milestones



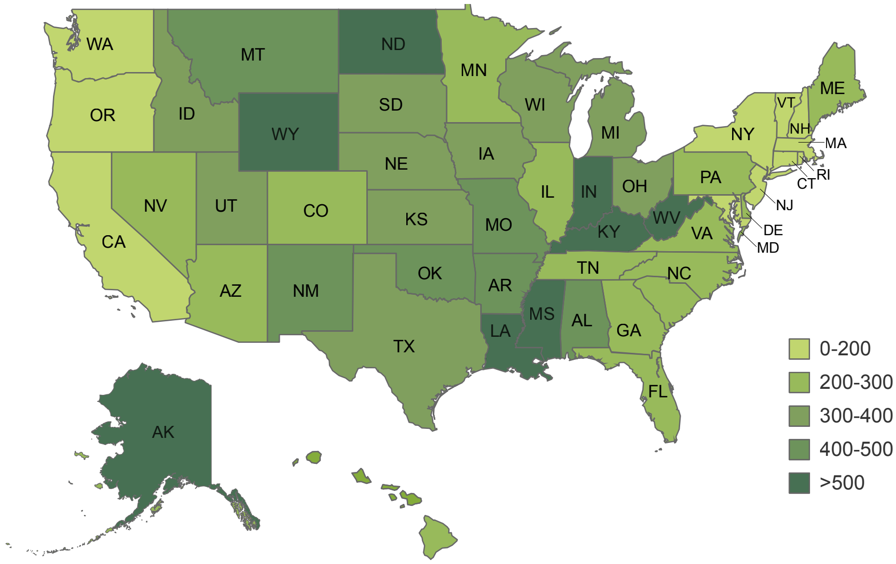
Sources and notes: U.S. data are from EIA (multiple years (b)). China nominal GDP data are from NBS (2022); the China deflator is from the World Bank's World Development Indicators series; and energy-related CO_2 emissions data for China are from Climate Watch, https://www.climatewatchdata.org

3.8.1 U.S. States

Levels and changes in states' CO_2 intensity are closely correlated with energy intensity, but they also reflect the substitution of coal with renewable energy and natural gas in the power sector over the past decade. Thus, in several states (Alabama, Arizona, Illinois, Iowa, Montana, Nevada, New Mexico, North Dakota, Oklahoma, South Dakota) – many of them in the Midwest – declines in CO_2 intensity were more than double declines in energy intensity between 2010 and 2020. For instance, Iowa saw a 34% reduction in CO_2 intensity but only a 10% reduction in energy intensity.

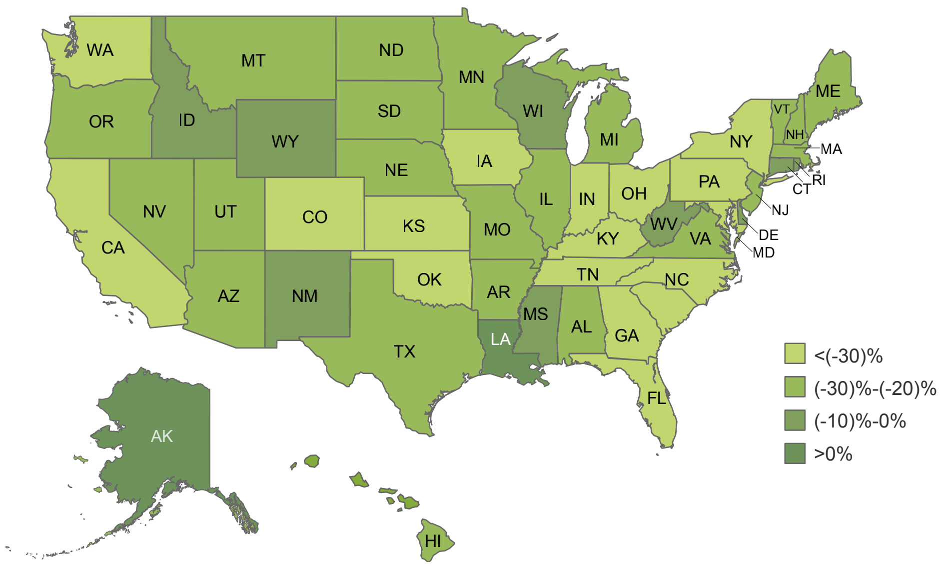
Nevertheless, CO_2 intensity still varies significantly across states. The most CO_2 intensive state (Wyoming, 1,011 tCO_2/$) is nearly 10 times more energy intensive than the least intensive state (New York, 103 tCO_2/$) (Figure 37). The decline in CO_2 intensity in Georgia (-45%) from 2010 to 2020 was 50 percentage points greater than in Alaska, which saw an increase in CO_2 intensity of 5% (Figure 38). As with energy intensity, most states and regions are reasonably close to the U.S. average (250 gCO_2/2012$) (Figure 37).

Figure 37 | CO_2 Intensity (gCO_2/2012$) by State, 2020



Sources: Data are from EIA (multiple years (b)).

Figure 38 | Change in CO_2 Intensity (%) by State, 2010 to 2020

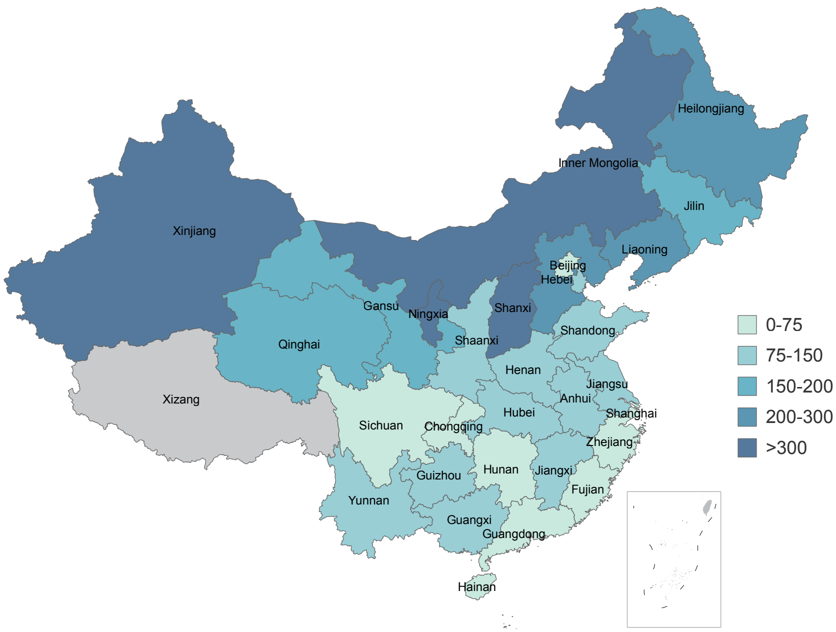


Sources: Data are from EIA (multiple years (b)).

3.8.2 Chinese Provinces

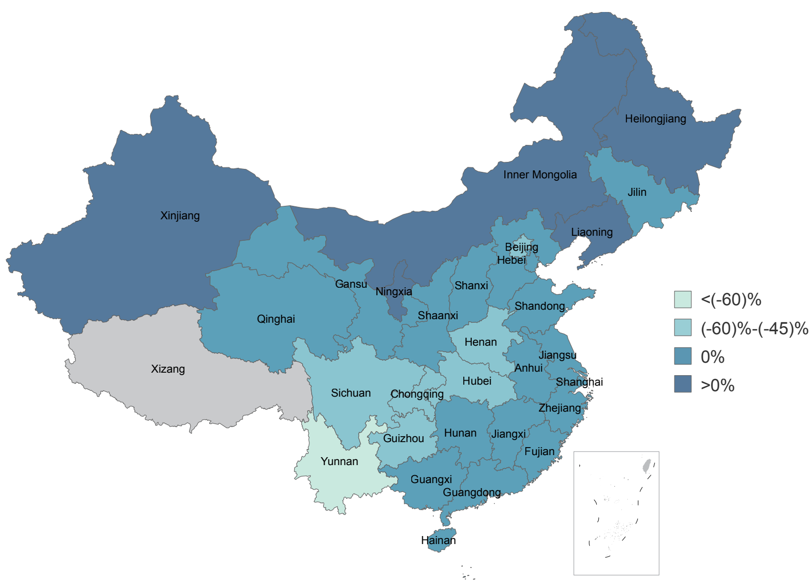
Provincial CO_2 intensity and energy intensity are closely aligned: the most energy intensive provinces are generally also the most CO_2 intensive ones. There is a wide range in CO_2 intensity among provinces: the most CO_2 intensive province (Ningxia, 586 gCO_2/yuan) had a CO_2 intensity more than 11 times higher than the least CO_2 intensive province of comparable size (Guangdong, 52 gCO_2/yuan) in 2019. Declines in CO_2 intensity also varied significantly among provinces. At the extremes, Xinjiang saw a 37% increase in CO_2 intensity between 2010 and 2019, whereas in Yunnan CO_2 intensity declined by 62%.

Figure 39 | CO_2 Intensity (gCO_2/2015 yuan) by Province, 2019



Sources and notes: Provincial CO_2 data are from Carbon Monitor China, https://cn.carbonmonitor.org/ . GDP data are from NBS (multiple years). We convert from nominal to real GDP using a national GDP deflator for China from the World Bank's World Development Indicator series.

Figure 40 | Change in CO_2 Intensity (%) by Province, 2010 to 2019

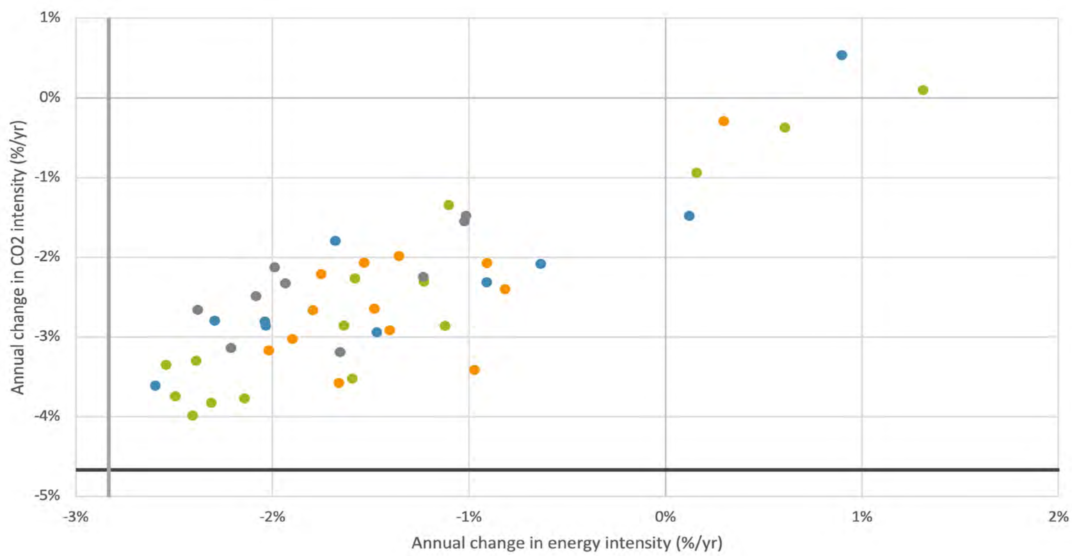


Sources and notes: Provincial CO_2 data are from Carbon Monitor China, https://cn.carbonmonitor.org/. GDP data are from NBS (multiple years). We convert from nominal to real GDP using a national GDP deflator for China from the World Bank's World Development Indicator series. Change is percentage change between 2010 and 2019.

3.9 Energy and CO_2 Intensity Trends Vis-à-Vis 2035 Milestones

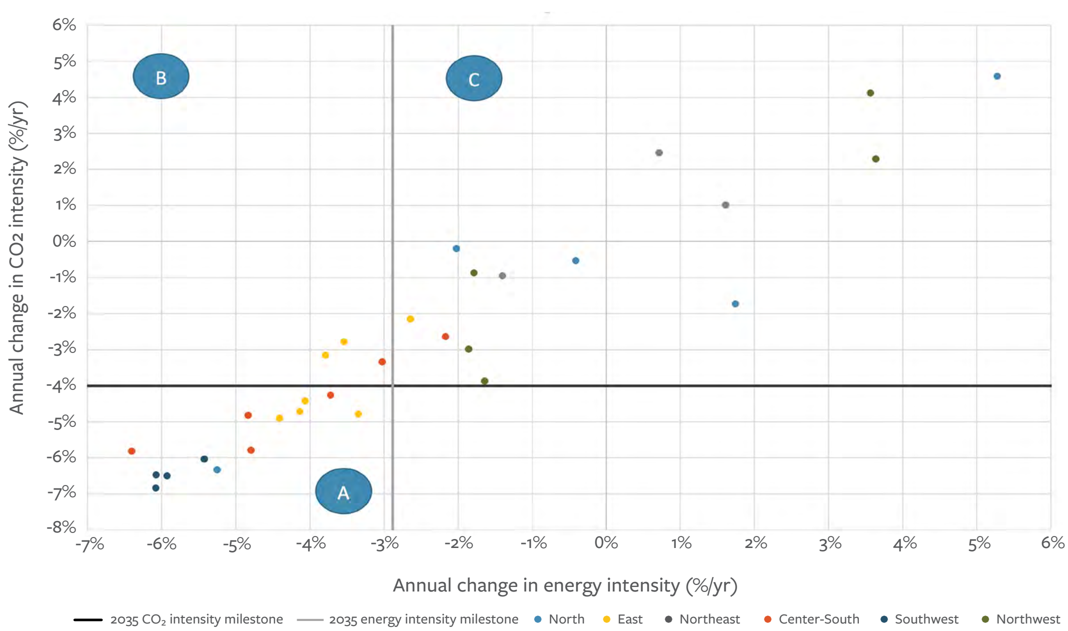
By converting 2035 energy and CO_2 intensity milestones into annual percentage declines, we can compare state and provincial trends in energy and CO_2 intensity over the past decade with what would be required to achieve these 2035 milestones. In other words, if current trends continue, which states and provinces would be on track to achieve these milestones, and which would not?

Figure 41 | U.S. State Annual Percentage Changes in Energy Intensity and CO_2 Intensity (%/yr) from 2010 to 2020, Relative to 2035 U.S. Milestones



Sources and notes: Data are from the EIA's State Energy Data System (SEDS), https://www.eia.gov/environment/emissions/state/. Change is percentage change from 2010 to 2020.

Figure 42 | Provincial Annual Percentage Changes in Energy Intensity and CO_2 Intensity (%/yr) from 2010 to 2019, Relative to 2035 Milestones



Sources and notes: Energy data are from CEYEB (multiple years). Total primary energy supply data for Heilongjiang was not available for 2010. We linearly interpolated this value between 2005, and 2015. Provincial CO_2 data are from Carbon Monitor China, https://cn.carbonmonitor.org/. GDP data are from NBS (multiple years). We convert from nominal to real GDP using a national GDP deflator for China from the World Bank's World Development Indicator series. Change is percentage change between 2010 and 2019.

Reducing CO_2 emissions to net zero levels implies that the annual rate of decline in CO_2 intensity (%/yr) must be significantly higher than for energy intensity. Thus, our 2035 CO_2 intensity milestone for the U.S. (70%, or 4.7% per year over 15 years) is 1.6 times higher than our energy intensity milestone (2.8% per year); our CO_2 intensity milestone for China (60%, or 4% per year) is 1.4 times higher than our energy intensity milestone (2.9% per year). For carbon neutrality, CO_2 intensity is the more important metric but the two are interactive: declines in energy intensity reduce the amount of energy supply decarbonization needed to meet CO_2 intensity goals.

In the U.S., historical annual rates of decline in CO_2 and energy intensity are all higher than our 2035 milestone rates, meaning that no states are currently on target to achieve these milestones (Figure 35). There are no clear regional patterns. Relative to Chinese provinces, the variance in annual rates of change in energy and CO_2 intensity among U.S. states is actually quite small.[69] The fact that no states are currently on track to meet energy or CO_2 intensity milestones should not be surprising or alarming. Our energy intensity milestone assumes that states return to long-run rates of decline in energy intensity in the U.S. through energy efficiency and changes in energy supply. Our CO_2 intensity milestone assumes more rapid reductions in CO_2 emissions than have occurred over the past decade.

In China, 13 provinces had lower annual percentage declines in energy and CO_2 intensity than the 2035 milestones from 2010 to 2019 (area A in Figure 42), 3 provinces had lower energy intensity but slightly higher CO_2 intensity declines, and 14 provinces had higher energy and CO_2 intensity declines. Most of the provinces in areas A and B are in the Southwest, Center-South, and East regions. Most of the provinces in area C are in the North, Northeast, and Northwest. Almost half of China's provinces have had annual declines in energy and CO_2 intensity that are on pace to reach these 2035 milestones, which suggests that they are not out of reach, though maintaining high rates of decline in energy and CO_2 intensity will likely require additional policy support from national and subnational governments. The large variance in rates of change in energy and CO_2 intensity among provinces reflects the federalist challenges in China's energy and climate policies – provinces have historically responded, and will likely continue to respond, differently to national targets.[70]

69 U.S. states have a coefficient of variation (CV) of -0.66 for annual changes in energy intensity and -0.43 for CO_2 intensity, whereas Chinese provinces have CV values of -1.29 and -1.16, respectively. CV is the ratio between the standard deviation and the mean and is a standardized measure of variability.

70 Downie (2021).

CHAPTER FOUR

CONCLUSIONS

Indicators and nearer-term milestones are a valuable tool for tracking subnational progress toward national carbon neutrality goals in the U.S. and China. They objectively measure meaningful change on shorter and longer time horizons, provide insight on regions and sectors that require more targeted support from national governments, and help both national and subnational governments prioritize policies and programs based on areas of progress. The indicators in this report aim to maintain balance between completeness and simplicity, focusing on the transition from fossil fuel to non-fossil fuel-based energy systems and forest-based nature-based mitigation solutions. The 2035 milestones balance feasibility and the ambition needed to reduce CO_2 emissions to net zero levels by about mid-century.

Different kinds of indicators provide different perspectives on the pace and scale of change. Flow indicators track changes in the flow of new energy infrastructure and equipment – for instance, car sales, new generation capacity, and new industrial production capacity. Stock indicators track changes in average energy production and consumption. Flow indicators will change more rapidly than stock indicators. For instance, even if EV sales increase rapidly over the next decade, the transportation energy mix will change only gradually. Flow indicators can thus provide a useful gauge of momentum and the direction of future charge. However, state- or provincial-level data for most of the flow indicators that we identified for this report are not currently publicly available. U.S. federal and China's central government agencies could consider collecting, standardizing, and publishing some of these data, to help support both national and subnational policy.

Over the past two decades, the main area of progress toward non-fossil fuel-based energy systems in the U.S. and China has been in electricity generation. In the U.S., the share of new non-fossil generation capacity (flow indicator) rose from 39% in 2010 to 76% in 2021, and in China from 33% in 2010 to 67% in 2020. Increases in the share of non-fossil generation (stock indicator) were steady but more gradual. Non-fossil generation rose from 30% to 40% of total generation in the U.S., and from 19% to 32% in China from 2010 to 2020. This trend looks set to continue in both countries over the next decade, driven by a mixture of policy and economics.

Across U.S. states and Chinese provinces, increases in the share of non-fossil generation have been driven by a complex mix of policy, resources, and economics. In the U.S., the most rapid increases in non-fossil generation shares have been concentrated in the Midwest and West, due to their high-quality wind resources. In China, increases in non-fossil generation shares were initially concentrated in the hydro-rich Southwest and wind-rich Northwest, North, and Northeast regions. Rapid growth in solar generation, however, led to greater national convergence in new non-fossil generation capacity and non-fossil generation. Lower cost solar may have a similar effect in the U.S. over the next decade.

Less progress has been made in the three energy consuming sectors: buildings, industry, and transportation. For buildings, the main strategies for reducing the share of fossil fuel energy consumption are currently electrification and, in China, district heating.[71] In the U.S., building electrification has slowed since the 2010s, perhaps due to energy price and demographic factors, and state and local policy has yet to have a meaningful impact on building energy use. Colder northern regions will present the greatest challenges and most important areas for gauging progress in increasing shares of non-fossil energy in buildings. In China, district heating policy has been a key driver of building energy use, and colder northern regions thus often have higher

71 See Section 2 for a description of how we deal with primary and secondary energy in the indicators in this report.

non-fossil shares than milder southern regions. China faces multiple challenges in transitioning buildings to non-fossil energy: strategies for decarbonizing heat supply, urban heating policy in regions that have historically not had centralized heat, the future of natural gas use in urban buildings, and rural heating policy. Unlike in the U.S., in China there is thus no single region of focus for tracking progress.

Neither the U.S. nor China has concrete plans for decarbonizing industry, due in part to the diversity of technologies and emission sources in the industrial sector. The share of non-fossil energy in U.S. industry has been relatively flat since the 1980s, but in China has recently increased due to policy- and technology-driven electrification. Progress in shifting to non-fossil energy in U.S. industry is likely to be sporadic and regionally specific, whereas in China there is greater potential for national policy to drive changes in industrial energy use across provinces. For both countries, sector-specific indicators in industry could help track progress in the highest CO_2 emitting sectors: steel, cement, chemicals, and refining.

Oil dominates U.S. and China's transportation energy, and despite biofuel and other policies to support non-fossil energy transportation, energy mixes have not changed significantly in the past two decades. However, adoption of non-fossil fuel vehicles is growing rapidly in both countries, driven by policy and improving economics. In the U.S., most ZEV policy has been at a state level, combined with federal incentives, which implies that increases in ZEV adoption and transportation non-fossil fuel shares may increase unevenly across states over the next decades. China has stronger national ZEV policies, though provincial and local policy may also lead to regional variation in ZEV adoption, and changes in the transportation energy mix in China.

Forests are likely to be the main source of terrestrial CO_2 sequestration in the U.S. and China. Both countries have seen large and sustained increases in forest carbon sinks over the past two decades. In the U.S., the largest increase in forest area and volume has occurred in the South. In China, increases in forest area have followed national forest policy and its focus on watershed protection. In both countries, expanding national forest policy to include CO_2 sequestration as an explicit objective should lead to increases in forest area and volume across a diverse set of states and provinces. Subnational trends in forests are thus important to monitor, though they require more patience than other indicators because national forest inventories are updated relatively infrequently.

Energy and CO_2 intensity are high-level indicators: they are not directly linked to sector-specific policies but are instead aggregate gauges of trends in energy consumption and CO_2 emissions. Historically, declines in CO_2 intensity were mainly the result of declines in energy intensity, but over the past decade the former outpaced the latter due to increases in non-fossil electricity generation. To achieve carbon neutrality goals, declines in CO_2 intensity will need to be significantly higher than declines in energy intensity. There is unsurprisingly significant variance in energy and CO_2 intensity among U.S. states and Chinese provinces, but variance is much higher among Chinese provinces than U.S. states. No U.S. states are currently on a trajectory to meet the 2035 milestones for energy and CO_2 intensity in this report, though some provinces in China are. It will be important to track whether U.S. states can move onto this trajectory, and whether Chinese provinces can remain or move onto it, in the next five years.

Though changes in indicator values over the past two decades provide helpful context, the most important signs of progress will occur in the next 10 to 15 years. It will be important to continue to monitor progress to examine the drivers of and obstacles to change.

CHAPTER FIVE
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APPENDIX A: MILESTONE CALCULATIONS

This appendix describes the methods used to calculate milestone values for the indicators in Table 2. It is primarily intended as a reference. Milestone calculations are sector-specific and rely on analytical methods rather than energy systems and land use models.

A.1 Electricity

A.1.1 Stock Indicator: Share of Non-Fossil Fuel Electricity Generation in Total Generation

For the U.S., our 2035 milestone for the share of non-fossil generation is based on the Biden administration's goal of 100% non-CO_2-emitting electricity generation by 2035.[72] The National Renewable Energy Laboratory (NREL) studied four scenarios in which the U.S. electricity system meets this goal.[73] Across NREL's scenarios, at most 4% of total electricity was generated from fossil fuels (natural gas). Our 2035 milestone (>95% non-fossil fuel generation) assumes that gas-fired power plants will, at most, generate a small amount of total electricity.[74]

The Chinese government has not released targets for non-CO_2-emitting or non-fossil generation for 2035.[75] Exponential growth in the share of non-fossil generation (with faster growth later) would imply a share at time *t* of:

$$\rho^E{}_t = \rho^E{}_0 \times (1 + r^E)^{T - t_0}$$

where $\rho^E{}_t$ is the share of non-fossil electricity generation in year t, $\rho^E{}_0$ is the share in a base year, r^E is the annual rate of growth in the share of non-fossil generation, T is the final year (2050 or 2060), and t_0 is the base year.

Including biomass, China's 2020 share of non-fossil generation was 34% ($\rho^E{}_0$ = 0.34, t_0 = 2020).76 Assuming that the share of non-fossil generation would need to be greater than 90% by 2050 ($\rho^E{}_0$ = 0.90, T = 2050) to meet a 2060 carbon neutrality goal, the rate of growth (r^E) will thus be:

$$r^E = \left(\frac{\rho^E{}_T}{\rho^E{}_0}\right)^{\frac{1}{T - t_0}} - 1 = \left(\frac{0.90}{0.34}\right)^{\frac{1}{2050-2020}} - 1 = 0.033$$

and the share of non-fossil generation in 2035 would be:

$$\rho^E{}_{2035} = 0.34 \times (1 + 0.033)^{(2035-2020)} = 55\%$$

72 The White House (2021).

73 Denholm et al. (2022).

74 There are open questions as to whether the U.S. electricity industry can meet the Biden Administration's 2035 goal for clean electricity. Even if it does not, incentives provided under the Inflation Reduction Act will likely bring the U.S. close to the goal, which implies that the share of fossil fuel generation will have declined significantly by 2035. Thus, we argue that a milestone of greater than 95% is still a meaningful goal, because it is consistent with current policy, even if the actual value turns out to be closer to 80%-90%. See Abhyankar et al. (2021) for an analysis of a 90% non-fossil electricity system in the U.S. by 2035.

75 The Chinese government set a target of 1,200 GW of wind and solar generation capacity by 2030 and has separate targets for hydropower and nuclear generation capacity that are set in five-year planning, though the effect of these goals on the share of non-fossil generation will depend on electricity demand growth.

76 All base year data in this section are from the sources described in the main text. See Appendix B for a more detailed description of data sources.

We use a "greater than" sign for this milestone (> 55%), reflecting several studies that have shown that it might be feasible to have much higher shares – as high as 80% – of non-fossil generation in China by 2035.[77]

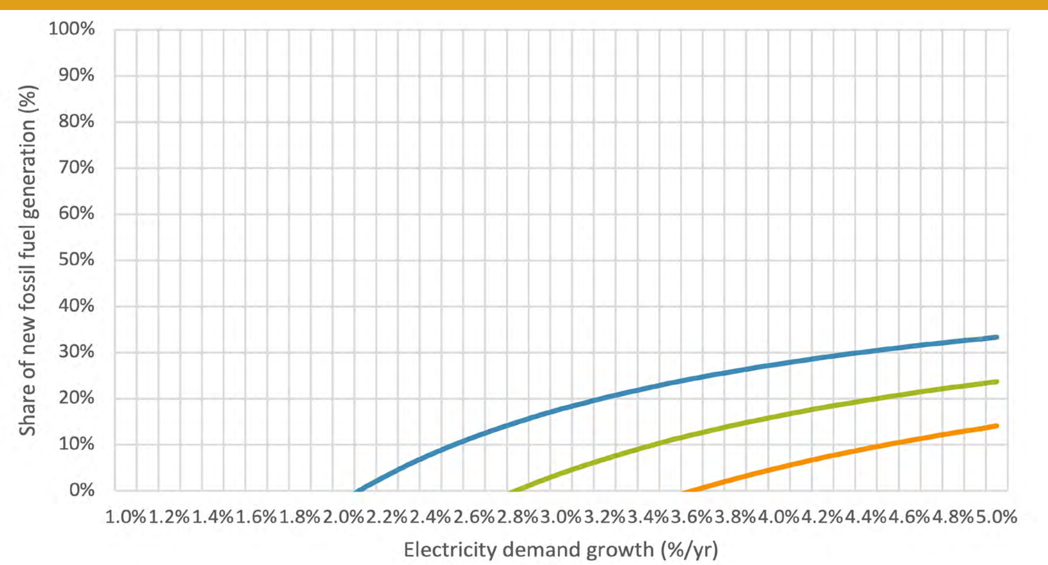
A.1.2 **Flow Indicator:** Share of New Non-Fossil Fuel Capacity in Total New Generation Capacity

Power plants are long-lived assets. Typical lifetimes for coal- and gas-fired power plants tend to be between 30 and 60 years, though they can, in principle, be maintained indefinitely through equipment upgrades, replacement, and maintenance. This means that the natural turnover of existing power plants may take decades, but also that new generation capacity would likely need to be mostly non-fossil fuel for more than a decade before existing fossil fuel generation (GWh of energy) would be replaced with non-fossil generation.

In the U.S., the share of new non-fossil generation capacity would likely need to be very high by 2035 to meet a net zero CO_2 electricity goal, though without new technologies like lower cost electricity storage it will unlikely be 100%.78 Residual new fossil fuel generation capacity would be used primarily for reliability (capacity and energy adequacy). Across scenarios in the NREL study mentioned previously, the maximum amount of new fossil fuel generation capacity was about 10%.79 Consistent with this estimate, we use a milestone of greater than 90% for the share of new non-fossil generation capacity for the U.S.

In China, a 50%-60% share of non-fossil generation by 2035 would also likely imply little to no new net fossil electricity generation (GWh) by 2035, though analytically the share of new fossil generation will depend on electricity demand growth and the share of non-fossil generation. Figure A.1 shows maximum shares of new fossil generation (GWh) for different rates of electricity demand growth and total non-fossil generation share. Below the x-axis (e.g., less than 3.6% demand growth for a 60% non-fossil share), all new generation (GWh) would need to be non-fossil to meet a given non-fossil share target.

Figure A.1 | Maximum shares of new fossil fuel generation in total new generation for different rates of electricity demand growth and different total shares of non-fossil generation



Note: This figure uses 2020 as a base year, with an electricity demand (including generator use and distribution losses) of 7,626 terawatt-hours and a non-fossil share of 32%. Data are from CEC (multiple years).

77 See, for instance, Abhyankar et al. (2022).

78 In particular, getting to 100% new non-fossil generation capacity would likely require more cost-effective longer duration electricity storage, to ensure energy adequacy as electricity systems become more reliant on intermittent wind and solar generation.

79 Denholm et al. (2022).

Because fossil fuel power plants tend to have lower capacity factors than non-fossil fuel ones (nuclear being the exception), the share of non-fossil generation capacity in new generation capacity (GW) will typically be higher than the share of new generation (GWh). For instance, in a scenario where 10% of new generation was from fossil fuels, about 90%-95% of new generation capacity would likely be non-fossil fuel.[80] Assuming that higher electricity demand growth would correspond to a higher non-fossil generation share (i.e., closer to 60% non-fossil share), greater than 90% would thus be a reasonable milestone for non-fossil fuel generation capacity in China by 2035.

A.2 Buildings

A.2.1 Stock Indicator: Share of Non-Fossil Fuel Energy in Residential and Commercial Final Energy Consumption

Neither the U.S. nor China has set goals for decarbonizing the building sector. In lieu of explicit policy goals, a reasonable assumption is that the share of non-fossil energy in building energy consumption grows exponentially between 2023 and 2050 or 2060, to a level that is consistent with longer-term economy-wide carbon neutrality goals. Exponential growth in the share of non-fossil energy is consistent with linear or S-shaped adoption of more efficient (non-fossil) end-use technologies, assuming similar levels of activity between fossil and non-fossil end-use technologies.[81]

Growing exponentially, the share of non-fossil energy for buildings (ρ^B) in a future year t will be

$$\rho^B{}_t = \rho^B{}_0 \times (1 + r^B)^{T-t_0}$$

where $\rho^B{}_t$ is the share of non-fossil building energy in year t, $\rho^B{}_0$ is the share in a base year, r^B is the annual rate of growth in the share of non-fossil building energy, T is the final year (2050 or 2060), and t^0 is the base year. The rate of growth (r^B) will be

$$r^B = \left(\frac{\rho^B{}_T}{\rho^B{}_0}\right)^{\frac{1}{T-t_0}} - 1$$

where $\rho^B{}_t$ is the share of non-fossil building energy in the final year. This implies that, with an estimate of $\rho^B{}_t$, we can estimate $\rho^B{}_t$.

For the U.S., long-term decarbonization studies suggest that a value of $\rho^B{}_t$ consistent with 2050 carbon neutrality would be on the order of 75%-100%, with any residual fossil fuel CO_2 emissions offset by negative emissions technologies.[82] Consistent with the Central scenario in Williams et al.,[83] we use a value of 90% for $\rho^B{}_t$. The share of non-fossil building energy in 2020 ($\rho^B{}_0$) was 51%. This implies an r^B value of 1.9% per year

$$r^B = \left(\frac{\rho^B{}_T}{\rho^B{}_0}\right)^{\frac{1}{T-t_0}} - 1 = \left(\frac{0.90}{0.51}\right)^{\frac{1}{2050-2020}} - 1 = 0.019$$

and a 2035 $\rho^B{}_t$ value of

$$\rho^B{}_{2035} = 0.51 \times (1 + 0.019)^{(2035-2020)} = 68\%$$

which we round to 70%.

80 For instance, if 10% of new generation was fossil fuel-based, new non-fossil fuel generation had a weighted average capacity factor of about 0.35 (15% hydro at a capacity factor of 0.5, 15% nuclear at a capacity factor of 0.9, and 70% wind and solar with a weighted average capacity factor of 0.2), and new fossil generation capacity has a capacity factor of 50%, non-fossil generation capacity would account for 93% of total new generation capacity. Some amount of new fossil generation capacity will be to replace existing coal units but given the relatively young age of China's coal-fired power plants this should be small relative to total new generation.

81 If non-fossil end-use technologies (e.g., for buildings, heat pumps) are more efficient than fossil fuel equivalents (e.g., a natural gas water heater and furnace), the share of energy use by new equipment in total final energy consumption will be lower than the average, which in turn will mean that the share of non-fossil energy will grow more slowly at first and then more rapidly in later years.

82 Larson et al. (2020); Williams et al. (2021).

83 Williams et al. (2021)

For China, we estimate that the share of non-fossil building energy in 2020 (*ρB0*) was 61%. Because of China's extensive district heating system and relatively large consumption of primary biomass energy in buildings, primary fossil fuel consumption in buildings in China is less than in the U.S. Most remaining primary fossil fuel consumption consists of natural gas (13% of total building final energy consumption), liquefied petroleum gas (9%), and coal (%) consumption in residential buildings.[84] Like the U.S., we assume a 90% value for ***ρBT*** in 2050, assuming that a combination of economics and public health policy drive all but a small amount of natural gas and liquified petroleum gas out of buildings by 2050. This gives an ***rB*** value for China of

$$r^B = \left(\frac{\rho^B{}_T}{\rho^B{}_0}\right)^{\frac{1}{T-t_0}} - 1 = \left(\frac{0.90}{0.61}\right)^{\frac{1}{2050-2020}} - 1 = 0.013$$

and a 2035 ***ρBt*** value of

$$\rho^B{}_{2035} = 0.61 \times (1 + 0.013)^{(2035-2020)} = 74\%$$

which we round to 75%.

A.3 Industry

A.3.1 Stock Indicator: Share of Non-Fossil Fuel Energy in Industrial Final Energy Consumption

As with buildings, a reasonable assumption is that the share of non-fossil energy in industry grows exponentially between 2023 and 2050 or 2060. The share of non-fossil final energy consumption for industry (ρ^I) in a future year t will thus be:

$$\rho^I{}_t = \rho^I{}_0 \times (1 + r^I)^{T-t_0}$$

Where $\rho^I{}_T$ is the share of non-fossil energy in industry in year t, $\rho^I{}_0$ is the share in a base year, ***rI*** is the annual rate of growth in the share of non-fossil energy in industry, T is the final year (2050 or 2060), and t_0 is the base year. For the U.S., $\rho^I{}_0$ = 0.23 (2021), including non-energy uses of fossil fuels. The value of $\rho^I{}_T$ for 2050 is uncertain, depending mainly on the availability and scalability of CCUS as a cost-effective strategy for reducing CO_2 emissions in industry. Based on the Central scenario in Williams et al.,[85] we use a value of 0.9 for $\rho^I{}_T$ (2050), which implies a $\rho^I{}_{2035}$ value of about

$$\rho^I{}_{2035} = 0.23 \times (1.05)^{14} = 0.45$$

For China, $\rho^I{}_0$ = 0.32 (2020) and we use a value of 0.9 for $\rho^I{}_T$ (2060), which implies a $\rho^I{}_{2035}$ value of about

$$\rho^I{}_{2035} = 0.32 \times (1.03)^{15} = 0.47$$

A.4 Transportation

A.4.1 Stock Indicator: Share of Non-Fossil Fuel Energy in Transportation Final Energy Consumption

The share of non-fossil transportation energy consumption in 2035 ($P^T{}_{2035}$) will be the total energy consumed by non-fossil fuel-powered vehicles divided by the energy consumed by fossil fuel-powered vehicles

$$\rho^T{}_{2035} = \frac{\sum_i nv_i \times ne_i \times d_i}{\sum_i nv_i \times ne_i \times d_i + \sum_i fv_i \times fe_i \times d_i}$$

where nv_i is the energy consumed by non-fossil fuel vehicles of mode i (cars, trucks, trains, planes, etc.), ne_i is the unit energy consumption (*MJ*/mile-vehicle) for non-fossil fuel vehicles

84 CEYEB (multiple years).

85 Williams et al. (2021)

of mode ***i***, d_i is the annual distance traveled for a mode ***i*** vehicle, ***fvi*** is the energy consumed by fossil fuel vehicles of mode ***i***, and ***fei*** is the unit energy consumption (*MJ*/mile-vehicle) for fossil fuel vehicles of mode ***i***.

The share of non-fossil fuel vehicles (ϑ) in total vehicles (TV) is

$$\theta = \frac{\sum_i nv_i}{TV}$$

If we assume that the shares of modes (α_i) are consistent between non-fossil fuel and fossil fuel vehicles,

$$\alpha_i = \frac{nv_i}{TV \times \theta} = \frac{fv_i}{TV \times (1-\theta)}$$

and that the ratio of unit energy consumption between non-fossil and fossil fuel vehicles (β) is constant across modes,

$$\beta = \frac{fe_i}{ne_i}$$

the share of non-fossil energy in transportation can be simplified to

$$\rho^T{}_{2035} = \frac{1}{1 + \beta \times \left(\frac{1}{\theta} - 1\right)}$$

Several studies have shown that non-fossil fuel vehicles would need to account for most new vehicle sales by 2035 to meet mid-century national emissions and global warming targets,[86] but there is a lag effect between vehicle sales (a flow) and total vehicles (a stock). Assuming S-shaped adoption, light-duty vehicle (LDV) sales of 80%-100% by 2035 would likely be consistent with non-fossil/fossil vehicle shares of about 50/50.[87] We assume the share of non-fossil vehicles for other, non-LDV modes would be lower than this but that LDVs constitute the majority of vehicles. If the value of theta is about 40%, and the value of beta is about 3, the share of non-fossil energy would be

$$\rho^T{}_{2035} = \frac{1}{1 + 3 \times \left(\frac{1}{0.4} - 1\right)} = 18\%$$

which we round up to 20%. Interestingly, this is higher than what would be implied by exponential growth. For instance, if the share of non-fossil energy in transportation grew to 90% by 2050, the annual rate of increase in the share (r^T) would be 16% per year, and the share in 2035, starting from a share of about 1% in 2020, would be 9%. In other words, our milestone implies more rapid adoption of non-fossil fuel vehicles than what would be implied under exponential interpolation.

A.4.2 Energy Intensity

As Section 3.7 describes, our 2035 milestones assume that energy intensity declines linearly between 2020 and 2035. In the U.S., the linear rate of decline is based on a long-term trajectory from 1949 to 2020. In China, it is based on a trajectory from 2002 to 2020. In both countries, this implies a 43% reduction in 2020 energy intensity by 2035.[88]

For the U.S., this rate of decline is somewhat high relative to long-term studies. For instance, Williams et al.,[89] project a 58% decline in 2020 energy intensity by 2050 in their Central scenario; a ~40% reduction by 2035 and a ~60% reduction by 2050 would imply that declines in energy intensity occur rapidly during 2020-2035 and then saturate at some point during 2035-2050. Nevertheless, we argue that, given the effects of electrification and fuel switching to renewables, linear declines in energy intensity are still a reasonable assumption. In China, a 43% reduction in energy intensity by

86 For the U.S., see Larson et al. (2020) and Williams et al. (2021). For China, see Zhang and Hui (2022).

87 Ibid.

88 The fact that both countries have the same rates of decline is coincidental.

89 Williams et al. (2021)

2035 is high but consistent with long-term studies. For instance, He et al.[90] assume 14% reductions in energy intensity from 2020-2025 and 2025-2030. Continuing this trend would lead to a 36% reduction in energy intensity from 2020 to 2035, which is in the same range as 43%.[91]

Lower energy intensity milestones imply more fuel supply decarbonization to meet a given CO_2 emission reduction or CO_2 intensity target: societies can either choose to consume less energy or make more of that energy zero CO_2 emitting.

A.4.3 CO_2 Intensity

We define CO_2 intensity narrowly as gross energy-related CO_2 intensity. To achieve carbon neutrality (net zero CO_2 emissions), energy-related CO_2 intensity would need to decline nearly to zero, but not necessarily to zero. Any remaining gross energy-related CO_2 emissions would be captured and sequestered or offset by sequestration in non-energy sectors. Following Williams et al.,[92] we assume that a decline in energy-related CO_2 intensity of about 90% would be consistent with carbon neutrality by 2050 and 2060.

The trajectory for CO_2 intensity from 2020 to 2050 depends on milestones for energy intensity, shares of non-fossil fuel energy consumption for different sectors, and the share of non-fossil fuel electricity generation. Mathematically, energy-related CO_2 intensity is the product of the CO_2 intensity of energy supply and the CO_2 intensity of energy supply

$$\left(\frac{C}{Y}\right)_t = \left(\frac{C}{E}\right)_t \times \left(\frac{E}{Y}\right)_t$$

where ***C*** is energy-related CO_2 emissions, ***Y*** is GDP, ***E*** is primary energy supply, ***C/Y*** is CO_2 intensity, ***C/E*** is the CO_2 intensity of energy supply, ***E/Y*** is energy intensity, and ***t*** is time ***t***. If percentage declines from a base period are known for each of these variables, the above equation can be rewritten as

$$\left(\frac{C}{Y}\right)_0 \times (1-\alpha) = \left[\left(\frac{C}{E}\right)_0 \times (1-\theta)\right] \times \left[\left(\frac{E}{Y}\right)_0 \times (1-\beta)\right]$$

where the ***0*** subscript denotes a base year, α is the percentage decline in CO_2 intensity, θ is the percentage decline in the CO_2 intensity of energy supply, and β is the percentage decline in energy intensity.

From the definition of ***C/Y***, this means that

$$(1-\alpha) = (1-\theta) \times (1-\beta)$$

The above equations illustrate that assumptions about any two variables (CO_2 intensity, the CO_2 intensity of energy supply, energy intensity), or changes in these variables, will infer the value of the third. It is thus important to be consistent among the three.

Our milestones for non-fossil shares in buildings, industry, transportation, and electricity imply a value for the CO_2 intensity of energy supply in 2035, though this value is not straightforward to calculate. As a high-level estimate, we start from a definition of gross CO_2 intensity of energy supply

$$\left(\frac{\square}{E}\right) = \sum_j \sum_i e_j \rho_i (1-\gamma_i) \tau_{ij}$$

where e_j is an emission factor for fossil fuel ***j***, ρ_i is sector ***i***'s share of total primary energy consumption, γ_i is the share of non-fossil energy consumption in sector ***i***, and τ_{ij} is fossil fuel ***j***'s share of sector ***i***'s fossil fuel consumption. The electricity sector is included as a separate sector, including its conversion and distribution losses in its ρ_i value. For China, we also include the heat sector.

90 He et al. (2020)

91 Three five-year periods of 14% reductions leads to a total reduction by 2035 of (1 – 0.14)3 – 1 = -36%. This calculation assumes that prices are in real (2020 yuan) terms across each five-year period.

92 Williams et al. (2021)

By changing the non-fossil fuel shares and assuming that the sector shares of primary energy consumption and the fossil fuel shares do not change, we can calculate a new CO_2 intensity of energy supply

$$\left(\frac{C}{E}\right)_1 = \sum_j \sum_i e_j \rho_{i0}(1-\gamma_{i1})\tau_{ij0}$$

where the *1* and *0* subscripts represent new (1) and base (0) values. This approach is not strictly accurate, because the ρ_i terms will almost certainly change as a result of shifts in demand and electrification. However, it does provide a useful approximation.

For the U.S., using this approach we calculate that base year (2020) CO_2 intensity of energy supply was 43.9 kilograms (kg)CO_2/million Btu (MMBtu).[93] Using the γ_i values for 2050 in Table 2, we calculate that the 2035 CO_2 intensity of energy supply would be 23.5 kgCO_2/MMBtu, or a reduction of 46% from 2020.

Solving the above equation for α and adding in the energy intensity milestone (43% reduction by 2035) and CO_2 intensity of energy supply (46% reduction by 2035) thus implies a CO_2 intensity reduction value (α) between 2020 and 2035 of

$$\alpha = 1 - (1 - 0.46) \times (1 - 0.43) = 0.69$$

We round this value to 70%.

For China, we calculate that base year (2020) CO_2 intensity of energy supply was 1.78 tCO_2/tons of coal equivalent (tce).94 Using the ***γi*** values for 2035 in Table 2, we calculate that the 2035 CO_2 intensity of energy supply would be 1.27 tCO_2/tce, or a reduction of 29% from 2020.

With energy intensity and this CO_2 intensity implies a value for α of

$$\alpha = 1 - (1 - 0.29) \times (1 - 0.43) = 0.59$$

We round this value to 60%.

A.5 Forestry

Ideally, milestones for forest CO_2 sequestration would be based on a target for sequestered CO_2. However, given the lack of standardized approaches to calculating CO_2 sequestration in forests, we instead use historical trends for our forest area and volume indicators.

For the U.S., our 2035 milestone for the percentage point change in forest area as a share of total land area (2.2%) is based on a 20 Mha increase in forest area. This is equivalent to 1 Mha and 0.1 percentage points per year between 2017 (the last year that the U.S. conducted a forest inventory) and 2035. This increase is roughly double the rate of forest area increase between 1997 and 2017 (0.5 Mha/yr) and would reflect a much greater emphasis on increasing forest area than has been the case over the last two decades.

Our 2035 milestone for forest volume per unit area assumes a continuation of trends over the past decade, during which forest volume (sound bole volume) increased by about 0.3 billion m3 per year. This implies that forest volume per unit area would increase by about 1 m3/ha-yr, which is roughly in line with trends over the past decade, and total forest volume would increase by a total of 4.5 billion m3 by 2035.

For China, our 2035 milestone for the percentage point change in forest area as a share of total

93 This estimate differs from the EIA's (49.5 kgCO_2/MMBtu in 2020), but differences should be largely due to scope. The EIA's estimate also includes CO_2 emissions from biomass combustion. Sector energy consumption data for this calculation are from EIA (multiple years (a)). We calculate fossil fuel emission factors using the EIA's estimate of fuel-specific CO_2 emissions divided by consumption of that fuel (EIA, multiple years (a)). This leads to emission factors of 95.7 kgCO_2/MMBtu for coal, 52.1 kgCO_2/MMBtu for natural gas, and 65.4 kgCO_2/MMBtu for oil.

94 Energy data are from CEYEB (multiple years). CO_2 emissions factors are from Zheng et al. (2019).

land area (3.1%) is based on a 30 Mha increase in forest area. This amounts to an increase of 2 Mha and 0.2 percentage points per year between 2020 and 2035, which is lower than the 2.5 Mha and 0.3 percentage point per year increase between 2010 and 2020. Given the large increase in forest area between 2000 and 2020, it seems reasonable that the rate of increase in forest area would decline over the next two decades, but this milestone assumes that afforestation continues to be a national priority.

Our 2035 milestone for forest volume per unit area assumes that the rate of increase in forest volume from 2000 to 2020 (0.3 billion m3/yr) continues from 2020 to 2035. Continued volume growth would likely occur as recently planted forests begin to mature, though this rate of volume increase assumes some amount of improvement in forest management. At 0.3 billion m3/yr, total forest volume would reach 22 billion m3 in 2035, an increase of 4.5 billion m3 relative to 2020 and 10 billion m3 relative to 2005.95

95 The year 2005 is the base year in China's NDC forestry goal.

APPENDIX B: DATA SOURCES AND PREPARATION

This appendix describes data sources and preparation of the data used to populate indicators.

B.1 U.S. Data

All state energy and CO_2 emissions data for the U.S. is from the Energy Information Administration (EIA). Table B.1 (pg. 52) describes data sources and notes for each indicator. For the electricity, buildings, industry, and transportation indicators, we calculate shares of non-fossil fuel energy as one minus the share of fossil fuel energy.

B.2 China Data

All provincial energy data for China are from the China Energy Yearbook series. The China Energy Yearbook has detailed provincial energy balance tables dating back to the 1990s, but the sectors reported in the Yearbook do not match the buildings, industry, and transportation sectors used here. Table B.2 (pg. 53) shows the mapping between final energy resources, final consumption sectors, and the building (B), industry (I), and transportation (T) sectors used in these indicators.

Provincial statistics in the China Energy Yearbook are in physical rather than energy units. To convert physical units to energy units, we use the implied conversion factors in the national energy balance tables for 2020, shown in Table B.3 (pg. 54). All energy resources except heat, electricity, and other energy (primary non-fossil energy) are fossil fuels.

All provincial energy data for China is from the China Energy Yearbook series. Table B.4 (pg. 55) describes the data sources and notes for each indicator.

More recent editions of the China Energy Yearbook do include energy intensity data by province, but these data do not have a constant base year for GDP and are thus difficult to compare against historical years. The National Bureau of Statistics changes its price year for calculating real GDP every five years rather than using a fixed index. To ensure more comparability over time and between energy and CO_2 intensity we use the World Bank's national deflator for China instead of directly using energy intensity metrics from the *China Energy Yearbook*.

Table B1 | Data Sources and Notes for U.S. Indicators		
Indicator	**Data Source**	**Notes**
Share of new non-fossil fuel capacity in total new generation capacity	EIA, Electric Power Monthly, Table 6.3, New Utility Scale Generating Units by Operating Company, Plant, and Month[1]	Data from before 2013 are from Table ES3.
Share of non-fossil fuel electricity generation in total generation	EIA, Historical State Data, EIA-923 Power Plant Operations Report, Net Generation by State by Type of Producer by Energy Source Net_Generation_1990-2021 Final[2]	None
Share of non-fossil fuel energy in residential and commercial final energy consumption	EIA, State Energy Data System (SEDS), Full reports & data files[3]	Fossil fuel consumption includes: CLRCB, NGRCB, PARCB, CLCCB, NGCCB, PACCB (CL = coal, NG = natural gas, PA = all petroleum products, RC = residential sector consumption, CC = commercial sector consumption, B = Btu)
Share of non-fossil fuel energy in industrial final energy consumption	EIA, SEDS, Full reports & data files[3]	Fossil fuel consumption includes: CLICB, NGICB, PAICB (CL = coal, NG = natural gas, PA = all petroleum products, IC = industrial sector consumption, B = Btu)
Share of non-fossil fuel energy in transportation final energy consumption	EIA, SEDS, Full reports & data files[3]	Fossil fuel consumption includes: CLACB, NGACB, PAACB (CL = coal, NG = natural gas, PA = all petroleum products, AC = transportation sector consumption, B = Btu) The EIA includes biomass-based ethanol (EMACB) and biodiesel (BDACB) in total petroleum products (PAACB). We remove these from the fossil fuel total.
Annual increase in forest area as a share of total land area	USDA Forest Service, Forestry Resources of the United States, 2017, Table 3, Forest area in the United States by region, subregion, and State, 2017, 2012, 2007, 1997, 1987, 1977[4]	None
Annual increase in forest volume per forest area	FIA EVALIDator 2.0.6[5]	Data are "Sound bole volume of live trees (at least 5 inches d.b.h./d.r.c.)." These are consistent with Forest Service estimates of forest volume in its state fact sheets.
Reduction in energy intensity	EIA, Table 5, Energy intensity by state[6]	None
Reduction in energy-related CO_2 intensity	EIA, Table 7, Carbon intensity of the economy by state[7]	None

Notes:

1 New capacity data are available from https://www.eia.gov/electricity/monthly/xls/table_6_03.xlsx
2 Generation data are available from https://www.eia.gov/electricity/data/state/annual_generation_state.xls
3 All SEDS data are available from https://www.eia.gov/state/seds/sep_use/total/csv/use_all_btu.csv . For technical notes on SEDS data see State Energy Data System 2020 Consumption Technical Notes (https://www.eia.gov/state/seds/sep_use/notes/use_technotes.pdf).
4 Forest area data are available from https://www.fia.fs.usda.gov/program-features/rpa/docs/Forest%20Resources%20of%20the%20United%20States%202017%20Tables%20WOGTR97.xlsx
5 EVALIDator is available at https://apps.fs.usda.gov/fiadb-api/evalidator
6 Energy intensity data are available from https://www.eia.gov/environment/emissions/state/excel/table5.xlsx
7 CO_2 intensity data are available from https://www.eia.gov/environment/emissions/state/excel/table7.xlsx

Table B2 | Mapping from Final Energy Resources and Final Consumption Sectors Used in the China Energy Yearbook and the SEctors Used in the Indicators

Energy Source	Agri-culture	Industry	Const-ruction	Trans-port	Trade	Others	Resi-dential
Raw coal	I	I	I	T	B	B	B
Cleaned coal	I	I	I	T	B	B	B
Other washed coal	I	I	I	T	B	B	B
Briquettes	I	I	I	T	B	B	B
Gangue	I	I	I	T	B	B	B
Coke	I	I	I	I	I	I	I
Coke oven gas	I	I	I	I	I	I	I
Blast furnace gas	I	I	I	I	I	I	I
Converter gas	I	I	I	I	I	I	I
Other gas	I	I	I	I	I	I	I
Other coking products	I	I	I	I	I	I	I
Crude oil	I	I	I	I	T	T	T
Gasoline	T	T	T	T	T	T	T
Kerosene	I	I	I	T	B	B	B
Diesel oil	I	I	I	T	T	T	T
Fuel oil	I	I	I	T	T	T	T
Naphtha	I	I	I	T	I	I	I
Lubricants	I	I	I	T	I	I	I
Paraffin waxes	I	I	I	T	I	I	I
White spirit	I	I	I	T	I	I	I
Bitumen asphalt	I	I	I	T	I	I	I
Petroleum coke	I	I	I	T	I	I	I
Liquefied petroleum gas	I	I	I	T	B	B	B
Refinery gas	I	I	I	T	I	I	I
Other petroleum products	I	I	I	T	I	I	I
Natural gas	I	I	I	T	B	B	B
Liquefied natural gas	I	I	I	T	B	B	B
Heat	I	I	I	T	B	B	B
Electricity	I	I	I	T	B	B	B
Other energy	I	I	I	T	B	B	B

Notes: In some cases, the columns here use shorthand. For those sectors, the longer descriptions include: Agriculture = Agriculture, Forestry, Animal Husbandry and Fishery; Transport = Transport, Storage and Post; Trade = Wholesale and Retail Trades, Hotels and Catering Services. In the table: I = industry, T = transportation, B = buildings.

Table B3 | Heating Values Used to Translate Physical Units to Energy Units		
Energy Source	**Units**	**Heating Value**
Raw coal	tce/ton	0.78
Cleaned coal	tce/ton	0.78
Other washed coal	tce/ton	0.54
Briquettes	tce/ton	0.61
Gangue	tce/ton	0.54
Coke	tce/ton	0.97
Coke oven gas	tce/10^4 m^3	5.71
Blast furnace gas	tce/10^4 m^3	1.29
Converter gas	tce/10^4 m^3	0.03
Other gas	tce/10^4 m^3	1.79
Other coking products	tce/ton	1.15
Crude oil	tce/ton	1.43
Gasoline	tce/ton	1.47
Kerosene	tce/ton	1.47
Diesel oil	tce/ton	1.46
Fuel oil	tce/ton	1.43
Naphtha	tce/ton	1.50
Lubricants	tce/ton	1.41
Paraffin waxes	tce/ton	1.36
White spirit	tce/ton	1.47
Bitumen asphalt	tce/ton	1.31
Petroleum coke	tce/ton	1.05
Liquefied petroleum gas	tce/ton	1.71
Refinery gas	tce/ton	1.57
Other petroleum products	tce/ton	1.33
Natural gas	tce/10^4 m^3	12.76
Liquefied natural gas	tce/ton	1.76
Heat	tce/10^8 m^3	3.41
Electricity	tce/10^4 kWh	1.23
Other energy	tce/tce	1.00

Notes: Tce is tons coal equivalent, a standard measure equal to 7,000 kilocalories (kCal).

Table B4 | Data Sources and Notes for China Indicators

Indicator	Data Source	Notes
Share of new non-fossil fuel capacity in total new generation capacity	China Energy Yearbook, new generation capacity by province (分地区新增发电装机容量)	Data only goes back to 2012
Share of non-fossil fuel electricity generation in total generation	China Energy Yearbook, provincial electricity generation (分地区发电量)	None
Share of non-fossil fuel energy in residential and commercial final energy consumption	China Energy Yearbook, provincial energy balance tables (地区能源平衡表)	See text above for details on sector classification and converting between physical and energy units.
Share of non-fossil fuel energy in industrial final energy consumption	China Energy Yearbook, provincial energy balance tables (地区能源平衡表)	See text above for details on sector classification and converting between physical and energy units.
Share of non-fossil fuel energy in transportation final energy consumption	China Energy Yearbook, provincial energy balance tables (地区能源平衡表)	See text above for details on sector classification and converting between physical and energy units.
Annual increase in forest area as a share of total land area	National Statistical Yearbook, forestry conditions by province (分地区森林资源情况)	None
Annual increase in forest volume per forest area	National Statistical Yearbook, forestry conditions by province (分地区森林资源情况)	None
Reduction in energy intensity	Energy data are from China Energy Yearbook, provincial energy balance tables (地区能源平衡表); GDP data are from National Statistical Yearbook, provincial GDP (地区生产总值)	Nominal GDP was converted to 2015 real GDP using a GDP deflator for China from the World Bank's World Development Indicators, https://databank.worldbank.org/
Reduction in energy-related CO_2 intensity	CO_2 data are from Carbon Monitor China, https://cn.carbonmonitor.org/; GDP data are from National Statistical Yearbook, provincial GDP (地区生产总值)	Nominal GDP was converted to 2015 real GDP using a GDP deflator for China from the World Bank's World Development Indicators, https://databank.worldbank.org/