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on China's Carbon Neutrality

ELECTRIFICATION IN CHINA'S CARBON NEUTRALITY PATHWAYS

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FOREWORD

Since President Xi Jinping announced the carbon neutrality goal in September 2020, the world has experienced persistent ups and downs. Under the new dynamics, China reiterates its unwavering goal of achieving carbon neutrality before 2060. In 2021, China has submitted an updated version of nationally determined contributions with strengthened targets, set out the Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy, and shaped the "1+N" policy framework guiding the nationwide carbon peaking and neutrality actions.

As a non-profit charitable organization, Energy Foundation China (EF China) has been dedicated to promoting prosperity through safe and sustainable energy since its establishment in 1999. It has been consistently and strategically supporting research and policymaking that target a carbon-neutral future. To better inform the formulation and implementation of China's Mid-Century Strategy, EF China established its flagship Long-Term Strategy for Decarbonization Task Force (LTS) in 2018, committed to exploring a multi-win low GHG emission development path for China. We hope this effort will help put China onto a trajectory of sustainable prosperity and carbon neutrality.

Up to today, the LTS has initiated three flagship projects (LTS I, II, and III), engaged more than 30 top Chinese think-tanks in over 50 high-level research projects, and formed a comprehensive research landscape covering all important sectors and thematic areas in China's decarbonization action. Encouraged by the success of the LTS I which presented an overall framework of China's carbon neutrality pathways in 2020, we continued deepening it by shifting its focus to China's low-carbon transformation implementation roadmap for 2035 in LTS II, and to the technology and innovation supporting carbon neutrality in LTS III. In parallel, to introduce international perspectives, EF China has continued to collaborate with leading international think-tanks, including International Energy Agency (IEA), the International Institute for Applied Systems Analysis, University of Maryland, Joint Research Centre (European Union), Potsdam Institute for Climate Impact Research (PIK), Netherlands Environmental Assessment Agency (PBL), 2050 Pathway Platform, and Lawrence Berkeley National Laboratory, in LTS modeling and technical discussions. These frequent exchanges have empowered and served the field of climate and energy research and created a multilateral open intellectual platform for wider cooperation. Meanwhile, EF China has organized international advisory roundtables and Economists Dialogues to underpin the strategic position of carbon neutrality in China's policymaking and to facilitate the development and mainstreaming of Carbon Neutrality Economics. Last but not least, the LTS Task Force has extended its working scope to support subnational decarbonization research and pilots in more than 15 cities and provinces, with the purpose to explore and demonstrate high-quality economic growth models that are compatible with the carbon neutrality vision.

In 2020, we proudly launched our first synthesis report featuring comprehensive views of China's new growth pathways toward a success in meeting the 2060 pledge and its long-term development goals. The report maps out the broad outlines of decarbonization and identifies key elements of strategy across the economy and within individual economic sectors. Regarded as one of the five pillars (electrification, energy efficiency, power decarbonization, low carbon fuel substitution, and carbon dioxide removal) to achieve carbon neutrality, electrification, coupled with power system decarbonization, presents not only a feasible option to reach substantial emissions reduction in electricity more quickly than in other sectors but also an opportunity to curb, and eventually reduce final energy consumption. Therefore, EF China has decided to proceed ahead with the deep-dive research into the role of electrification in China's grand carbon neutrality landscape, and the dynamics of the double transitions of the end-use sector and power sector.

Today, we are even more excited to release our second synthesis report of the series. It is a collaborative achievement of 9 leading international research and modeling teams in climate change and has gathered a pool of experts to review and consolidate the outcome. This report dives into the role of electrification and the associated electricity system transformation in achieving China's carbon neutrality goals, and identifies sectoral near-term actions and long-term strategies that reflect technology availability, regional disparity, and economic costs. The proposed immediate action, long-term strategy, and policy frameworks will accelerate the electrification and power sector decarbonization and put China on a successful, low-emissions growth pathway.

We stand in a time mixed with opportunities and challenges, competition and cooperation. Sustained research is needed to facilitate China's decarbonization and economic transition and EF China will continue supporting such endeavor. We will genuinely and unremittingly pursue multi-win solutions with all partners to create, develop, and share a sustainable future and to help narrate China's "New Growth Story" .

Here, I sincerely congratulate the author team on this marvelous triumph and thank all the expert friends for their continued and wholehearted support of EF China's development. I would also like to thank EF China's dream team, without whose efforts this gift cannot come so alive. Thank you!

Zou Ji

Zou Ji

CEO & President of Energy Foundation China

TABLE OF CONTENTS

LIST OF FIGURES

01 INTRODUCTION

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In September 2020, President Xi pledged that China would peak its carbon dioxide (CO_2) emissions before 2030 and achieve carbon neutrality before 2060. In April 2021, he announced China's plan to strictly limit the increase in coal consumption over the 14th Five Year Plan (FYP) and phase it down in the 15th FYP. In September 2021, President Xi made further pledges that China would stop building new coal-fired power plants overseas. Throughout 2021, President Xi and other high-level Chinese officials reiterated and reinforced China's commitment to the "30/60" goals on multiple occasions, signaling the country's intention to accelerate low-carbon transition.

These pledges communicate a serious commitment to climate change mitigation. But, like other countries moving forward on climate, the pathway to reach these goals is not free of obstacles or choices about which of many different possible roads China should take. Many of these obstacles are present today, as China implements its 14th FYP and perceives its 15th and subsequent FYPs on the horizon.

Energy security is one of the top priorities of China's development strategy. Current world events pose new challenges to China's energy and economic development. In the wake of the Russia-Ukraine conflict, global energy markets are in turmoil with rising oil and gas prices. China, as an energy importer, has been experiencing higher energy costs and commodity prices. Domestically, China has struggled with several power shortages in 2021 and 2022, making stable and reliable energy supply the country's prime concern.

Meeting China's climate pledges will require significant energy system transition. Ensuring energy security in this transition is a key priority. Electrification is a core part of China's pathway to carbon neutrality. Electrification of end-use sectors, coupled with demand-side measures and power system decarbonization, can help achieve a low-emissions future while promoting energy security. As the Chinese electricity mix is currently quite carbon intensive, transitions in end-use sectors and the electricity system need to go hand in hand. By replacing fossil fuels in buildings, industry, and transportation with electricity generated from low- or zero-emissions fuels, significant CO_2 emissions reduction can be achieved. Meanwhile, modernizing the grid system and using more indigenous renewable resources in electricity generation can foster a flexible and reliable power system and improve energy security.

This report is the second in a series of multi-institution reports that assess China's carbon neutrality transition. The first report, published in 2020, highlights China's pathways towards carbon neutrality and transitions throughout the economy. This report provides an overview of China's new policies and energy and emissions trends since 2020. It also conducts deep dives into the role of electricity and focuses on the double transitions of electrifying end-use sectors and decarbonizing the electricity sector to achieve China's carbon neutrality target. It is developed based on new, multi-model, multi-institution analyses, deep-dive working papers on specific sectors, and an assessment of existing research (Box 1.1). It aims to: explore integrated strategies for China's carbon neutrality transition, provide an updated understanding of pathways to carbon neutrality; present and synthesize both existing and new transition scenarios from multiple modeling and research teams; assess recent policy development in China; and analyze the alignment between China's near-term policy targets and its long-term goals. This report particularly highlights the role of electrification and associated electricity system transformation in achieving China's "30/60" goals and identifies a set of near-term sectoral actions and long-term sectoral strategies that can be taken to accelerate electrification and power sector decarbonization to put China on a successful, low-emissions growth pathway.

BOX 1.1: ANALYSES USED IN THIS REPORT

This report synthesizes a number of quantitative analyses from national and global models, including China DREAM, China TIMES, GCAM-China, MESSAGEix-China, AIM-China, PECE_LIU_2021, and PECE V2.0 (see Table B1.1 for detail). Participating models conduct analyses based on two coordinated scenarios: *Updated Nationally Determined Contribution (NDC) to Carbon Neutrality* and *Original NDC to Carbon Neutrality*. These scenarios achieve net-zero greenhouse gas emissions by 2060, but have different peaking times (see Section 3.1 for detailed scenario description). We do not attempt to harmonize assumptions across models, and the results shown in this report reflect model-specific interpretation of socioeconomic and technological development in China. Building on these modeling analyses, teams also developed deep-dive analyses to address key issues and technology options for electrification in different sectors. These deep-dive papers include provincial-specific renewable energy investment needs, stranded assets and credit risks in China's coal power transition, and electrification and transition strategies in industry, transportation, and buildings. Insights from these deep-dive papers are synthesized in this report to provide additional sectoral, spatial, and technological granularity to the analyses. These deep-dive papers are published with this report to provide additional context and information.

TABLE B1.1: SUMMARY OF PARTICIPATING MODELING TEAMS

Model Name	Organization	Spatial Resolution	Modeling Methods	Scenarios Modeled	Gases Modeled[1]	Documentation/ Source
GCAM-China	Pacific Northwest National Laboratory (PNNL) / University of Maryland (UMD)	Global (China is an independent region in GCAM)	A dynamic recursive model that represents the behavior of, and interactions between, five systems: the energy system, water, agriculture and land use, the economy, and the climate.	Updated NDC to Carbon Neutrality; Original NDC to Carbon Neutrality	CO_2 FFI, CO_2 AFOLU, CH_4, F-Gases, N_2O	(GCAM, 2022); (Calvin et al., 2019)
AIM-China	Beijing University of Technology	National	The currently used models and methods include: computable general equilibrium model; the dynamic economic model; the partial equilibrium model; the minimum cost optimization model, based on linear programming techniques described in detail and industry simulation models.	Updated NDC to Carbon Neutrality; Original NDC to Carbon Neutrality	CO_2 FFI, CO_2 AFOLU, CH_4, F-Gases, N_2O	(IPAC, 2020)

[1] CO_2 FFI refers to Fossil-Fuel Combustion and Industrial Process emissions, CO_2 AFOLU refers to Agriculture, Forestry and Other Land Use.

Model Name	Organization	Spatial Resolution	Modeling Methods	Scenarios Modeled	Gases Modeled[1]	Documentation/ Source
MESSAGEix-China	International Institute for Applied Systems Analysis (IIASA)	Global (China is an independent region)	Global systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development.	Updated NDC to Carbon Neutrality; Original NDC to Carbon Neutrality	CO_2 FFI, CO_2 AFOLU, CH_4, F-Gases, N_2O	(IIASA, 2021); (Huppmann et al., 2019)
China DREAM	Lawrence Berkeley National Laboratory (LBNL)	National	A bottom-up national energy system model whose primary drivers include physical and socioeconomic activity, energy intensity, and technology trends, built using the Low Emissions Analysis Platform (LEAP).	Updated NDC to Carbon Neutrality	CO_2 FFI, CH_4, and N_2O	(LBNL, 2022)
China TIMES	Tsinghua University	National	A dynamic linear programming energy system optimization model used for near- and long-term energy system analysis and climate change mitigation pathway development.	Updated NDC to Carbon Neutrality; Original NDC to Carbon Neutrality	CO_2 FFI	(S. Zhang & Chen, 2022)
PECE_ LIU_2021	Harbin Institute of Technology, Shenzhen; Renmin University of China	National	A national energy system model which focuses on China's long-term low-carbon transition roadmap for climate targets, built in Low Emissions Analysis Platform (LEAP)	Updated NDC to Carbon Neutrality; Original NDC to Carbon Neutrality	CO_2 FFI, CO_2 AFOLU	(J. Liu et al., 2021)
PECE V2.0	Energy Foundation China; Renmin University of China	National	An integrated energy system model, which is based on partial equilibrium framework and quantifies the future energy demand, supply, and emissions.	Updated NDC to Carbon Neutrality; Original NDC to Carbon Neutrality	CO_2 FFI, CO_2 AFOLU, CH_4, F-Gases, N_2O	(Fragkos et al., 2021)

02 RECENT DEVELOPMENT IN CHINA'S CLIMATE POLICIES

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2.1 RECENT SOCIOECONOMIC, ENERGY, AND EMISSIONS TRENDS

Changing Economic, Energy, and Emissions Trends Since 2020

Starting in 2020, the Chinese economy has entered a new era marked by the "Dual Circulation" strategy (Xinhuanet, 2020). This strategy emphasizes both expanded domestic markets (domestic circulation) and growing exports (international circulation). The carbon neutrality goal aligns with the "dual circulation" strategy of greater self-reliance through more clean energy resources and advanced clean technologies and facilitates China's complete transformation in both the economy and the energy system. In the past years, new trends in China's energy sector have been observed, including fast renewable expansion, an uptick in coal consumption, and a relatively steep increase in carbon emissions.

With growing additions of renewables, China's dependence on coal has declined in recent years. China is the world's biggest energy producer and consumer since 2009 and relies heavily on coal. In 2021, coal still supplied 56.0% of China's total energy consumption of 5.24 billion tonnes of standard coal equivalent (SCE), compared to 72.4% of 2.61 billion tonnes in 2005 (NBS, 2022c). Meanwhile, China's renewable energy capacity has expanded rapidly in recent years. China had a record expansion of renewables in 2020, a rapid expansion that continued during 2021, when the grid-connected wind power generation went up by 40.5% and solar power generation rose by 25.2%, compared to 8.4% increase of thermal power (CEC, 2022a). Moreover, China installed slightly below 17 GW of offshore wind capacity in 2021, compared to 3 GW in 2020, an extraordinary expansion before the expiration of feed-in tariffs, making it operate almost half of the world's installed offshore wind (CPNN, 2022). At the end of June 2022, China had 2,446 GW of installed power capacity, of which, hydropower, wind power, and photovoltaic (PV) reached 400 GW, 342 GW and 336 GW, respectively, ranking the highest across the world (CEC, 2022c). The amount of renewable power generation (including hydropower and biomass) in China reached 2,480 TWh, accounting for 29.7% of the annual power generation in 2021 (The State Council, 2022b).

China's impressive growth in renewables is expected to well exceed the government's Nationally Determined Contribution (NDC) target of over 1,200 GW installed solar and wind power capacity by 2030. Since August 2021, the government has ended the central subsidies for new photovoltaic power projects and onshore wind projects. Stepping into the post-subsidy era for renewables, the National Development and Reform Commission (NDRC) announced its first batch of clean energy bases (large-scale solar and wind energy projects) for 97 GW in November 2021 and revealed the second batch of 455 GW in February 2022, concentrated in the resource-rich desert area in northern China. In total, China nearly added 54.8 GW new renewable electricity generation capacity, accounting for 80% of the total newly-installed power generation capacity in the first half of 2022 (NEA, 2022a). Along with the national-level projects, provincial-level targets and project pipeline installation reflect a far more aggressive deployment pace than the NDC target. Based on progress to date, China's 1,200 GW target will be met years earlier than 2030.

The rapid expansion of renewable energy and related up- and down-stream industries (manufacturing, installation, etc.) have become China's new growth drivers and created numerous job opportunities (CCICED, 2022). As the largest producer of wind and solar energy, China claims the bulk of worldwide renewable energy related employment. With 5.37 million jobs in 2021, China accounts for 42.3% of total renewable energy employment worldwide (IRENA & ILO, 2021). Furthermore, China is the dominant producer of components for batteries and the largest market for electric vehicles (EVs) as well. In 2021, new energy vehicles (NEVs) sales totaled 3.52 million, including electric vehicles (BEVs) (82.8%), plug-in hybrids (17.1%), and fuel cell vehicles (0.1%), an increase of 160% compared to 2020 (MIIT, 2022). China's EV market currently accounts for more than 50% of new EV sales globally. With an average 13.4% penetration rate of EVs in 2021, China has set national targets to reach 20% by 2025 and 40% by 2030. In the first half of 2022, the penetration rate of NEVs has already exceeded the target and reached 21.6% (CAICT, 2022). China's EV industry has been and is expected to continue to trigger industry-wide changes and spark economic growth and job creation. Although China's hydrogen industry is in an early stage of development, the rising awareness of the importance of hydrogen at both the national and local levels has created a favorable environment for the hydrogen industry to boom in the near future. By 2050, hydrogen is expected to make up 10% of China's energy mix, with an output value of $1,772 billion (CHA, 2020).

The outbreak of Covid-19 led to more fluctuations in China's energy consumption and emissions. With a strict lockdown and plummeting output in early 2020, both energy use and emissions temporarily fell, and China's economy hit a historical low growth rate (2.2% in 2020) in more than four decades. The government implemented a new infrastructure investment and business-oriented stimulus package to boost the economy, and China's economy saw a strong rebound, achieving 8.1% growth for 2021, the fastest in nearly a decade (The State Council, 2022a). As a result, emissions rose in 2021, and, according to IEA's estimate, China's energy sector CO_2 emissions increased by 750 Mt over the two-year period between 2019 and 2021(IEA, 2022a). Another COVID-19 outbreak in early 2022 (especially in Shanghai and Beijing) exacerbated weak household consumption and worsened the troubled real estate market. China's economy grew by just 0.4% in the second quarter and only 2.5% in the first half, far below the official yearly goal of 5.5% in 2022 (NBS, 2022b). Energy consumption and emissions appear highly likely to remain high in 2022 as a result of strong coal consumption, even in the context of the continued real estate slowdown and fast expansion of renewables.

Entering 2022, the Russia-Ukraine crisis has exerted both short- and long-term impacts on China's energy industry. China's crude oil imports from Russia hit a record level in 2022, as refiners bought up discounted Russian supplies. High global energy prices caused by the crisis and slower energy demand growth have resulted in China's lower energy imports. China's natural gas imports were down by 10% in the first six months of 2022, compared to the same period in 2021; crude oil down by 3.1%, and coal down by 17.5% in the same period (China Economic Net, 2022). The government has boosted domestic coal production to ensure supplies and energy security in a tight global market. Raw coal output reached 2.19 billion tonnes, up 11.0% over the first half of 2022 (China Economic Net, 2022). Also as a result of demand for electric vehicles booming globally and the crisis's impact on commodity markets, the market price of battery-grade lithium carbonate has risen outrageously (the price as of June 2022 was almost six times higher than in June 2021), placing a financial strain on battery manufacturers and hindering China's adoption of EVs. A similar situation with silicon, a major material used in PV equipment, threw another price shock to China's PV market. Since the beginning of 2021, silicon has seen prices tripled, due to the rising demand from downstream PV manufacturers driven by the rapid PV expansion, supply-side disruption of China's "Dual-control" policy (control the high energy use and high emissions projects), and the crisis's impact. The silicon price increase slowed the expansion of production capacity in the PV industry and further caused the total installed capacity of new PV projects in 2021 to be less than the expected.

Owing to the rebound in coal use, China's carbon emissions have reached a record high in 2021 and may enter a carbon emissions plateau in the next few years. Driven by economic growth, China's carbon emissions had been on an upward track since the 1990s until 2013, when it reached a plateau. However, since 2017, coal consumption has witnessed an uptick, as the Chinese economy faced headwinds and the government sought to stimulate industrial growth. As of 2020, China's greenhouse gas (GHG) emissions reached around 13 $GtCO_2$-equivalent (CO_2-eq), equating to 9 tCO_2-eq per capita. This accounts for about a quarter of global emissions, up from 10.2% in 1990. Nevertheless, the carbon intensity of GDP dropped from a peak of nearly 810 gCO_2 in 2005 to 450 gCO_2 over the year 2020 (IEA, 2021a, 2021b). With rapid GDP growth and strong export performance, electricity demand in China grew by 10.3% in 2021, faster than economic growth of 8.1% (CEC, 2022a). Half of the 790 TWh increase in electricity demand was met by coal, and China's CO_2 emissions (fossil fuel and industry, FFI) had reached a record high of 11.9 billion tonnes, accounting for 33% of the global total in 2021 (IEA, 2022a). Over the next few years, significantly growing renewable power will probably outstrip coal and become the dominant source to meet the rise in electricity demand.

Regional Disparity in Energy Deployment and Emissions

China is a vast country characterized by huge regional disparity. While Beijing and other places have already entered the carbon emissions plateau period, northwestern provinces such as Ningxia, Xinjiang, and Inner Mongolia have witnessed a fast emissions growth in the past decade. As of 2021, Jiangsu, Guangdong, and Henan are the leaders in wind capacity addition; while the top three provinces of China's new installed solar capacity are Shandong, Hebei, and Henan (NNECM, 2022).

Going back to 2021, although the decision-makers emphasize carbon peaking and carbon neutrality plans to be hierarchical and orderly, planning and implementation vary across local governments. Under the current "Dual-control" mechanism, aimed at reducing energy intensity and limiting total energy consumption, some provinces curb dual-high projects and resort to power rationing to meet Dual-control targets. This partially results in a shortfall in coal and power supply. At the same time, the reopening of the global economy after the pandemic brought about a surging demand for China's export industries and the corresponding increased electricity demand, which coincided with the shortfall in coal supply and pushed up coal prices and costs of generating electricity. As the government strictly controls electricity prices, coal-fired power plants are reluctant to operate at a loss, hence many have reduced their output. China encountered a severe shortage of electricity that started in the summer in 2021 and rippled across most of eastern China. Energy-intensive industries, such as cement, steel, and aluminum smelting are among the industries most hit by the power outages. Silicon prices were also affected by the lack of power supply. To guarantee winter heat and power supplies, the NDRC had adopted a series of measures to lower down the record-high coal prices. Coal producing companies are ramping up production, and coal-fired power plants are expanding coal procurement channels. The boost in coal production puts the production of raw coal at a record high of 4.07 billion tonnes for past years. Coal consumption as of 2021 has nearly reached the previous coal consumption peak in 2013 of 4.24 billion tonnes (NBS, 2022a).

There exists a large spatial mismatch between supply and demand of renewable energy in China. Most renewable energy sources are located in the northwest, while the highest power demand is in the southeast. This geographical mismatch, combined with the limited grid connections from renewable energy power plants to the electricity grid, underdeveloped cross-regional power transmission grids, lack of power trading systems across provinces, and restricted energy-storage facilities, has resulted in the continued curtailment (deliberate reduction in output) of renewables and further hindered renewables development. As of the end of 2021, the wind curtailment rate – the ratio of curtailed electricity to total wind generation – exceeded 10% in Qinghai. The PV curtailment rate reached almost 20% in Tibet and nearly 14% in Qinghai (NNECM, 2022).
In addition, as the government speeds up the construction of clean energy bases concentrated

mainly in northern China, fast expansion of the transmission capabilities connecting energy sources in the northwest with power-hungry needs in the east is becoming increasingly challenging.

2.2 RECENT POLICY DEVELOPMENT

2021 is the first year of China's 14th Five-Year Plan (2021–2025). It also marks the first year of the nationwide endeavor to peak carbon emissions since President Xi's announcement of the dual carbon, "30/60", goals at the 75th session of the United Nations General Assembly in September 2020. Throughout 2021, the political will in advancing the dual-carbon agenda has remained high. Important policy signals have been announced at national and international meetings, and the "1+N" series of policies directing carbon neutrality and carbon emissions peaking efforts were released.

Political Commitment to Climate Action

Throughout 2021, the political will to marshal the entire nation to peak carbon emissions and reach carbon neutrality has stayed strong. President Xi and other high-level national officials reiterated and reinforced China's firm dedication to "30/60" goals in multiple important international events and venues. These goals are also reflected in China's updated NDC and Long-term Strategy. Domestically, the integral role of carbon peaking and carbon neutrality in achieving overall prosperity for China have also been emphasized on several high-level political occasions. For example, a top-level "Leaders Group on the Works of Carbon Peaking and Carbon Neutrality" headed by Vice Premier Han Zheng and consisting of heads of ministries involved in the work of peaking carbon emissions and reaching carbon neutrality, has been formed (You, 2021). Serving as the high-level coordinator in climate neutrality, the Leaders Group holds regular plenary meetings to review progress and emphasizes priorities in achieving the climate goals (Boer, 2022; Xinhuanet, 2021a).

Entering 2022 the Russia-Ukraine conflict and its ramifications for the global energy supply have shaped the political agenda for co-prioritizing securing energy supply and achieving carbon neutrality. It was emphasized during the 13th National People's Congress that, while taking proactive and prudent steps to advance dual carbon goals, China must also ensure the security of energy, food, and industrial and supply chains, echoing previous policy signals sent at a Politburo session earlier this year (Bloomberg News, 2022; Global Times, 2022). In addition, under the bleak macroeconomic climate, the green economy that is closely associated with carbon neutrality is believed to be the new growth engine, which, in turn, enhances the political will at the highest levels to commit to climate actions.

The "1+N" Policy Framework

In October 2021, China announced a "1+N" policy framework for carbon peaking and carbon neutrality, which consists of a series of implementation plans for CO_2 emissions in key sectors and areas with a variety of supporting policies (MEE, 2021c). On the eve of the 2021 United Nations Climate Change Conference, the highest-level guiding document for China's climate action, *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy* (referred to as *Working Guidance*) was published by Central Committee of the Chinese Communist Party and State Council, setting out the fundamental principle of the country's future development. This document is known as the "1" in "1+N" policy framework (Xinhuanet, 2021b). The *Working Guidance* sets high-level goals for crucial energy and carbon indicators by 2025, 2030, and 2060 (Table 2.1). Closely following the *Working Guidance*, China submitted its updated NDC and China's Mid-Century Long-Term Low

Greenhouse Gas Emission Development Strategy, outlining the new goals and measures for climate change mitigation and adaptation and reaffirming the aforementioned climate targets.

TABLE 2.1: GOALS SET IN THE *WORKING GUIDANCE FOR CARBON DIOXIDE PEAKING AND CARBON NEUTRALITY*.

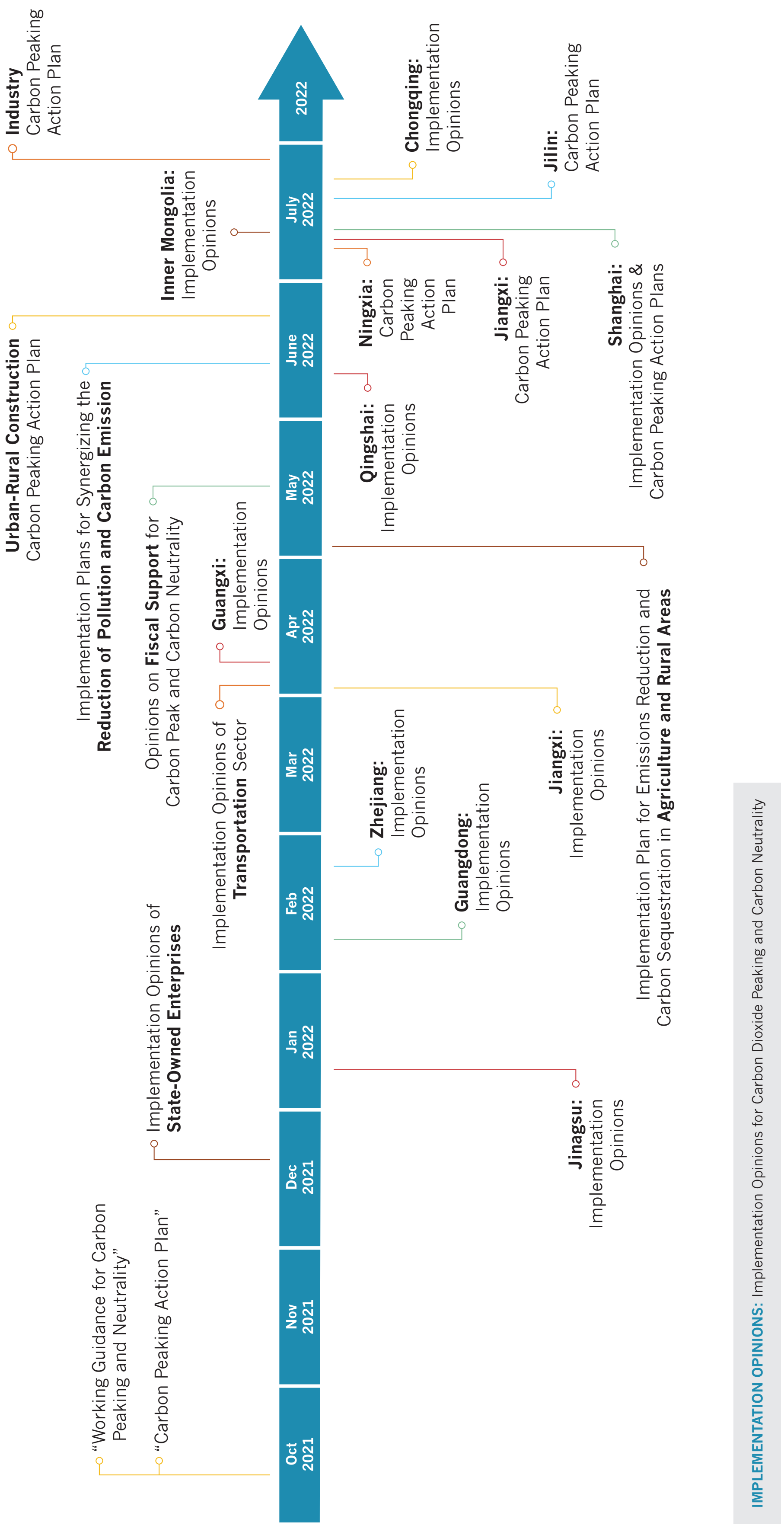
	Goals
2025	▸ To establish an initial framework for a green, low-carbon, and circular economy. ▸ To greatly improve energy efficiency of key industries. ▸ To reduce energy consumption per unit of GDP by 13.5% compared to 2020 level. ▸ To decrease carbon dioxide emissions per unit of GDP by 18% compared to 2020 level. ▸ To increase the share of non-fossil energy consumption to around 20%. ▸ To increase forest coverage to 24.1% and to increase forest stock volumes to 18 billion m^3.
2030	▸ To align energy efficiency in key energy-consuming industries with international levels. ▸ To significantly reduce energy consumption per unit of GDP. ▸ To decrease carbon dioxide emissions per unit of GDP by over 65% compared to 2005 level. ▸ To increase non-fossil energy consumption to around 25%. ▸ To increase total installed capacity of wind and solar power to over 1,200 GW. ▸ To increase forest coverage to 19 billion m^3. ▸ To peak and to reach the plateau of carbon emissions, and carbon emissions start to decline.
2060	▸ To increase the share of non-fossil energy consumption to over 80%. ▸ To achieve carbon neutrality.

Soon later, a nation-wide carbon peaking action plan describing how China intends to peak its carbon emissions by 2030, known as the *Action Plan for Carbon Dioxide Peaking Before 2030* (referred to as the *Action Plan* below), was announced (Xinhuanet, 2021c). It is regarded as the first in the "N" series of policy, including the major actionable areas in the endeavor for peaking carbon emissions. The "1+N" policy framework emphasizes that China's carbon mitigation action should take a whole-of-nation approach that features a balance between development and emissions reduction, between overall and local imperatives, and between short-term and long-term considerations. Guarding against risks is also highlighted in the *Working Guidance,* in line with the recent change of tone on coal-related policies during the first half of 2022 .

Into 2022, sectoral and thematic plans have been subsequently released to support carbon peaking action under the guidance of the Leadership Group, putting the "N" framework into shape. As outlined in Figure 2.1 below, sectoral plans have been sequentially released for industry, urban-rural construction, and agriculture and rural regions, while the mitigation efforts of the transportation sector are guided by a high-level implementation opinion on achieving the dual carbon goals. Also, guidelines to mobilize fiscal instruments and policies to achieve dual carbon goals and to synergize carbon reduction with pollution abatement have been released. Research into and drafting of action plans for iron and steel, petrochemicals, non-ferrous metal, electricity, oil, and gas are in full swing and might be unveiled in the coming months (NDRC, 2021a). Additional enabling policies are on the way for instance, the action plan for using science and technology to support carbon emission peaking and carbon neutrality will be published by NDRC in the near future (NDRC, 2021b).

FIGURE 2.1: TIMELINE OF "1+N" POLICIES RELEASED BY JULY 2022.

By announcement time



Similarly, subnational roadmaps to carbon emission peaking are being developed across the nation. By the end of July 2022, eleven provinces and cities have released their own guiding documents and/or carbon peaking action plans, as displayed on Figure 2.1. The national carbon peaking goal is further broken down and manifested as quantitative targets in the subnational roadmaps, reflecting the overall philosophy of peaking CO_2 emissions hierarchically and in an orderly progression across all regions by promoting green and low-carbon development compatible to local conditions. For example, to unlock the tremendous potential of green finances in the Greater Bay Area, Guangdong province has established a sound and prudent green finance service system to support climate actions and investments that lead to carbon peaking in the province (People's Government of Guangdong Province, 2022). With as many as 37 sectoral, industrial, and thematic policies incorporated into the "1+N" framework, the next step will focus on synergistic efforts to advance towards the dual carbon goals and to design and implement detailed rulebooks (L. Zhang, 2022).

Sectoral and Thematic Policy Development

In addition to the aforementioned "1+N" policies, important policies concerning the low-carbon transition at central and local levels that cover a wide range of sectors and cross-cutting topics have been released (see Figure 2.2). Since relevant work was launched years ago, the formulation and release of supporting policies are leading the entire policymaking process, including compulsory GHG emission information disclosure by carbon-intensive enterprises, the yearly updates of green bond endorsed projects catalog, and the development of ecological compensation mechanism (MEE, 2021a, 2021b; PBC et al., 2021). New arrangements of supporting measures have been put into effect to facilitate the entire economy and society to engage actively with low-carbon transition. For example, last November, People's Bank of China rolled out a carbon emission reduction facility to mobilize social capital in the development of clean energy, energy conservation, carbon reduction technologies, and other relevant key action areas (PBC, 2021).

Moreover, it is worth noting that China has put the development of a modern and new power system featuring a high proportion of stable renewable energy and secure grid connection high on its national task list, especially during the 14th FYP period. As shown in Figure 2.2, beginning in May 2021, a series of planning documents have been released to map out the future development of key technologies and components of the new power system, such as expansion of pumped storage hydropower for energy security; hydrogen development as an alternative energy source and energy storage; other new energy storage technologies and projects; and energy pricing reform and interprovincial power trading schemes.

Another milestone was the first anniversary of China's national emission trading scheme (ETS) in July, 2022. Until now, China's national ETS covers 2,162 key emitters in the power sector, which together contribute to 4.5 billion tonnes of CO_2 emissions per year (MEE, 2022b). Over the past year, the cumulative transaction volume of CEA (Carbon Emission Allowance) in the world's largest carbon market reached 194 million tonnes. The cumulative transaction value is around RMB 8.45 billion, with a carbon price fluctuating between 40 to 60 yuan per tonne (MEE, 2022b; K. Wang et al., 2022). The current allowance allocation mechanism is based on emission intensity of emitters rather than an absolute cap on their emission amounts, and only the power sector is included. Parallel to the national market are the subnational ETS pilots, where emitting enterprises in cement, iron and steel, petrochemicals, paper making, and aviation industries conduct transactions to comply with their emission reduction goals (Zeng et al., 2021). During the first and current compliance cycles, China Certified Emission Reductions (CCER) credits were allowed to be used to offset no more than 5% of emissions by each emitting entity, and a cumulative amount of 169 million tonnes were transacted by the end of 2021 (Tan, 2022). As regulations and standards on ecological compensation and environmental equity financing instruments take shape, the national CCER market is likely to be rebooted late in 2022 or in 2023 (Xu, 2022).

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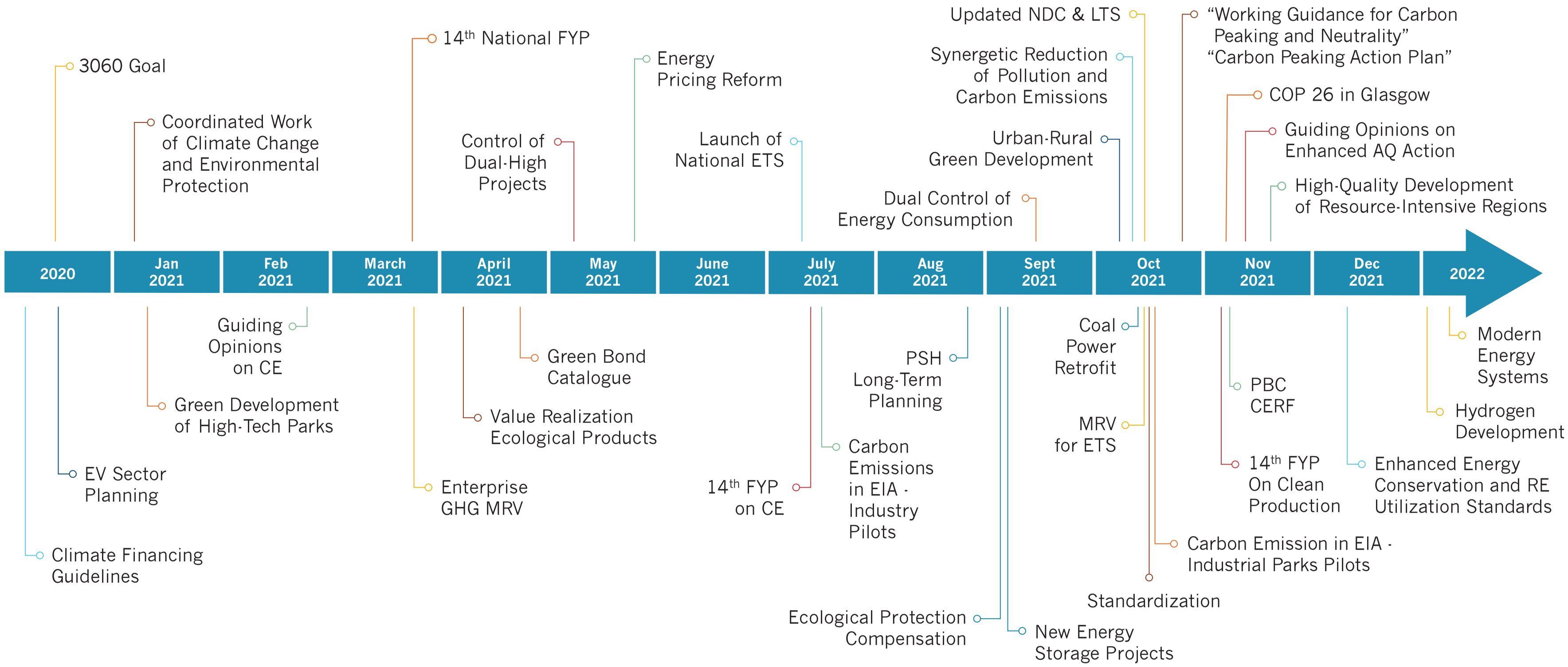
FIGURE 2.2: TIMELINE OF KEY CLIMATE POLICIES RELEASED IN 2021 AND 2022.

By announcement time



RE	Renewable Energy	**CERF**	Carbon Emission Reduction Facility	**CC**	Climate Change
MRV	Measurement, Reporting, and Verification	**CE**	Circular Economy	**EP**	Environmental Protection
ETS	Emission Trading Scheme	**PSH**	Pumped Storage Hydropower	**LTS**	Long-Term Low Greenhouse Gas Emission Development Strategies
EIA	Environmental Impact Assessment	**FYP**	Five Year Plan		
GHG	Greenhouse Gas	**NDC**	Nationally Determined Commitment		
PBC	The People's Bank of China				

Policy Highlights

The *Working Guidance* and *Action Plan* are two of the most high-level documents concerning China's delivery of its climate commitment under the Paris Agreement. These documents highlight an array of policy areas as prioritized working fields in the coming years.

Several new one-of-a-kind policies in China's climate endeavor are proposed. First, a new long-term climate goal: the share of non-fossil energy consumption would be over 80% by 2060, together with accompanying goals to control the consumption of other types of fossil fuels, including the public commitment to peak oil consumption during the 15th FYP (2026–2030).

Second, this marks the beginning of mainstreaming climate change and the low-carbon mindset in overall socioeconomic development, at both national and subnational levels. All medium- and long-term plans should and would incorporate carbon emission peaking and neutrality goals. Specific action plans are formulated in different sectors and subnational territories to promote and guarantee the achievement of the 30/60 goals.

Third, it highlights the critical role played by subnational governments in the ultimate achievement of 30/60 goals. The subnational governance performance evaluation system will incorporate indicators related to peaking carbon emissions and carbon neutrality with great weights assigned. Accordingly, the oversight and assessment of carbon targets will be strengthened and be subjected to the Central Inspections on Environmental Protection. Local authorities have often prioritized economic development over climate and energy goals, and the *Working Guidance* is believed to give them enough political motivation to overturn the economic-focused mindset (Hsu, 2021).

Fourth, the *Working Guidance* underscores the strength of market mechanisms and socioeconomic instruments, particularly stressing the imperative role of investment policies, green finance, and tax, fiscal, and pricing policies. It also, identifies the need to upgrade existing laws and regulations and formulate an auxiliary or supporting policy framework to cover several key areas, such as: deepening energy and power market reform; improving the measurement, reporting, and verification system; containing irrational expansion of dual-high projects; upgrading the standardization system; and promoting a low-carbon lifestyle and working philosophy among the public and businesses.

Finally, the *Action Plan* rolls out ten major action areas that cover almost all key sectors of China's economy, including energy, industry, transportation, residential sector, urban-rural development, and circular economy. For each sector, the *Action Plan* lays out a brief roadmap, with key enablers and leverage points, to reduce energy consumption and shift towards sustainable methods. The holistically-designed *Action Plan* emphasizes that peaking carbon dioxide emissions and achieving carbon neutrality are two society-wide undertakings and should progress in tandem with China's transition to a high-quality growth mode.

Policy and Implementation Gaps

Though a range of restrictive and quantitative targets is set to guide the low-carbon transition, there are not a set of quantitative targets or dwindling cap on total carbon dioxide emissions at either national or subnational/sectoral levels. The current carbon market is not of a cap-and-trade design either. This indicates the absence of a nationwide and political recognition of carbon as a production factor, without which it will be hard for China to plan and implement an orderly peaking of carbon dioxide emissions at subnational and sectoral levels (Caijing, 2021; Gao, 2020; T. Ma, 2020). The absence of these targets is also observed in the previously released 14th FYP and updated NDC. However, releasing quantitative carbon emissions caps in the near future may be on the horizon. In December, the Central Economic Work Conference discussed that China should expedite the shift from an energy-based dual control system to a carbon-based dual control system (Sino-German Cooperation on Climate Change, 2021).

Legislation still lags behind the fast-paced policymaking process in climate action. For example, the Renewable Energy Law and the Energy Conservation Law should be updated to accommodate the new restrictive targets and strict control over dual high projects. More important, a Climate Change Law or Climate Act is needed to grant legal status to the restrictive energy and carbon targets and to strengthen implementation from a law enforcement level. In addition, a Climate Act will also provide a legal basis for the establishment of the national carbon emission cap and facilitate the transition of carbon allowance allocation mechanism from performance-based to a cap on absolute amount by determining the initial allocation of carbon ownership (T. Ma, 2020).

Emissions inventory and a sound MRV (Measurement, Reporting, and Verification) system lay the very foundation of scientific and equitable carbon mitigation action and policies.The most updated official GHG inventory is available only for year 2014. Many sectors (e.g., transportation, industries, and agriculture) are still waiting for a standard MRV manual and inventory methodology to direct real-world MRV practices at all levels, be it sectoral or emitting unit level. Lacking reliable base data has already postponed the expanding of the national carbon market to include other industries, making it an urgent gap to be fulfilled as soon as possible (Tao, 2022). Furthermore, to foster an honest and transparent transaction environment for future scaled up and development, governmental capacity to oversee MRV processes should be enhanced to eradicate data fraud events.

In terms of goal-setting, the "1+N" policy series has put forward clear-cut targets for the 14th FYP (for the year 2025) and the 15th FYP (for the year 2030). The next milestone in the policies jumps to 2060, missing the important year of 2035. According to the 14th FYP and Vision 2035, China should have basically achieved the socialist modernization and the Beautiful China Initiative by then. 2035 marks an important year point for the transition period from peaking. By 2035 China's carbon dioxide emissions would steadily decline after peaking; however, no quantitative and detailed targets for total carbon emission, carbon intensity, total energy consumption, or energy intensity have been specified. The current landscape also lacks quantitative goal-setting for non-CO_2 GHG emissions, such as methane, HFCs, N_2O, PFCs, and SF_6.

Finally, several thematic areas are not given sufficient consideration in the current policy framework. They include cross-sectoral coordination at subnational level, an overall plan for orderly subnational action roadmaps, and enabling policies to take care of stranded assets for retired capacity and vulnerable communities. For example, transition risks became a major concern for subnational governments and sectors that have high dependence on fossil fuels. Yet no specific Action Area is dedicated to exploring and proposing a fair and just transition mechanism to help ease the pain exerted upon certain populations and enterprises, and to guarantee that no one is left behind in China's low-carbon transition.

03 THE PATHWAY TO NET ZERO BEFORE 2060

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To better understand the different pathways for meeting ambitious climate targets, and to determine how near-term policies align with long-term goals, this report evaluated results from seven modeling teams (see Box 1.1) across two different scenarios that are defined by different near-term policy choices. This analysis can help to identify priorities for climate change mitigation policy and outline areas of uncertainties across modeling teams.

3.1 SCENARIOS

This year's report explores two main scenarios designed to assess the implications of reaching net-zero GHGs before 2060[2] (Table 3.1). The scenarios are identical in that they require GHG emissions to reach net-zero in 2060, but they differ in how quickly China's emissions peak before declining to meet 2060 goals. In the *Updated NDC to Carbon Neutrality* scenario, in line with the updated NDC submitted by China to the United Nations Framework Convention on Climate Change in October 2021, China's emissions peak before 2030 (which means, between 2025 and 2030), allowing it to rapidly turn toward the long-term goal. To achieve the earlier peaking, this pathway would call for policies over the coming decade that are more ambitious than those are currently on the books. The *Original NDC to Carbon Neutrality* scenario explores the consistency of current policies that are aligned with China's original NDC submission from 2015 and the long-term goal. In this scenario, current policies are kept in place, and China's CO_2 emissions do not peak earlier than 2030. The majority of this report focuses on the *Updated NDC to Carbon Neutrality* scenario. Model results shown in Chapters 4–9, if not specifically explained, are from the *Updated NDC to Carbon Neutrality* scenario.

TABLE 3.1: SCENARIO DEFINITIONS.

Scenario	Net-Zero GHG Year	Net CO_2 Emissions Peak Year	Alignment with Near-Term Policies
Updated NDC to Carbon Neutrality	2060	Before 2030	Aligns with updated NDC up to 2030
Original NDC to Carbon Neutrality	2060	2030	Aligns with first NDC submission up to 2030

Not all models in this study include all GHGs. For models that only include CO_2 emissions, net CO_2 emissions were assumed to reach zero in 2050 in both scenarios. This assumption is based on the results from the scenarios in this report and in the Synthesis Report 2020, which show that CO_2 emissions will reach zero about ten years before total GHG emissions reach zero. In this sense,

2 In China's Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy, China reiterated the goal of achieving carbon neutrality before 2060. In a speech delivered in 2021, Minister Xie mentioned that China is working towards net-zero GHG emissions by 2060. The target of net-zero GHG emissions by 2060 reflects our understanding of China's long-term climate goals and is consistent with the target of achieving carbon neutrality before 2060.

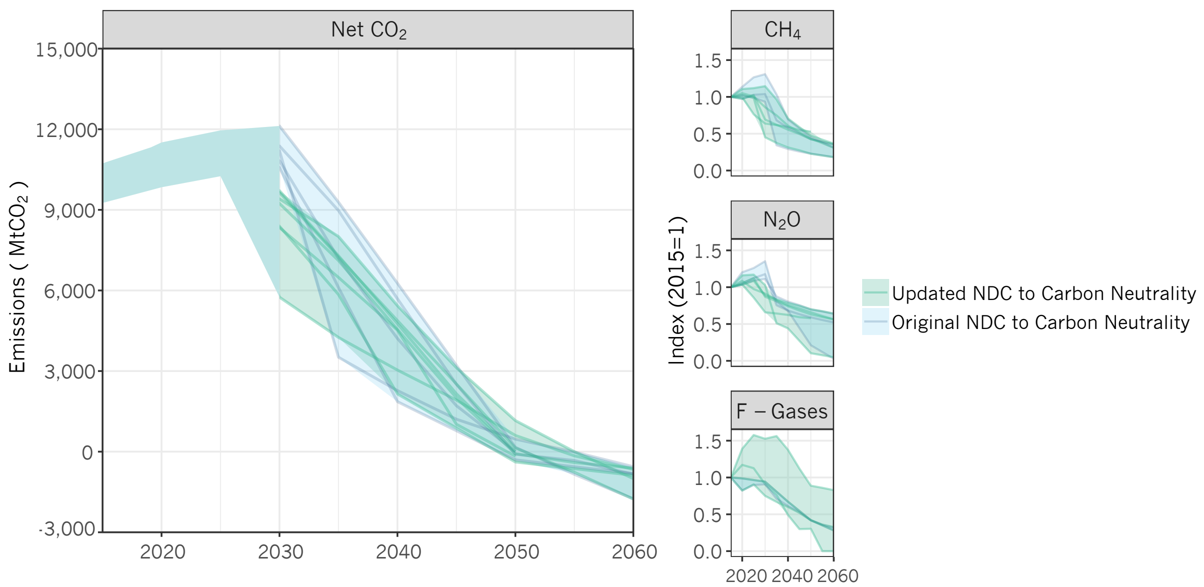
a 2060 net-zero GHG goal is roughly equivalent to a 2050 net-zero CO_2 goal. In addition, China DREAM and China TIMES do not include land-use sector emissions. Instead, they use an estimated amount of -500 $MtCO_2$-eq annually from other sources in their reporting (Forsell et al., 2016). Land-use emissions from other models are either endogenously calculated or calculated based on emissions inventory or domestic expert estimates.

3.2 EMISSIONS PATHWAYS

To achieve carbon neutrality before 2060, as shown by the multi-model results (see Figure 3.1), China needs to peak its CO_2 emissions before 2030 and dramatically reduce emissions afterwards. The peak amount of net CO_2 emissions between 2025 and 2030 is within the range of 10.3–11.7 and 10.5–12.1 $GtCO_2$. China's CO_2 emissions from energy and industrial processes peak around the same time, with the range of 11.0–11.9 and 11.3–12.2 $GtCO_2$ in the *Updated NDC to Carbon Neutrality* and *Original NDC to Carbon Neutrality* scenarios, respectively. China's net CO_2 emissions reach zero around 2050/2055 and get to about negative 0.6–1.8 $GtCO_2$ by 2060 to offset remaining non-CO_2 emissions. In terms of net GHG emissions, China's GHG emissions peak around 2025/2030 at the level of 12.3–14.3 and 12.9–14.7 $GtCO_2$-eq in the *Updated NDC to Carbon Neutrality* and *Original NDC to Carbon Neutrality* scenarios, respectively, and get to around zero by 2060.

FIGURE 3.1: EMISSIONS PATHWAYS TO NET-ZERO GHG EMISSIONS BY 2060.

The left panel shows China's net CO_2 emissions across models in *Updated NDC to Carbon Neutrality* pathways (green) and *Original NDC to Carbon Neutrality* pathways (blue). These two scenarios indicate larger variations in system transition and emissions reduction in the near term across models and between scenarios. The right panels show normalized trajectories (2015=1) of emissions reductions for non-CO_2 GHGs. Absolute emission levels of non-CO_2 GHGs are not used here due to large inventory uncertainties: CH_4 ±30%; N_2O ±60%; F-gases ±30% (Shukla et al., 2022).



Non-CO_2 emissions in China were about 2 $GtCO_2$-eq in 2015. Among them, CH_4, N_2O and F-gases (HFCs, PFCs, and SF_6) account for about 56%, 31%, and 12%, respectively (ICCSD, 2020). The multi-model results show that non-CO_2 emissions peak around 2025-2030. N_2O and CH_4 decline relatively quickly, between 2025/2030 and 2040. The near-term F-gases emissions trend varies across models before 2030, but after 2030, emissions decline rapidly (see Figure 3.2). CH_4 emissions are mainly from coal extraction and from livestock and rice cultivation of the agricultural sector (about 0.54 and 0.47 $GtCO_2$-eq in 2015, respectively) (ICCSD, 2020). In the *Updated NDC to Carbon Neutrality* scenario, driven by the phase-out of coal use in the energy sector and reduction in coal production, CH_4 emissions decrease significantly over time, with 60–80% reduction between 2020 and 2060.

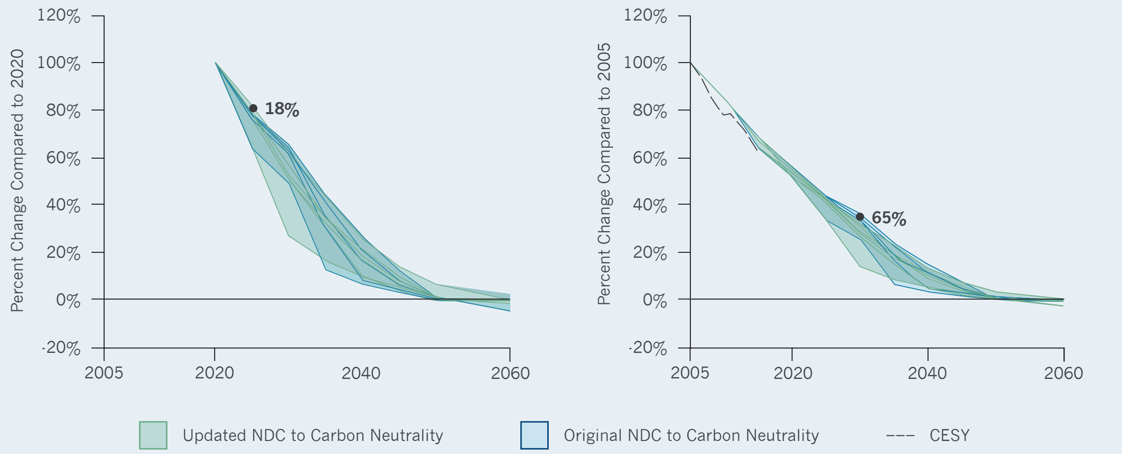
Most of the remaining emissions are from the agricultural sector. N_2O is emitted mainly from fertilizer use, manure management, and certain industrial processes, about 0.6 $GtCO_2$-eq in 2014 (ICCSD, 2020). With more effective use of fertilizer, better manure management, and improved pipeline controlling in related industrial processing, models indicate a range of 45–95% reduction of N_2O emissions between 2015 and 2060. F-gases emissions primarily come from the production processes of refrigerants, blowing agents for foams, etc. There are larger variations across models on F-gases emissions reduction, as models indicate different rates of reduction in HFCs, PFCs, and SF_6. Not all models could submit all three F-gases, so only four models are included in the panel. F-gas emissions are reduced by 40–71% by 2060, as compared to 2020 emissions.

BOX 3.1: HOW DO CHINA'S CARBON INTENSITY TARGETS ALIGN WITH NET-ZERO PATHWAYS?

China's 14th FYP targets reducing the carbon intensity (i.e., energy CO_2 per unit GDP) of the country by 18% in 2025 compared to 2020. In addition, China's updated NDC requires carbon intensity reduction by over 65% in 2030 compared to the 2005 level. The multi-model results show that China's 14th FYP and updated NDC targets on carbon intensity reduction are roughly aligned with the net-zero transition pathways but can be further enhanced. All the participating models achieve these targets in the *Updated NDC to Carbon Neutrality* scenario (see Figure B3.1).

FIGURE B3.1: CARBON INTENSITY REDUCTION IN ALIGNMENT WITH CHINESE POLICY TARGETS.

Carbon intensity is measured as energy-related CO_2 emissions per unit of GDP. To assess the alignment with China's 14th FYP target (18% reduction in energy CO_2 per unit of GDP between 2020 and 2025), we use modeling results for 2020 and beyond. To assess the alignment with China's updated NDC target (over 65% reduction in 2030 compared to the 2005 level), we use model data for models that report 2005 data and use historical 2005 CO_2 emissions and GDP data for models that do not have 2005 data. Historical data is from the Chinese Energy Statistical Yearbook (CESY). GDP assumptions are not harmonized across models in this study, and, therefore, changes in carbon intensity reflect differences in both the rate of economic growth and mitigation pathways across models.



As shown by the multi-model results in Figure 3.2 and Table 3.2, in the *Updated NDC to Carbon Neutrality* scenario CO_2 emissions from the industrial sector peak around 2020–2025 with the amount of emissions about 4.2–4.8 $GtCO_2$, then decrease to about 0.4–1.4 $GtCO_2$ in 2050 and to 0.09–0.5 $GtCO_2$ in 2060. Although the industrial sector would not be fully decarbonized by the mid-century, models indicate 69–92% reductions by 2050 and 87–98% reductions by 2060, compared to 2020 levels. CO_2 emissions from the transportation sector peak between 2025–2035 across models, at the level of 1.04–1.3 $GtCO_2$. In order to achieve net-zero GHG emissions by 2060, 2020 emissions need to be reduced by about 54–100% in 2050 and by 84–100% in 2060. As for the buildings sector, the peak time of its CO_2 emissions is quite uncertain with different models. For the involved seven models, three models in 2015, two models in 2020, and two models in 2025, the amount of peak emissions of the buildings sector ranges from 0.65–0.81 $GtCO_2$, and such peak emissions need to decrease significantly, by about 70–100%, in 2060. The modeling analysis indicates that CO_2 emissions from the electricity sector peak around 2020–2025, with an amount of 3.8–4.9 $GtCO_2$, and reach zero or negative emissions between 2040 and 2050 across models. Four of the models indicate that the electricity sector would be a source of negative emissions to offset the remaining emissions from the energy system. However, estimates for negative emissions from AFOLU and the electricity sector vary, highlighting uncertainty in potential offset from these sectors. For land sinks, the range across models was about negative 100–650 $MtCO_2$ in 2050 across scenarios, with one model estimating AFOLU offset (including other CDR) of about negative 1,300 $MtCO_2$. Several models foresee biomass with carbon capture, utilization and storage in the electricity sector being a significant source of negative emissions, with estimates ranging from negative 500–900 $MtCO_2$, while three models project limited negative even positive emissions from the power sector by 2050.

FIGURE 3.2: GHG EMISSIONS BY SECTOR IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

"Other" includes "Heat", "Solids", "Gases", and "Liquids" (which includes feedstock use, upstream oil refining, heating, coal to gas/oil). China DREAM and China TIMES do not include land use sector emissions, instead they use an estimated amount of -500 $MtCO_2$-eq annually. Land use emissions from other models are either endogenously calculated or calculated based on emissions inventory or domestic expert estimates. Some models run through 2050, therefore are not included in the 2060 chart. MESSAGEix-China estimates for 2030 are lower than other models, because it assumes rapid retirement of coal plants under low-carbon scenarios. Historical data is from the Chinese Energy Statistical Yearbook (CESY). And the AFOLU result for PECE V2.0 includes other CDR.

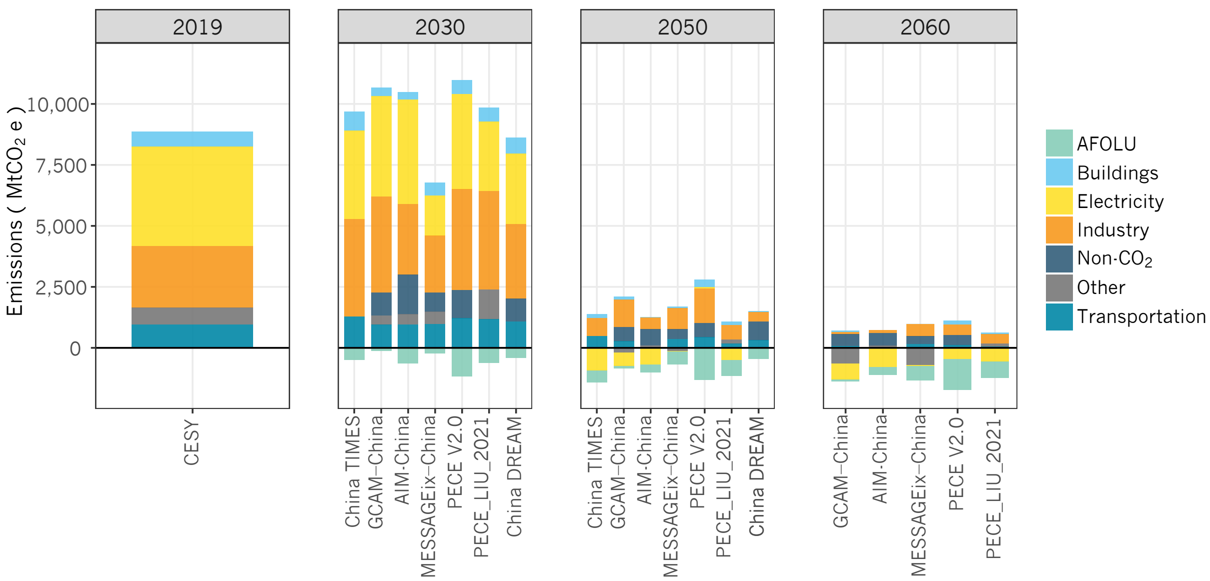


TABLE 3.2: RANGES ACROSS MODELS OF DIRECT EMISSIONS CHANGE COMPARED TO 2020 LEVELS IN *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

Emission percent changes were calculated in relation to modeled 2020 values, and sectors that exceed 100% indicate emissions have negative emissions.

Sector	2030		2050		2060	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Industry	-10%	-40%	-70%	-90%	-85%	-100%
Buildings	5%	-50%	-40%	-95%	-70%	-100%
Transportation	25%	-10%	-55%	-100%	-85%	-100%
Electricity	5%	-65%	-100%	-120%	-100%	-120%[3]

3.3 ENERGY TRANSITIONS

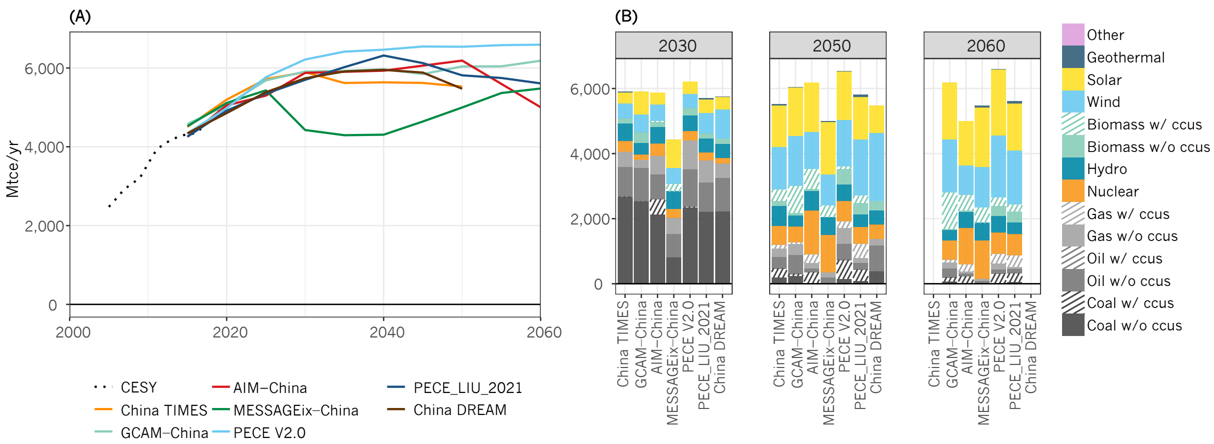
Primary Energy

Meeting China's net-zero commitment requires a rapid transition of the energy system, from fossil fuels to a new system dominated by low-carbon fuels. Our results suggest slow but continued growth in primary energy demand in the near-term followed by a decline after mid-century (Figure 3.3). There is significant agreement among base-year primary energy across models, and differences after 2025 are largely due to different assumptions about coal phase-out and energy supply make-up. In the *Updated NDC to Carbon Neutrality* scenario, fossil primary energy, including fossil fuels with carbon capture, utilization and sequestration (CCUS), declines from 79–85% in 2020 to 46–71[4]% in 2030, and less than 16% in 2060. The fossil fuel with the largest and most rapid decline across models is coal, which comprises the majority of China's primary energy supply today. Coal declines from 51–62% of total primary energy supply today to 18–45%[5] by 2030 and less than 6% by 2060. Gas may increase until about 2040, then decline (Figure 3.4), suggesting that it may be relied on during the transition to renewable energy and other low-carbon sources.

3 Mean power sector emissions reduction is the same in 2060 and 2050, because of rounding. This suggests that emissions reduction in the power sector will largely occur in the near-term, and may level out between 2050 and 2060.
4 Range across models without MESSAGEix-China is 64–71% by 2030.
5 Range across models without MESSAGEix-China is 38–45% coal share of primary energy by 2030.

FIGURE 3.3: PRIMARY ENERGY TRANSITIONS IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) TOTAL PRIMARY ENERGY, (B) PRIMARY ENERGY BY TECHNOLOGY.

All results were calculated using the average efficiency method. Historical data is from the Chinese Energy Statistical Yearbook (CESY). The rapid reduction and increase in MESSAGEix-China primary energy is due in part to rapid retirement of coal plants under low-carbon scenarios, the fast growth of renewables, and conversion between direct equivalent and average efficiency substitution methods.



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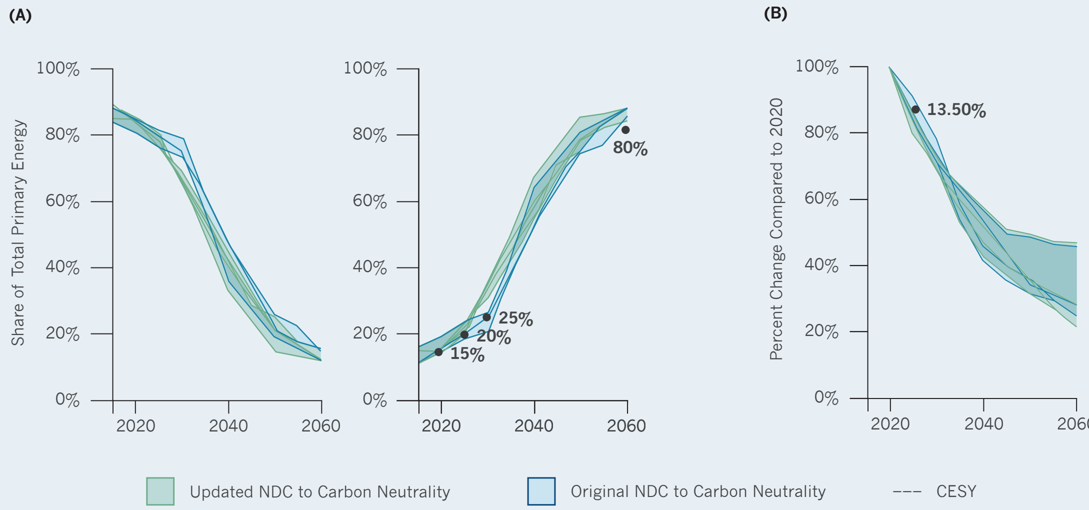
BOX 3.2: HOW ARE NATIONAL PRIMARY TARGETS ALIGNED WITH MODELING ANALYSIS?

To accelerate the long-term transition from fossil fuels, several short-term targets have been adopted. Most models show greater savings than the 13.5% below 2020 primary energy per unit of GDP target, with a 14–31% reduction by 2025, compared to 2020. Modeling analysis also shows non-fossil share of primary energy meets or exceeds Chinese policy targets in 2025. Non-fossil energy use in 2030 is affected by peaking times. In the *Updated NDC to Carbon Neutrality* scenario, models shows 29–54[6]% of non-fossil primary energy, exceeding the national target of 25% non-fossil primary energy in 2030. Non-fossil share continues to increase to 84–97[7]% by 2060, exceeding the 80% target outlined in China's long-term strategy. Higher non-fossil targets indicated by modeling analysis suggest that there is room for higher ambition and more rapid system transition. Near-term policy targets can be reassessed in the light of increasing long-term ambition as to whether they are aligned with long-term carbon neutrality goals and sufficient to facilitate expedient coal phase-out and renewable transition.

FIGURE B3.2: NATIONAL PRIMARY ENERGY TARGETS AND COMPARISON WITH MODELING ANALYSIS: (A) SHARE OF FOSSIL AND NON-FOSSIL ENERGY IN PRIMARY ENERGY, (B) PRIMARY ENERGY PER UNIT OF GDP.

Non-fossil sources include solar, wind, geothermal, hydro, biomass with and without CCUS, and nuclear. Fossil sources include coal, oil and gas with and without CCUS. These figures exclude one model, MESSAGEix-China, which had rapid fossil reduction in primary energy.



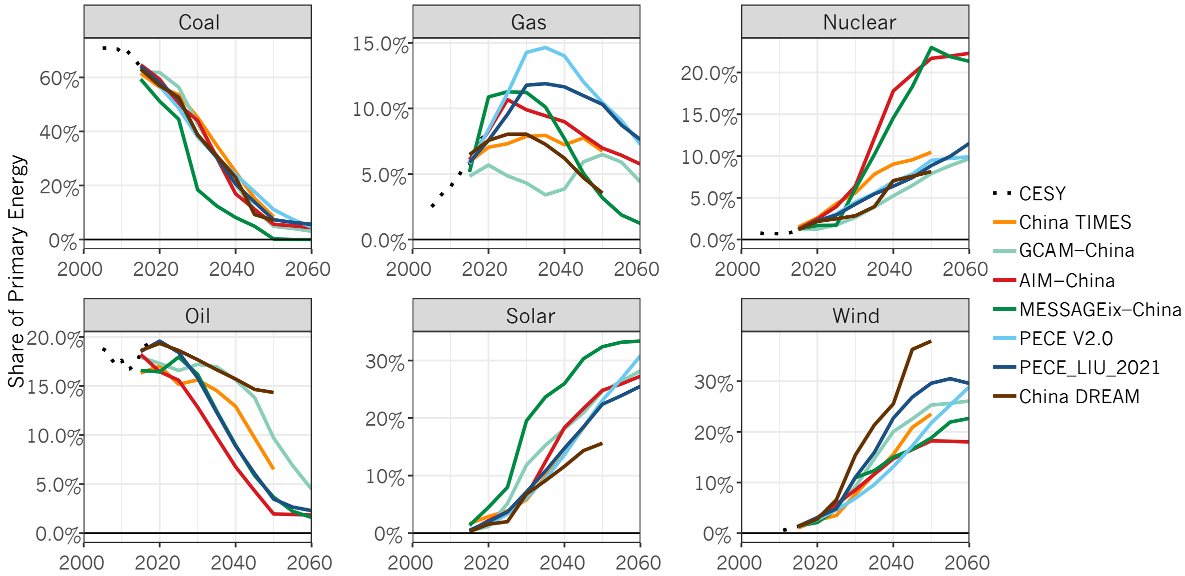
In response to declining use of fossil fuel resources, there is a significant growth in cleaner energy. Energy supply make-up varies across models, particularly for two key resources – solar and wind, which depend on a range of economic and policy choices in the near- and long- term. In the *Updated NDC to Carbon Neutrality* scenario, solar and wind contribute 6–20%[8] and 7–15%, respectively, by 2030, and by 2060, 26–33% and 18–30%[9] (Figure 3.4). By 2060, solar and wind combined become the dominant fuel source, providing over 50% of total energy supply. The remaining supply will come from biomass (with or without CCUS), hydro power, nuclear, and

6 Range across models without MESSAGEix-China is 29–36% non-fossil primary energy of the total primary energy in 2030.
7 Range across models without MESSAGEix-China is 84–88% non-fossil primary energy of the total primary energy in 2060.
8 Range across models without MESSAGEix-China is 6%–12% solar share of primary energy by 2030.
9 The wind power maximum declines from 2050 to 2060, because the model with the highest percentage of wind power in primary energy reports only through 2050. No models suggest wind power would decline between 2050 and 2060.

fossil with CCUS. Biomass with CCUS projections vary across models in the mid-century, with GCAM-China anticipating lower AFOLU negative emissions and higher industry emissions, therefore adopting more biomass with CCUS to meet mitigation targets.

FIGURE 3.4: PRIMARY ENERGY SHARE IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

Fossil sources include fossil fuels with and without CCUS. Historical data is from the Chinese Energy Statistical Yearbook (CESY).



The growth of nuclear energy is uncertain, driven by uncertainties in costs, policies, and other non-technical factors. Most models have a similar base-year share of nuclear in primary energy, of less than 2%. Projections of nuclear energy across models fall within two groups. One group has relatively conservative assessment of nuclear energy, with nuclear making up roughly 10% of total primary energy by 2060. The other group shows more optimistic assessment of nuclear energy, with more than 20% of nuclear by 2060; as a result, this group of models shows either less shares of fossil fuels with CCUS or less renewables. The differences in nuclear deployment reflect model differences in costs, deplorability, and policy choices.

CCUS becomes increasingly prominent after 2030, from less than 500 $MtCO_2$/yr, to up to 850–3,172 $MtCO_2$/yr by 2050, in the *Updated NDC to Carbon Neutrality* scenario. CCUS could potentially play a role in refining, hydrogen production, power, and end-use sectors to offset emissions. Our results suggest that CCUS would be deployed most extensively in the power sector, given the high level of emissions from the power sector, matching between emission sources and storage reservoirs, and negative emission opportunities, such as biomass with CCUS (S. Yu et al., 2019). Additional factors for CCUS deployment include geological potential for onshore CCUS storage, which varies by province (S. Yu et al., 2019).

Final Energy

The transformation pathways of end-use sectors show consistency across models. All models indicate that the final energy demand would peak around 2025–2030, then drop rapidly (Figure 3.5).

However, the amount of the final energy demand varies significantly, with a range of 3,250–4,000 Mtce/yr and 2,400–3,700 Mtce/yr at the peak and the carbon-neutral time point (2050), respectively. This is caused mainly by different energy service demand projections, various scale of energy efficiency technologies deployment, and diverse portfolios of fuel alternatives.

BOX 3.3: DIFFERENCES IN HISTORICAL ENERGY CONSUMPTION ACROSS MODELS.

Differences in base-year (2015) energy data across models are caused mainly by different data sources used for model calibration. Models calibrate historical energy consumption to different energy statistics. Global models MESSAGEix-China and GCAM-China model use IEA energy balances, while national models China DREAM, China TIMES, AIM-China, PECE_Liu_2021, and PECE V2.0 calibrate historical energy consumption based on China Statistical Yearbook and China Energy Statistical Yearbook. Differences in sectoral scope and methodologies between IEA energy balances and Chinese statistics result in base-year discrepancies across models.

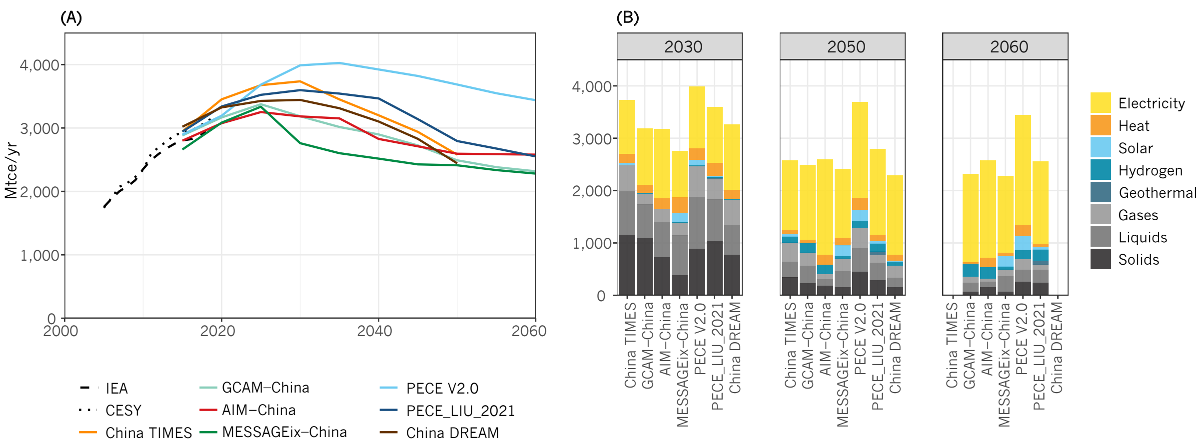
Additional efforts were taken to adjust base-year energy use and ensure that sectoral scope is the same across models in this report. Remaining differences in 2015 energy use in buildings, industry, and transportation across models are primarily caused by two factors. First, model calibration can be affected by changes in energy statistics across years. For example, although both models use IEA energy balances, MESSAGEix-China uses the 2017 IEA energy balances, and GCAM-China uses the 2019 IEA energy balances. China's total and sectoral energy use in 2015 in these two versions of IEA energy balances are different, resulting in base-year differences between MESSAGEix-China and GCAM-China. Second, models sometimes make specific adjustments to energy balances in the calibration process, leading to different base-year energy use across models. For example, the statistical methods adopted by the China Statistical Yearbook include only fuel consumption by transportation companies in the transportation sector. Transportation energy use by manufacturing facilities and households are accounted for in other sectors. As a result, models that adopt Chinese statistics made model-specific assumptions on reallocating fuel consumptions from industry, buildings, and agriculture to the transportation sector, which leads to slight differences in sectoral energy consumption across models.

End-use electricity consumption shows a substantial increase before 2030, while hydrogen does not increase rapidly until 2030. The overall electrification rate in 2050 varies from about 49–70%, with industry, transportation, and building sector electrification rates of 42–65%, 29–61%[10] and 60–88%, respectively. The share of hydrogen in total final energy demand, which includes hydrogen consumed in the building, industry, and transportation sectors, in 2050 varies from about 2–7%. Despite the different assumptions about the solar water heaters, building integrated photovoltaics (BIPV)[11], etc., an increase of solar energy is observed in models, with a range of 18–218 Mtce/yr in 2050. Therefore, the above factors collectively contribute to a significant decline in traditional fossil fuel consumption (Gases, Liquids, and Solids) in end-use sectors.

[10] Model range without AIM-China, which assumes a high level of electrification in transportation, is 29–46% in 2050.
[11] Models may use different reporting methods for solar in end-use sectors. Some models include BIPV in the electricity sector, while others include it in the buildings sector.

FIGURE 3.5: FINAL ENERGY TRANSITIONS IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) TOTAL FINAL ENERGY, (B) FINAL ENERGY BY FUEL.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA).



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BOX 3.4: ROLE OF HYDROGEN IN ACHIEVING CARBON NEUTRALITY IN CHINA

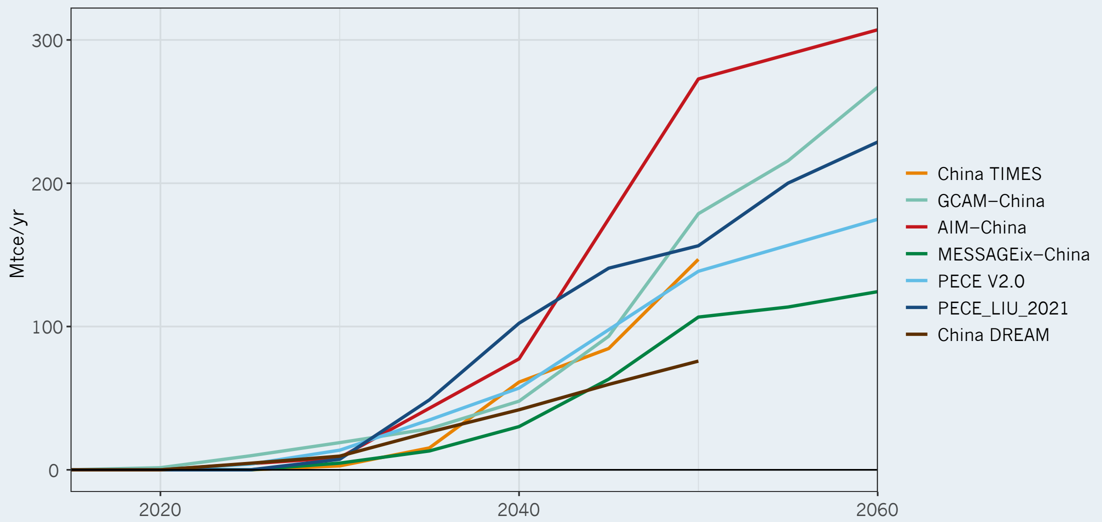
As a clean and sustainable secondary energy, hydrogen energy is an important energy carrier for China's energy system transition. Hydrogen energy has the potential for storage applications across time and space and is an important way to achieve deep decarbonization in the end-use sector.

Currently, about 85% of hydrogen is used as industrial feedstocks in methanol production, ammonia production, and petroleum refining industries. Although only a limited amount of hydrogen is currently used as energy input, hydrogen energy will become more commonly used in the next 15 years. In the *Updated NDC to Carbon Neutrality* scenario, 5–45 Mtce of hydrogen would be used as an energy source in the industrial and transportation sectors by 2035. After that, hydrogen energy will enter a period of rapid diffusion. Hydrogen energy consumption increases to 43–175 Mtce in 2050 and further expands to 57–250 Mtce in 2060, with the share of the freight transportation sector rising to 36–58% of total hydrogen energy consumption. Road freight, hydrogen ironmaking, and oil refining are the main sources of the popularization of hydrogen energy, while hydrogen use in the building sector (natural gas blended hydrogen combustion) and the power system (hydrogen storage) also contributes to hydrogen expansion.

At this stage, hydrogen in China is mainly produced from fossil energy, such as coal gasification to hydrogen, steam methane reforming, and naphtha reforming to hydrogen. These technologies, although technically mature and suitable for large-scale production, do not meet the future requirements of clean, low-carbon, and green hydrogen energy. New hydrogen production technologies, such as water electrolysis, nuclear energy hydrogen production, and biomass hydrogen production, have the advantages of flexible production and low pollution. Green hydrogen accounts for 70% of the total hydrogen production after 2040 in the *Updated NDC to Carbon Neutrality* scenario. The vast majority of models favor the use of water electrolysis for hydrogen production, due to the decreasing price of electrolyzers and promotion of renewable energy sources. With its ability to contribute to negative emissions, biomass to hydrogen with CCUS technology also has a bright future.

Hydrogen energy can enable large-scale decarbonization production in hard-to-electrify industries, such as steel and chemical production, and reduce oil consumption in the transportation sector, making it an important technological option for the industrial and transportation sectors. The hydrogen energy industry chain is divided into several links, including hydrogen production, storage and transportation, refueling, and end-use. The industry chain is long and requires much new infrastructure. As a result, there is a large demand for research and development (R&D) in each of these segments. Although the cost of hydrogen production and end-use has declined in recent years, there are still problems of low conversion efficiency and harsh production conditions. To accelerate hydrogen production and deployment, it is critical to mobilize significant investment to improve the distribution system and cultivate the whole industry chain to support the sustainable development of hydrogen energy. It is also important to prioritize R&D into sectors that cannot directly electrify or adopt energy efficiency measures, as it is unclear what the future cost, availability, applications, and efficiency of hydrogen technologies will be (Ueckerdt et al., 2021).

FIGURE B3.4: HYDROGEN PRODUCTION ACROSS MODELS IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.



04 THE ROLE OF ELECTRIFICATION IN END-USE SECTORS

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The electrification of a wide range of energy end uses across industry, transportation, and building sectors, coupled with the rapid decarbonization of power supply, is an important pillar of China's strategy for achieving carbon neutrality. Electrification, energy efficiency, power decarbonization, low-carbon fuel substitution, and carbon dioxide removal are regarded as the five pillars needed to achieve carbon neutrality (Edenhofer et al., 2014; IEA, 2020a; IRENA, 2019; Keramidas et al., 2020; S. Yu et al., 2020). To achieve China's 2060 carbon neutrality goal, electrification combined with power decarbonization could contribute to 61% of total carbon reduction, and electrification alone would reach 27% (K. Wang et al., 2021). Electrification is such an important low-carbon transition option, not only because it will be feasible to achieve substantial emissions reductions in electricity more quickly than in other sectors, but it also offers the opportunity to curb, and eventually reduce, final energy consumption due to significantly higher efficiencies in many applications. Promoting electrification in the context of carbon neutrality requires comprehensive and cross-sectoral integration. Enhanced coordination between end-use sectors and the power sector will help develop cost-effective and efficient policies. However, currently, each end-use sector in China has proposed some electrification goals which are disaggregated, unsystematic and lacking inter-sectoral linkages.

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4.1 CURRENT STATUS

China has been pursuing increasing electrification in end-use sectors for years. The economy-wide electricity share of final energy use was about 27% in 2019 (IEA, 2021d). Electricity use per capita was approaching 5,600 KWh, already exceeding the UK and Italy, and close to Germany and France. Several policies have been implemented with a target of expanding electrification in the buildings, transportation, and industry sectors (Table 4.1). However, China's electrification rates in the residential and commercial building sector are still below the average of the Organization for Economic Co-operation and Development (OECD) and the United States (Table 4.2). The buildings sector has the highest electrification rate in all end-use sectors, with the electrification rate reaching 26% in residential, and 45% in commercial buildings in 2019 (IEA, 2021d). Industry already meets close to a third of its total energy needs from electricity, and, despite leading the world in electrification of road transport, only 4% of all transport is electrified in China (Table 4.2).

TABLE 4.1: KEY ELECTRIFICATION POLICIES IN CHINA.

Sector	Policy Name	Outcome
Buildings	*Implementation Plan for Carbon Emission Peaking in Urban-Rural Construction*	Sets a 65% building electrification rate by 2030, pushes for full electrification of new buildings (20% new public buildings in 2030).
Buildings	*Guiding Opinions on Advancing the Replacement by Electricity (2016)* and *Energy Supply and Consumption Revolution Strategy (2016-2030)*	Urban and rural electrification as a key area in reshaping energy consumption (NDRC & NEA, 2016a) could be treated as the key policies to drive that process.
Total Final energy	*13th FYP on Energy Development*	China set targets to increase the share of electricity in final energy consumption to 27% in 2020 (from 25.8% in 2015) and for fuel-switching to electricity (across all end-use sectors), to lead to a total of 450 TWh of demand (NDRC & NEA, 2016a).
Power, Buildings, Transport	14th FYP (2021-2025) and *Guiding Opinions on Further Advancing the Replacement by Electricity (2022)*	Promotes coal-to-electricity switching, the expansion of recharging infrastructure and clean heating and industrial furnace management in Northern areas (The State Council, 2021), and the 14th FYP on modern energy system and Guiding Opinions on Further Advancing the Replacement by Electricity further set up targets to increase the share of electricity in final energy consumption to 30% in 2025 (NDRC & NEA, 2022a, 2022b).
Transport	China's *NEV Industry Development Plan*	Strategy for innovation in automotive technologies, including EVs. Targets for the share of NEVs (battery, plug-in and fuel-cell electric vehicles) in light-duty vehicle sales: 20% by 2025 (General Office of the State Council, 2020).
Transport	*Action Plan for Carbon Dioxide peaking before 2030*	By 2030, the share of incremental vehicles fueled by new and clean energy will reach around 40%, carbon emission intensity of commercial vehicles measured on the basis of converted turnover will be cut by about 9.5% compared with 2020 (The State Council, 2021).
Buildings	*Clean Heating[12] Plan for Northern China in Winter (2017–21)*	Targets 70% of clean heating coverage in northern regions by 2021 (up from 34% in 2016).To tackle air pollution in the provinces of Beijing, Tianjin, Hebei, Henan, Shanxi and Shandong, it sets a specific target for 28 Chinese cities to use 100% clean energy sources for heating by 2021. The plan also set targets for expanding solar, biomass, and geothermal heating in buildings (NDRC & NEA, 2017).
Industry	2016 *Guiding Opinions on Advancing the Replacement by Electricity* and *2022 Guiding Opinions on Further Advancing the Replacement by Electricity*	Identified key sectors and regions for electrification, as well as measures to promote industrial electric boilers for steam demand, particularly textiles and wood processing on the southeastern coast, and electric furnaces in various sectors, including metal processing, ceramics, mineral wool, and glass (NDRC & NEA, 2016a, 2022b).

12 According to the Clean Heating Plan, clean heating refers to the use of natural gas, electricity, geothermal heat, biomass, solar energy, industrial waste heat, clean coal-fired (ultra-low emission), nuclear energy and other clean energy sources to achieve low-emission and low-energy heating methods through high-efficiency energy consumption systems. It includes the whole heating process with the goal of reducing pollutant emissions and energy consumption.

TABLE 4.2: COMPARISON OF SECTORAL ELECTRIFICATION RATE BETWEEN CHINA AND THE OECD AVERAGE IN 2019.

Electrification rate is defined as the share of electricity consumption in end-use final energy consumption (IEA, 2021d).

Sectors	China	OECD Average	United States	OECD Europe
Industry	28%	32%	24%	35%
Transportation	4%	1%	0.2%	2%
Residential Buildings	26%	37%	46%	26%
Commercial Buildings	45%	54%	54%	50%

Existing electrification rates in China suggest there is room for growth across all end-use sectors, even in sectors where electrification is higher or comparable to the OECD average. The State Grid estimates that electrification during the 14th FYP could result in 600 TWh of additional consumption (nearly 8% of annual electricity consumption in 2020), while the China Electricity Council estimates that the share of electricity in final energy consumption could reach 38% by 2035 (CEC, 2020; State Council Information Office of the People's Republic of China, 2020).

4.2 FUTURE ELECTRIFICATION PATHWAYS

According to our results, the share of electricity in final energy in China is projected to grow to 61–73% in 2060 in the *Updated NDC to Carbon Neutrality* scenario[13] (Figure 4.1). This doesn't include indirect use of electricity for making other final forms of energy, such as the use of electrolysis to produce hydrogen, and synthetic fuels accounting for most of the difference. Electricity becomes the main energy carrier in all end-use sectors, though trends vary significantly. While end-use electricity demand will likely increase through mid-century, per capita electricity will likely not exceed consumption in other OECD countries (Figure 4.2). Challenges of pervasive electrification remain high in the industry sector and freight transportation sector, with alternative fuels, such as hydrogen and bioenergy, potentially serving as options in the longer-term, when emissions will need to be driven out of the hard-to-decarbonize sectors.

[13] All the model results from this section and forward, if not specifically explained, are from the *Updated NDC to Carbon Neutrality* scenario.

FIGURE 4.1: FINAL ENERGY ELECTRIFICATION RATE IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA). The electrification rate of PECE V2.0 does not include the electricity from distributed PV in building and industry.

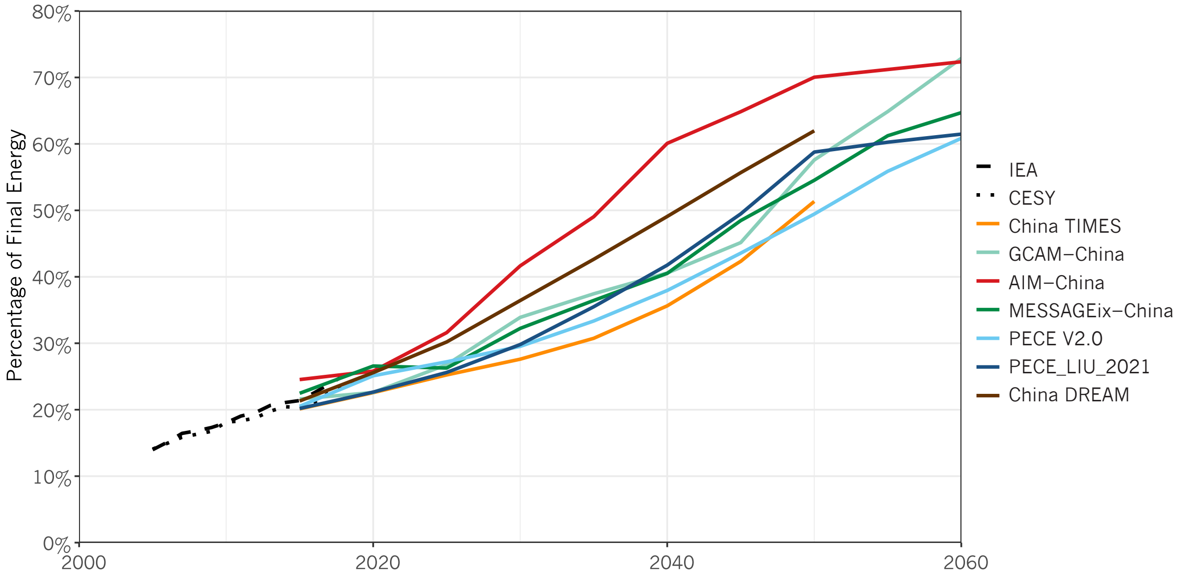
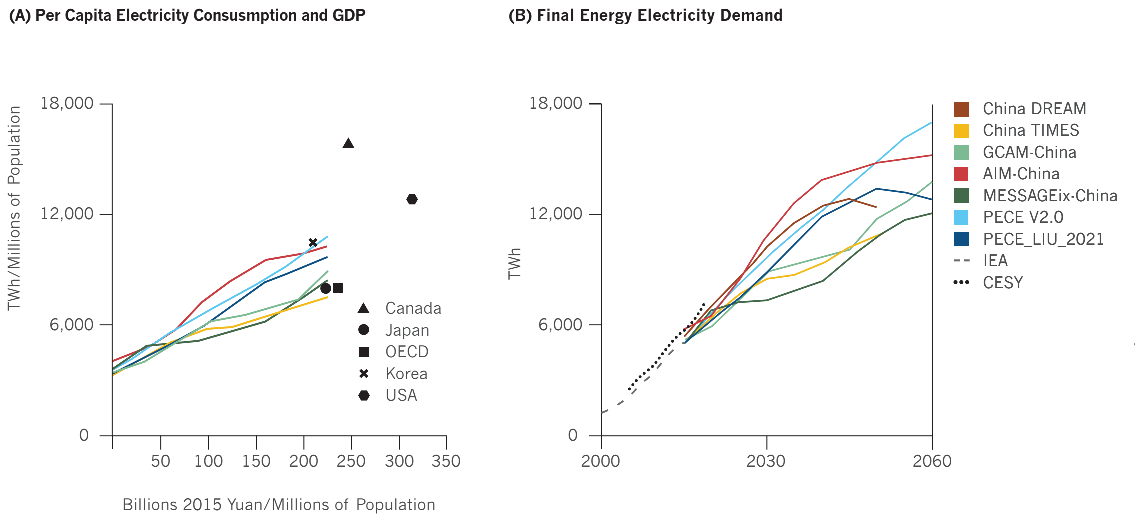


FIGURE 4.2: ELECTRIFICATION IN NET-ZERO PATHWAYS IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) PER CAPITA ELECTRICITY CONSUMPTION RELATIVE TO GDP IN CHINA AND ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD) COUNTRIES, (B) FINAL ENERGY ELECTRICITY DEMAND ACROSS MODELS.

Historical final energy data in the right panel is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA). Per capita electricity consumption and GDP 2015 data for the OECD countries in the left panel is from the OECD.



Rapid electrification requires systematic transition in China, with transformation in all end-use sectors and accelerated decarbonization in the power sector (see Figure 4.3 on electrification roadmap). The largest share of CO_2 reductions (101–117% across models in the *Updated NDC to Carbon Neutrality* scenario) by 2060 compared to 2020 occur in the power sector, from rapid phasedown of fossil fuels, adoption of carbon capture and storage technologies, and expansion of renewable energy sources. Indirect electrification of fuels supply, mainly via the production of electrolytic hydrogen for direct use and hydrogen-based fuels production, is projected to increase across models, to 75–272 Mtce of hydrogen produced annually by 2050 in the *Updated NDC to Carbon Neutrality* scenario.

Significant emissions reductions (85–100% between 2020 and 2060 in the *Updated NDC to Carbon Neutrality* scenario) are projected to stem from the transport sector, mainly through the direct electrification of light-duty vehicles initially and heavy-duty vehicles in the longer term using batteries. Across the entire transportation sector, the electrification rate reaches an average of 50% (37–57%) by 2060. The use of hydrogen and hydrogen-derived fuels produced by electrolysis also contributes indirectly to transport emissions reductions, particularly after 2035. By 2060, electricity will overtake oil as the main transport fuel. Electricity accounts for nearly 37–57% of energy use for all transportation with improvements in battery technology. EVs will dominate the passenger car fleet by then, with many trucks also converting to electric powertrains. Though their adoption is slower than passenger vehicles, the share of electricity in freight vehicles reaches nearly 22–39% in 2060 in the *Updated NDC to Carbon Neutrality* scenario.

Electrification rate in industry will increase to 64% (58–69% across models in the *Updated NDC to Carbon Neutrality* scenario) by 2060, driven by a shift away from fossil fuel-fired heating towards industrial heat pumps and electric boilers for low and medium-temperature heating needs in light industries, and increasing production of steel from scrap in electric arc furnaces. Industrial electricity demand increases from around 456–541 Mtce in 2020, to 672–1,100 Mtce in 2060 in the *Updated NDC to Carbon Neutrality* scenario. Direct use of electricity grows to satisfy the demand for low- and medium-temperature heat, particularly in light industries for manufacturing, heat pumps, and other electric heating technologies. In the energy-intensive steel and aluminum industries, secondary production (using scrap metal) is an important contributor to electricity demand growth, despite falling production of these metals. The other key area of growth is indirect electrification of primary materials production, mainly in the steel and chemicals sectors, through the use of hydrogen as a reduction agent in the steel industry and as a feedstock for ammonia and methanol production in the chemical industry.

Electricity demand in the buildings sector, the largest user of electricity today, surges by more than 129–171% between 2020 and 2060 in the *Updated NDC to Carbon Neutrality* scenario to nearly 531–684 Mtce, reaching an 81% (66–93% across models) electrification rate by 2060, driven mostly by increased use of electrical appliances and switching from traditional biomass and fossil fuels for cooking and water heating. Progressive improvements in buildings performance and equipment efficiency will reduce demand for electrified space heating, cooling, and lighting.

4.3 POLICY IMPLICATIONS

Major barriers to reaching the high electrification rate noted above still exist. Achieving these goals will require major technological breakthroughs, tremendous infrastructure investment, power grid changes, and policies and regulations to promote scaling up of technologies and to accommodate the transition risks across China.

Further technology innovation to improve performance and reduce costs is critical. Technologies such as EVs and heat pumps are commercially available today, but are not always competitive yet with alternative non-electric technologies. Other end-use technologies are further behind, particularly in heavy industry and long-haul transportation. Direct electrification of heavy industry poses an important technical challenge, particularly for processes with high-temperature thermal needs. Most technologies in this area are at the prototype stage today. In primary steelmaking, for instance, the use of electricity to convert iron ore into steel through electrolysis is still at pilot stage. In aviation, prototypes of electric planes for the short-haul market and part of the medium-haul market are currently being developed and tested by several companies, but they are far from commercial viability because of the technical limitations of the low energy density of batteries.

Electrification brings huge challenges on both supply and demand sides. For the supply side, if not managed well, the unprecedented increase in peak electricity demand relative to average demand in end-use sectors will result in possibly enlarged peak-to-valley difference of power load, posing huge challenges to grid security. For example, EV charging may raise daily peaks substantially, while heat pumps could increase the seasonal peak (such as winter in northern China). However, demand side responses, such as smart charging, necessary to support accelerated electrification, could significantly reduce peak electricity demand. Moreover, drawing power from plugged-in vehicles (V2G) could even provide extra flexibility. On the demand side, electrification will require adjustment of key production processes and supporting infrastructure investment in key end-use sectors, which will result in transition risks, such as stranded assets of existing infrastructure, cost sharing issues, and just transition problems.

In addition, sectoral electrification goals and actions are still disaggregated and unsystematic, requiring better coordination to unlock synergies among sectors. For instance, the decision on roll-out of EV charging stations will need the involvement of local stakeholders, urban planners, distribution operators, and central regulators.

Current policy is not adequate for achieving deep electrification, policy reform and market redesign are needed. For instance, storage and demand response providers need to be ensured that they can be rewarded for the value they deliver, and that barriers to their participation in the electricity system are removed. In parallel, a shift in consumer behavior will be needed to support demand response. Consumers and utilities will need to move from fixed to real-time pricing, and to engage with new technologies and business models to vary their electricity demand in line with the value they place on it. Moreover, further incentives or funds need to be provided for technology innovation and widespread adoption and use of technologies such as heat pumps, electric boilers, motors, and other appliances. Vertical (national, provincial, and local) and horizontal (cross-ministerial) policy coordination also need to be improved, to address and overcome regulator silos.

FIGURE 4.3: ELECTRIFICATION ROADMAP.

Power supply make-up and electrification rate across sectors are the mean value across models in the Updated NDC to Carbon Neutrality scenario. Near-term and long-term policy options are summarized from actions outlined in the following chapters.

	2030	2050	2060
POWER SECTOR	Adjust electricity market design, deploy demand response programs, time-varying pricing and other digital tools Solar + Wind · **Up to 35%** Coal without CCUS. · **Down to 35%**	Further increase the adjustable capacity of existing sources and expand the long-term and seasonal energy storage Solar + Wind · **Up to 60%** Coal without CCUS. · **Down to 0%**	Develop a new grid system for high share of renewable power and increase inter-connectivity between grid regions Solar + Wind · **Up to 65%** Coal without CCUS. · **Down to 0%**
ELECTRIFICATION RATE	Building · **50%** Industry · **30%** Freight Transportation · **5%** Passenger Transportation · **15%** **Total 2030 - 35%**	Building · **75%** Industry · **50%** Freight Transportation · **25%** Passenger Transportation · **55%** **Total 2050 - 55%**	Building · **80%** Industry · **65%** Freight Transportation · **35%** Passenger Transportation · **60%** **Total 2060 - 65%**

END-USE SECTORS

RATES AND POLICIES:
NEAR-TERM CHANGES

- Convert to electric space heating in public buildings
- Offer financial incentives for switching to electric heating, stoves and water heaters
- Transition to industrial heat pumps and electric boilers for low and medium temperature heating in light industries
- Develop an industry electrification technology standard
- Implement low carbon fuel standards for trucks
- Adopt public or municipal fleet electrification targets
- Offer subsidies for direct purchase of EVs and charging infrastructure

RATES AND POLICIES:
LONG-TERM CHANGES

- Promoting the application of PEDF (Photovoltaic, Energy storage, Direct current, and Flexibility) solution in buildings to utilize more renewable power from distributed PV by better demand side management
- Deploy public education programs to change residential energy use behavior
- Research and develop advanced industrial electrification technology for medium and heavy industry
- Develop hydrogen fuel cell technologies and advanced electrification technologies that can provide longer ranges for heavy-duty utility trucks
- Research and develop fuel alternatives for air and water transport
- Promote the coordinated and effective expansion of charging infrastructure

SECTOR KEY Building · Industry · Freight Transportation · Passenger Transportation

05 ELECTRIFICATION ROADMAP FOR BUILDINGS

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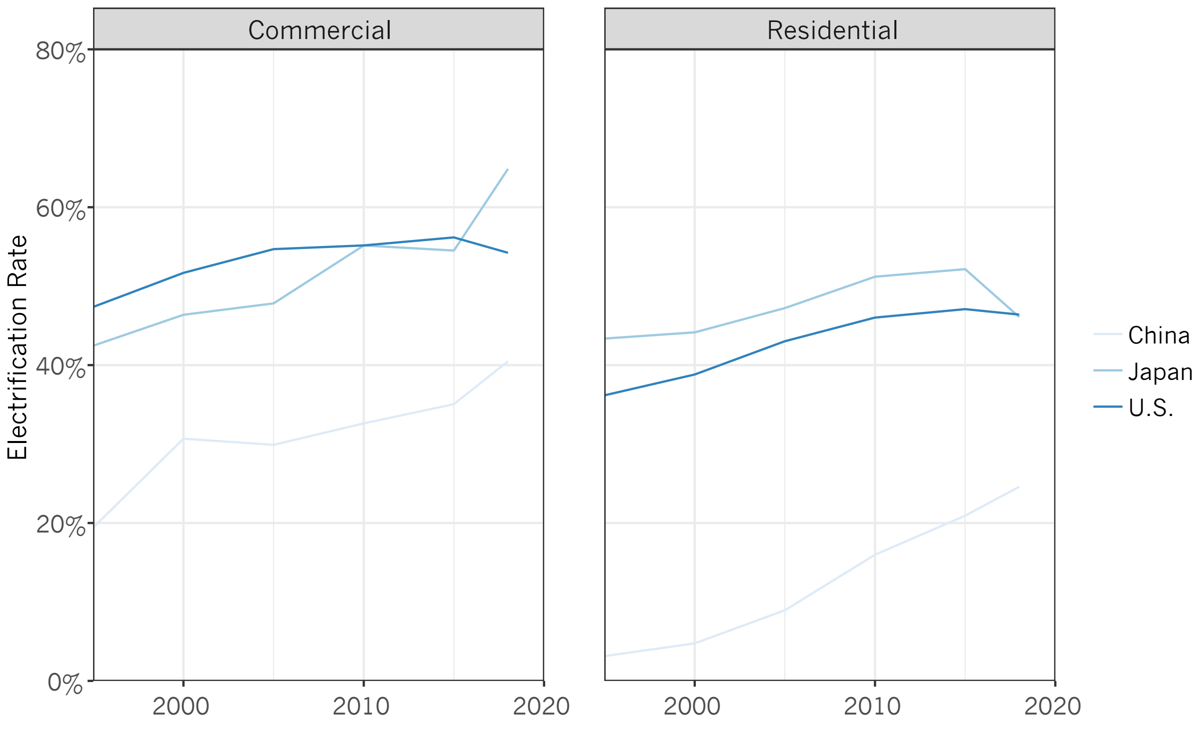
5.1 CURRENT STATUS

China's buildings sector currently utilizes mostly fossil fuels and biomass, which combined account for over 60% of final energy use in 2019 (IEA, 2021d). Electrification in the Chinese buildings sector has increased significantly during the past two decades, from only 4.4% in 1995 to 28% in 2018 (IEA, 2021d), due to changes in China's energy supply structure and economic growth. While electrification has increased in China, building electrification rates still are about half of some other developed countries. For example, the commercial electrification rate in China is about 40%, compared to 55% and 65% in Japan and the U.S., respectively. The gap widens even more when looking at the share of electricity use in residential buildings, where China only has a 26% electrification rate, compared to 45% in Japan and the U.S. (IEA, 2021d) (see Figure 5.1).

Not only do China's electrification rates vary across sectors, they also vary by location. Rural and urban, and commercial and residential buildings rely on different types of energy. The electrification rate in Chinese rural households is only about 9.7%, compared to 47% in urban residential homes (BERC, 2019). Space heating in northern urban China primarily comes from centralized coal-fired combined heat and power (CHP) plants and heat plants and consumes about one quarter of the total final energy use in the buildings sector (BERC, 2019). But in rural residential buildings, biomass contributes to around one-third of final energy use (BERC, 2021). Reducing consumption and fossil fuels in urban district space heating and traditional biomass in rural households and adopting location and sector-specific approaches should be targeted to improve electrification across the buildings sector.

FIGURE 5.1: HISTORICAL TREND OF ELECTRIFICATION IN THE BUILDINGS SECTOR OF CHINA, JAPAN AND THE U.S.

(Source: IEA, 2021d).



5.2 ROLE OF BUILDING ELECTRIFICATION IN CARBON NEUTRALITY

In order to meet the ambitious 2060 carbon neutrality target, our modeling results show that increasing electrification in buildings will be critical. Final energy use will likely increase, peaking between 2025–2045, before declining. By 2060, final energy consumption may be similar to today's levels, or even increase, from about 530–766 Mtce/yr in 2020 to about 588–980 Mtce/yr (Figure 5.2). The electricity demand of the buildings sector may reach 531 to 684 Mtce/yr in 2060 from the current 231–284 Mtce/yr in 2020, which implies that the electrification in buildings sector needs to increase to 41–65% in 2030 and 66–93% in 2060 from the current level of less than 30% (Figure 5.3).

FIGURE 5.2 : BUILDING FINAL ENERGY CONSUMPTION IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) TOTAL FINAL ENERGY, (B) FINAL ENERGY BY FUEL.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA).

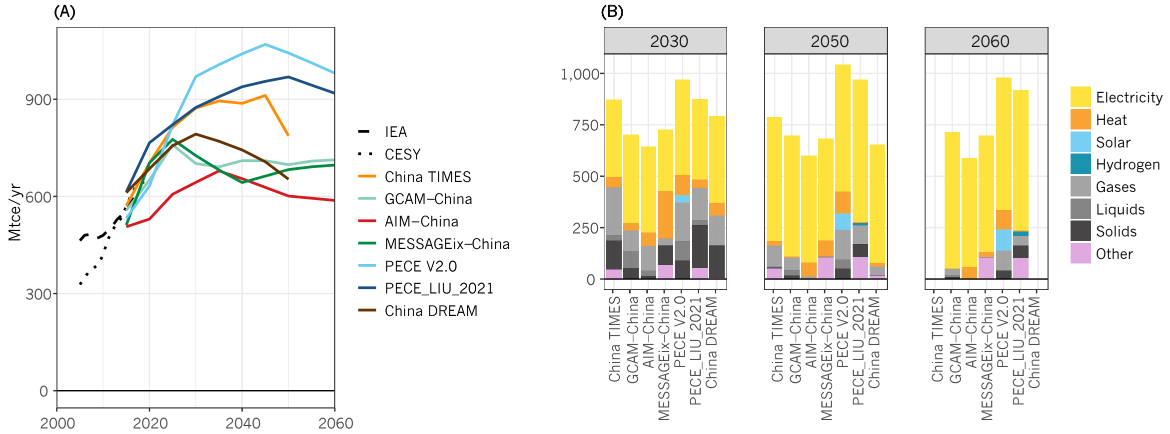
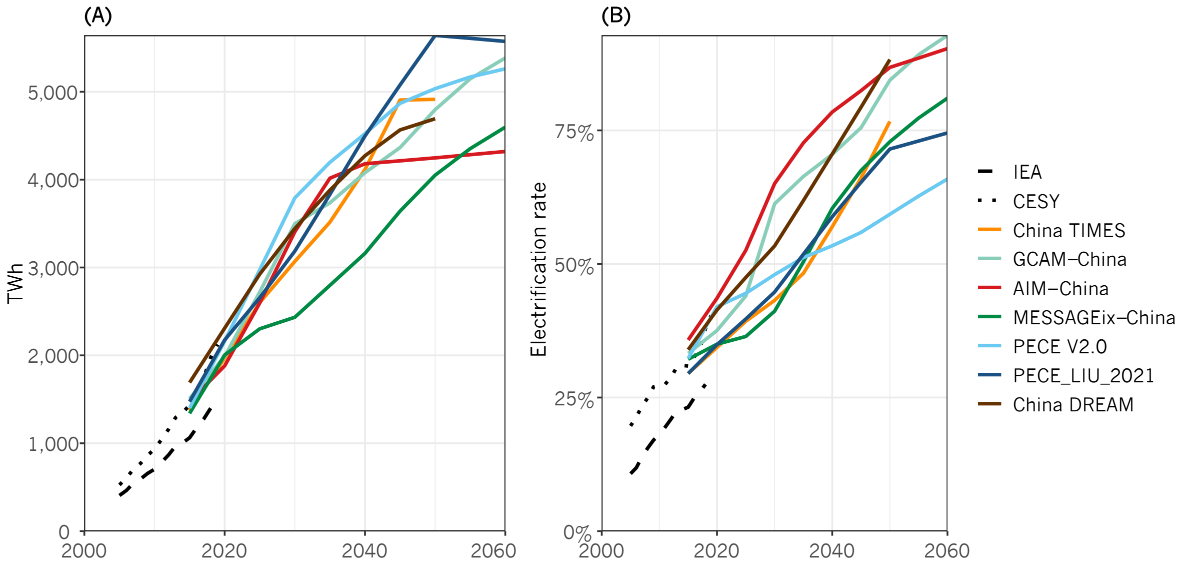


FIGURE 5.3: ELECTRIFICATION IN THE BUILDINGS SECTOR IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO. (A) ELECTRICITY DEMAND. (B) ELECTRIFICATION RATE.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA). The electrification rate of PECE V2.0 does not include the electricity from distributed PV in building.



5.3 CHALLENGES AND OPPORTUNITIES

Challenges

There exist several types of challenges for promoting electrification in the buildings sector, including technological, financial, and cultural obstacles. To address these challenges, well-designed and comprehensive incentives and policies from governments at different levels are needed. They include research investment in electrification technologies, market penetration promotion and cost reduction of these technologies, either by economies of scale or subsidies, and shifts of people's energy use preferences.

As a key prerequisite for promoting electrification in space heating, improving the energy performance of building envelopes is essential. Although the insulation in Chinese northern urban residential buildings has significantly improved in the past few years, buildings are still not as well insulated as some developed countries. For example, the thermal performance requirements in the current Chinese building code (GB 55015-2021) for exterior walls and windows in northern China are about 0.25–0.45 W/m^2 K and 1.4–2.2 W/m^2 K, respectively (depending on location), while such requirements are 0.28 W/m^2 K for exterior walls and 1.3 W/m^2 K for windows in Germany (BERC, 2017; CABP, 2021). Improving insulation for new and retrofitted buildings calls for advanced building materials and construction techniques that are commercially available. Besides the building insulation, some electrification measures for space heating need to be further developed to improve their reliability, such as low temperature air source heat pumps (ASHP), and power supply infrastructure. Conventional ASHPs are not very efficient in colder climates, so resolving technical challenges and increasing the reliability of low temperature ASHPs during the winter are critical for these regions. The low temperature ASHPs used in colder regions should be able to retain a majority of their capacity when low temperatures are reached (e.g., -20°C), and avoid the use of resistance heating for buildings. In addition, power supply infrastructure needs to be upgraded to meet the increasing adoption of electrification in buildings.

Adopting residential electrification measures usually requires a high initial financial investment. For instance, the investment cost of low temperature ASHP (in terms of per unit square meters) is usually 2–3 times that of coal-fired district space heating (Q. Zhang et al., 2017). The high initial investment of electrification measures have hindered the diffusion of these technologies.

Energy use preferences also present an obstacle to building electrification. Coal-fired, biomass-fired and gas-fired stoves are widely used in Chinese households because high temperature cooking and the use of round-bottom pans is an integral part of Chinese diet and culture. Electric stoves that use flat-bottom pans and provide a relatively lower temperature for cooking, would require a consumer behavioral shift for wide-spread adoption of electric stoves. Additionally, promoting electrified space heating in northern China may require the use of more decentralized space heating systems, like ASHP and ground source heat pump (GSHP),to replace the existing centralized, district heating. For residents accustomed to having district heating, maintaining their own buildings' heating systems by themselves may be a deterrent to electrification.

Opportunities

Opportunities for prompting electrification include expansion of new building stock, co-benefits for rural households, and increasing PV adoption across China.

China is currently experiencing a construction boom, creating a key window to adopt new electrification measures in new buildings. New buildings in China make up 2.5 billion m^2 annually (BERC, 2019). As buildings and related HVAC (heating, ventilation, and air conditioning) systems have a lifetime of usually more than a few decades, replacing existing building infrastructure before the end of its useful life increases the often already higher initial cost for electrification measures. Integrating new electrification measures into the development of new buildings is critical for avoiding the so-called lock-in effects of obsolete or high-carbon technologies in buildings.

Additionally, promoting electrification in rural residential buildings can greatly improve the standards of living in rural households, improve indoor air quality, and achieve better health outcomes (J. Li et al., 2019). Replacing fossil fuels and traditional biomass with electricity could not only help to reduce carbon emissions from the buildings sector, but it would improve indoor air quality by avoiding emitting indoor air pollutants from cooking and space heating. A study has shown that using coal for space heating in rural northern China might have resulted in a 5-year reduction in life expectancy for residents who use coal for heating (Y. Chen et al., 2013).

Electrifying the buildings sector could also promote the wide deployment of distributed PV systems in both urban and rural buildings, decreasing consumer electricity costs while allowing for increased utilization of more renewable energy. When combined with other measures, such as improved energy efficiency, direct-current (DC) type microgrids and EV charging stations, buildings can act as flexible absorbers for the grid, even providing electricity to the grid when needed (EFC, 2020).

5.4 KEY AREAS FOR ELECTRIFICATION

Residential Space Heating

There are more than ten Chinese provinces (or municipalities, autonomous regions) lying north of the Qin Mountain and Huai River line of China, located in the so-called “severe cold” and “cold” climate zones of China, which have significant needs for space heating in winter. In the urban areas of these regions, district space heating is the dominant form of heating, accounting for about 85% of households' space heating in terms of floor space (BERC, 2019). Over 40% of China’s urban population, which is around 322 million people, live in regions that require heating (IEA & Tsinghua University, 2018).

Currently, space heating in northern urban China accounts for about 25% of the total final energy use in the entire buildings sector, about 214 Mtce per year, and the energy intensity of space heating on average is about 0.4 $GJ/m^2 \cdot year$ (BERC, 2022). Due to rapid urbanization, total floor area in northern urban China with district space heating is increasing quickly, at an average rate of about 13% per year from 2006 to 2017, comprising about 12 billion square meters in 2017 (BERC, 2019). Coal-fired combined heat and power (CHP) and heat plants account for about 77% of district heated floor space. Gas-fired CHP and heat plants account for 14% of district heated floor space, while electric space heating only makes up less than 5% (BERC, 2019). In rural residential buildings, space heating accounts for about 44% of the total final energy use and heavily depends on coal and biomass (X. Zheng et al., 2016). Biomass currently accounts for about 62%; coal for about 28%; and electricity for only about 2% of space heating in rural residential buildings (X. Zheng et al., 2016).

There are several electric space heating technologies that can be used for space heating in northern urban China to replace fossil fuel based district space heating. They include low temperature ASHP, ground source heat pump (GSHP), electric boilers, and radiant heating film. Promoting electric space heating requires upgrading the electricity supply infrastructure in buildings. In addition, the application of heat pump systems in urban communities needs enough space for equipment installation and may also cause noise pollution. Direct electric heating measures, including electric boilers and radiant heating films, have much lower energy efficiency than heat pump technologies, so they should be used only in buildings or locations not suitable for heat pumps. Given the reliance of direct heating measures on power sector supply make-up, these technologies shouldn’t be prioritized in the near-term, as China remains largely dependent on coal-fired power for electricity supply. With more renewables in the future, these direct electric heating measures will be a viable solution for the communities that have difficulty adopting heat pumps. In addition, solar district heating (SDH), along with heat pumps, could be also a promising way for replacing the existing coal- and gas-based space heating in China. SDH has been used in Denmark and Germany, and is estimated to be suitable for China’s regions that have rich solar resources, a long heating season and cheap land, such as Xinjiang, Qinghai, Inner Mongolia and Gansu (ADB, 2019).

There is also significant potential to electrify space heating in rural residential buildings by adopting ASHPs or GSHPs as a complement to using solar and compacted biomass for space heating. Using electric space heating measures to replace currently widely used coal-fired and traditional biomass space heating systems in rural households could significantly improve indoor air quality, thereby reducing related negative health effects from burning coal and traditional biomass in poor and low-efficient stoves. Promoting the use of clean biomass for space heating in rural households is important in the near-term, considering its lower operation cost and co-benefits for residents. The thermal performance of rural residential buildings is usually poor. Improving the building envelope performance beforehand is critical for using electric space heating systems in the rural area, to improve efficiency and limit operating costs. Also, given the high initial cost of ASHPs and GSHPs, subsidy programs are important for prompting their application in rural households.

Air Source Heat Pump

Conventional ASHP are usually used in China's Yangtze river area for space heating in winter, but in northern China, the use of conventional ASHPs can result in poor performance or malfunction of the heat pumps..

In order to use ASHP for space heating in northern China, low temperature ASHPs have been developed. Some adjustments include using new refrigerants, combined with phase change material, along with a new circulation system (e.g., two-stage compression, cascaded compression) and defrost technology and optimal defrosting strategies (Yang et al., 2020; Y. Zhang et al., 2017). To further improve the Coefficient of Performance (COP) of low temperature ASHP in northern China in winters, floor radiant heating indoor systems are recommended as it could lower the running temperature at the condensation side of ASHPs. Some studies have shown that the low temperature ASHP could maintain acceptable COP in cold weather. For example, in Harbin, the capital of the northernmost province in China, the COP of ASHP could be over 2.2, which means that 1 unit energy of electricity could provide about 2.2 units energy of heat, when the indoor and outdoor temperature difference is about 35°C, namely with an outdoor temperature of around -15°C (Q. Zhang et al., 2017).

Low temperature ASHPs can have operating costs comparable to traditional coal-fired district space heating systems and household gas-fired boilers. In one study (M. Yu et al., 2021), the operating cost of two types of low temperature ASHP (quasi-two-stage ASHP and ASHP with latent thermal energy storage) is analyzed and compared with that of several other space heating measures in three cities in Northern China – Beijing, Shenyang and Harbin (see Table 5.5). The operating cost of ASHP is rather competitive with that of coal-fired district heating system in the "cold" climate zone (like Beijing) and a bit higher than conventional district heat (about 15%) in some regions of the "severe cold" climate zone (i.e., Zone C & B of "severe cold", like Harbin) (M. Yu et al., 2021). A case in Beijing showed that the average COP of an ASHP system during the whole heating season could be 3.0 (2.6 in the coldest day in that winter), and the expense could be only about 22.8 yuan/m^2 (\$3.37/m^2), with peak-valley electricity pricing (BERC, 2015).

The current technological development of low temperature ASHP is applicable to space heating in most regions of northern urban China and can be adopted to replace district space heating in these regions – with having both reasonable COP and economical operating cost (Table 5.1). The low temperature ASHP is particularly appropriate for use in low-rise residential buildings, attached or detached houses, and small-scale commercial buildings in the "cold" climate zone of China.

TABLE 5.1: OPERATING COSTS ACROSS SPACE HEATING MEASURES.

(Source: M. Yu et al., 2021)

Space heating measures	Operating cost (Yuan/m^2)		
	Beijing	Shenyang	Harbin
Coal-fired boilers	33.84	40.83	42.09
Household gas boilers	31.93	38.77	40.01
Direct electricity heating	105.3	128.31	132.47
ASHP (quasi-two-stage)	29.45	41.61	48.91
ASHP (with latent thermal energy storage)	30.67	40.97	47.39

Ground Source Heat Pump (GSHP)

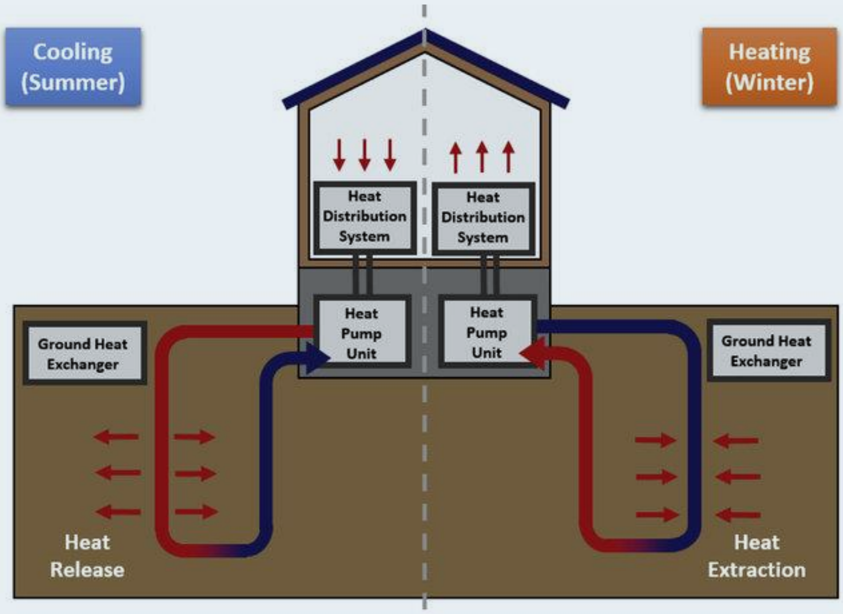
Ground source heat pumps (GSHP) utilize geothermal energy for space heating in buildings. GSHPs have a higher COP than ASHPs (usually around 3.5–4), because the ground temperature is usually higher than the ambient air temperature in heating seasons. The GSHP system consists of the heat pump, the distribution system, and the ground heat exchanger (usually in the form of closed-loop) (see Box 5.1).

One of the largest challenges for applying GSHP for space heating in a building is balancing the heating and cooling load of the building. If the cooling load of a building in summer is much less than its heating load in winter, the ground temperature decreases with operation over years and could result in poor COP or malfunctions of GSHP for space heating in winter. By exploring the feasibility of using GSHP in three cities in northern China – Qiqihar, Shenyang and Beijing – one study (Z. Liu et al., 2015) found that it might be difficult to use the GSHP system in the city of Qiqihar because, after several years' operation, the temperature in buried pipelines in winter might be lower than 0°C. This is because the GSHP system could not store balanced heat in the ground in summer for use in winter. This challenge could be addressed by building more pipelines in grounds or by using the system only in winter. It could also be solved by developing the so-called deep borehole heat exchanger (DBHE)- based GSHP, which utilizes geothermal energy from medium or deep layer, instead of shallow layer. A project of shallow-layer GSHP system in the city of Jinan showed a heat pump COP of about 3.42 and electricity use of 15.5 kWh/m^2 (EFC, 2016). Another medium-deep layer GSHP system in the city of Tianjin showed that the COP of the whole system in heating seasons could be 5.72, with only 11 kWh/m^2 electricity consumption (BERC, 2019).

BOX 5.1: GROUND-SOURCE HEAT PUMPS FOR SPACE HEATING

FIGURE B5.1: GROUND-SOURCE HEAT PUMPS PUMPS FOR SPACE HEATING.

(Source: Cazorla-Marín, 2019)



A GSHP system (sometimes called geothermal heat pump, or GHP) extracts heat from the soil or groundwater for space heating or cooling in buildings (Figure B5.1), because ground temperature keeps quite stable year-round and is warmer than the air in winter and cooler than the air in summer.

The system includes heat pump units, ground heat exchanger and indoor distribution system. The heat pump units transfer heat from a lower temperature resource to a higher temperature resource via a thermal setting based on a reverse Carnot thermodynamic cycle (Figure B5.1). The ground heat exchangers (GHE) are usually plastic-type pipes, which circulate an antifreeze solution through a closed loop. The GHEs are buried into the ground either horizontally (shallow trenches, 2–4m deep) or vertically (boreholes, 30–200m deep). The horizontal system is less expensive, but needs sufficient land for digging trenches, so it is more appropriate for new buildings or rural areas. In contrast, the vertical system can be used for existing buildings with limited land, as building boreholes requires relatively small space. The indoor floor heating system (using heating pipes under the floor) is preferred over a radiator system (using radiators to heat buildings) for a GSHP system, because of the relatively lower condensing temperature.

To install a GSHP system, three important aspects need to be assessed: soil conditions, heating and cooling needs of buildings, and land availability. GSHP contractors often drill an exploratory well to investigate local hydrological and geological conditions and estimate the construction cost.

The energy efficiency of a GSHP system is measured by its Coefficient of Performance (COP), typically around 3.5–4, which means that 1 unit energy of electricity could provide about 3.5–4 units energy of heat. Accordingly, compared to other types of space heating systems, the GSHP system has lower CO_2 emissions (see Table B5.1).

TABLE B5.1: CO_2 EMISSIONS OF DIFFERENT HEATING SYSTEMS

(Source: Ahmadi et al., 2017).

System	Primary Energy Efficiency (%)	CO_2 emissions (kg CO_2/kWh heat)
Oil-fired boiler	60–65	0.45–0.48
Gas-fired boiler	70–80	0.26–0.31
Condensing Gas Boiler + low temperature system	100	0.21
Direct electric heating under current grid conditions	36	0.9
Conventional electricity + GSHP	120–160	0.27–0.20
Green electricity + GSHP	300–400	0.00

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Cooking

Cooking accounts for about 20.7% of energy use in Chinese urban households and 44.1% in rural households (X. Zheng et al., 2015, 2016). Appliance electricity use, like that for rice cookers, microwaves, etc., is only a small share of cooking energy use in urban households (15.7%) and rural households (6.2%) (X. Zheng et al., 2015, 2016). After excluding electricity use in cooking appliances, it is estimated that cooking by using coal, gas, and biomass consumes about 19% of total final energy use in the entire buildings sector (BERC, 2019; X. Zheng et al., 2015, 2016). The thermal efficiency of stoves in rural and urban areas varies. Gas-fired cooking stoves have around 55–63% thermal efficiency for built-in type and 58–66% for desktop type. In contrast, the energy efficiency of traditional biomass and coal-fired cooking stoves widely used in rural areas is only around 15% and 30–40%, respectively (BERC, 2016).

Improving the penetration of electric stoves and induction stoves to replace gas-fired, coal-fired and traditional biomass-fired stoves is needed. Compared to gas-fired cooking stoves, the thermal efficiency of electric resistance stoves and induction stoves is higher, about over 70% and 90%, respectively, while the capital cost of electric induction and resistance stoves is comparable to that of gas-fired stoves (W. Feng et al., 2021). Since Chinese cooking culture prefers the use of cooking stoves with open-flame over induction technology, changing diet habits and cooking preferences by implementing extensive public education programs might be necessary.

Water Heating

Domestic water heating in China is supplied mostly by decentralized gas, solar, and electric water heaters. Water heating accounts for about 14.4% of total final energy use in Chinese urban households and 5.7% in rural households (X. Zheng et al., 2015, 2016). The share of electric water heating is about 13.2% and 16.1% in Chinese urban and rural households in terms of final energy use for domestic water heating, respectively, (a bit higher in rural areas because of relatively lower access to gas) (X. Zheng et al., 2015, 2016). In comparison, gas water heating accounts for about 68.3% of final energy use for domestic water heating in urban households and 55.6% in rural households, while the rest is mostly solar water heating.

One of the significant barriers to replacing gas water heaters with electric water heaters is the relatively larger size of the accompanying water tanks, possibly a key concern for consumers, especially in urban areas, or homes with limited space. In addition, some consumers may not purchase electric water heaters because they need more time to heat the water in water tanks than gas water heaters, which is not always convenient for certain consumers.

PV Onsite Use in Buildings

Onsite use of PV in buildings is important for promoting electrification in the buildings sector and reducing CO_2 emissions. Along with China's new Nationally Determined Contributions (NDCs) on promoting the capacity of solar and wind power generation, distributed PV systems, including rooftop PV, are expected to experience a fast increase in the next few years, owing mainly to the government's incentives on higher feed-in tariffs (China Daily, 2022). About 27 GW of rooftop PV in China was installed in 2021, and half of the new commercial buildings that receive government funds will be covered with rooftop PV in 2025 (China Daily, 2022).

Rooftop PV potential may be limited in large-scale Chinese cities, because low-rise and high-rise buildings dominate in these areas. Using remote sensing images, one study estimated that the available rooftop area in the Chaoyang district of Beijing city is only about 679,000 m^2 , while the annual PV electricity potential is around 63.8 GWh/yr (Song et al., 2018). Given the population size and household electricity consumption per capita of the Chaoyang district, it is estimated that deploying the full potential rooftop PV could only provide less than 2% of the household electricity use in this area (Chaoyang District Government, 2022; Song et al., 2018). For such densely populated urban areas, BIPV is another option for onsite utilization of PV in buildings, although its deployment is currently limited and still in early stage of development. Obstacles that need to be addressed to promote its wide deployment include: its adverse impact on internal spaces (e.g., the surface temperatures of an unventilated vertical BIPV can be 40°C higher than the air) and higher maintenance costs than rooftop systems.

The onsite use of PV in buildings could be more promising for electrifying buildings in Chinese rural areas. Launched in 2014, a rooftop PV demonstration project in a rural village with 129 households (about 12 PV panels on average per household) in Jiangsu province shows that annual electricity generation from the rooftop PV system is about 393 MWh, which could provide the entire electricity consumption in this village and also send about 20% of the generated electricity back to grids (NEA, 2014).

The currently developed PEDF (Photovoltaic, Energy storage, Direct current and Flexibility) technology offers a promising and integrated solution for promoting electrification in the buildings sector. With this solution, the buildings with direct-current-type micro-grid are integrated with distributed PV (e.g., rooftop PV) and energy storage equipment (e.g., electric battery, ice thermal) could serve as flexible electricity users to better consume intermittent electricity. Facilitated by digital technologies, the PEDF solution could realize excellent demand side management (Y. Jiang, 2021). It is estimated that the deployment of PEDF solution in China's rural households could not only meet their full energy demands but also feed a significant share of the generated power into grids (Y. Jiang, 2021). A pilot PEDF project with 27 rural households launched in 2019 in a village named Zhangshang in Ruicheng county of Shanxi province shows that with the PEDF solution, about 40% of the electricity generated by onsite-PV panels could fed into local grids (Yuncheng city government, 2021). The PEDF solution has been included into the *Action Plan* (The State Council, 2021).

It is worth noting that, compared to the onsite use of PV, measures that have direct impacts on building sector electrification, namely adopting electric space heating, cooking, and water heating, are most essential for increasing electrification.

5.5 KEY POLICY APPROACHES

Considering the electrification potential, availability of technical measures in the market, cost-effectiveness, and difficulties of implementation, electrifying space heating essential near-term actions, electrifying cooking, and domestic water heating are also high priorities. Key policies in the building sector to reach these end goals are outlined in Table 5.2.

To improve electrification in space heating in northern China, it is essential to promote wide adoption of electric space heating systems, particularly the ASHP and GSHP systems, to replace the current dominant coal-fired based district space heating system in the region's urban areas, and coal- and traditional biomass-based space heating in the rural areas. This significant energy transition requires comprehensive incentives and policies from the governments at various levels.

The development of ASHP and GSHP for space heating in northern China is still at the initial stage; poor-quality projects could significantly impede its acceptance by the public. Subnational governments need to design specific development plans of electric space heating in their jurisdictions, for both short-term and long-term.

Especially for the promotion of GSHP systems, local hydrological and geological conditions need to be well investigated beforehand, then, based on the results, the local governments need to design a solid and comprehensive GSHP development plan to identify its applicable regions and related potentials. Regulations for controlling the commercial license of related equipment manufacturers, parts suppliers, and project contractors to ensure the quality of implemented projects and meet relevant national standards and criteria need to be developed.

Additionally, financial incentives should be adopted to promote the market share of these electrification technologies by the governments, particularly in the areas with favorable climate and geographic conditions for technology development and deployment. For example, offering a favorable electricity price to electric space heating providers (e.g., using the residential electricity price instead of the commercial electricity price, or discounted residential electricity price); exempting the groundwater charge of the GSHP systems; providing subsidies to the operators of the electric space heating systems; and encouraging local banks to provide loans with prime rates to project developers could help promote deployment.

Finally, electric space heating should be included in public procurement processes. Government office buildings and the buildings that receive government funds, such as schools and hospitals, need to take the lead in adopting electric space heating systems when it is technically feasible. To improve the competitiveness of electric space heating systems, the government may consider including coal-fired and gas-fired district space heating plants in the already-established emission trading system (ETS) in China. The CHP plants are already covered by China's ETS. As the coal-fired and gas-fired heat plants account for around half of the heated floor space of district space heating in northern China, including coal-fired and gas-fired district space heating plants in China's ETS could be an important next step for promoting electrification in the Chinese buildings sector.

There are other options than electrification for decarbonizing space heating in the Chinese buildings sector, including using the waste heat from industrial and power facilities as the heat sources of district space heating and adopting the clean use of biomass for space heating in rural households. All feasible space heating decarbonization measures, including electric and non-electric, should be considered and implemented, based on local conditions for better cost-effectiveness.

To improve the electrification of cooking and water heating in Chinese households, extensive publicity programs and effective financial incentives are the key. Owing to traditional diet habits, Chinese people prefer to use biomass, coal and gas stoves, rather than electric stoves, for high temperature cooking. Therefore, to promote cooking electrification in Chinese households, it is critical, as a first step, to implement extensive publicity programs to encourage changing the diet habits of Chinese people by presenting the potential health and indoor air quality benefits from lower temperature cooking with electric stoves. In addition, the governments at different levels could require the developers of new buildings to pre-install these electric measures (e.g., electric stoves and water heaters). This is particularly important given the yearly increase in the number of new buildings in China.

TABLE 5.2: SUMMARY OF ACTIONS FOR ELECTRIFICATION IN THE BUILDINGS SECTOR.

Near-term Actions	Long-term Strategies
► Incorporate electric space heating into public procurement and facilitate adoption of electric space heating in government office buildings and the public buildings that receive government funds. ► Develop national commercial licensing system for regulating related building equipment manufacturers, parts suppliers, and project contractors, to ensure the quality of implemented electric space heating projects to meet relevant national standards and criteria. ► Adopt financial incentives to promote the market share of electrification technologies, including tax incentives and subsidies to contractors, related appliance manufacturers, and consumers. ► Pre-install electric measures for cooking and domestic water heating in suitable new buildings. ► Adopt electric space heating in rural residential buildings, as complement measures after using clean biomass. ► Regularly tighten relevant building energy codes to promote electrification measures in buildings. ► Promote the use of digital technologies in buildings to facilitate the course of electrification in buildings.	► Design specific long-term development plans of electric space heating in administrative jurisdictions. ► Cover current coal-fired or gas-fired district space heating plants by the current emissions trading system (ETS) in China. ► Deploy public education programs to change residential energy use behavior in buildings. ► Promoting the application of PEDF in buildings to utilize more renewable power from distributed PV by better demand side management.

06 ELECTRIFICATION ROADMAP FOR INDUSTRY

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6.1 CURRENT STATUS

Industry is second only to the power sector in terms of CO_2 emissions in China, accounting for around 35% of the country's total combustion-related emissions in 2020 (IEA, 2021a). China's goal of comprehensive modernization has brought sustained demand for infrastructure development domestically, and, with it, demand for industrial products such as crude steel and cement. New industrialization is one of the principal driving forces for the construction of China's modern economic system in 2035 (NPC, 2021), that is, an industrial development strategy with higher technical level, greater economic benefits, lower resource consumption, less environmental pollution and better allocation of human resources. The overall value-added of China's manufacturing industry has comprehensively surpassed that of the United States. In 2018, China's output surpassed that of the United States in 18 among the 19 major categories of manufacturing industries (UNIDO, 2021). China produced nearly 60% of the world's cement and crude steel, 55-65% of primary steel and aluminum, and 30% of the primary chemicals used to make plastics and fertilizers (IEA, 2021a).

The industrial sector is highly dependent on energy consumption to provide equipment power and heat. Smelting and pressing of ferrous metals, nonmetal mineral products, raw chemical materials and chemical products, petroleum processing, and coking are the most energy-intensive and high-emission industries in China[14]. Their combined energy consumption accounted for 61.71% of all industry in 2019 (NBS, 2021). Energy consumption is most concentrated in a few products, including iron and steel, cement, and synthetic ammonia. A significant portion of fossil fuels are consumed in these industrial subsectors, resulting in a high carbon emissions (Figure 6.1).

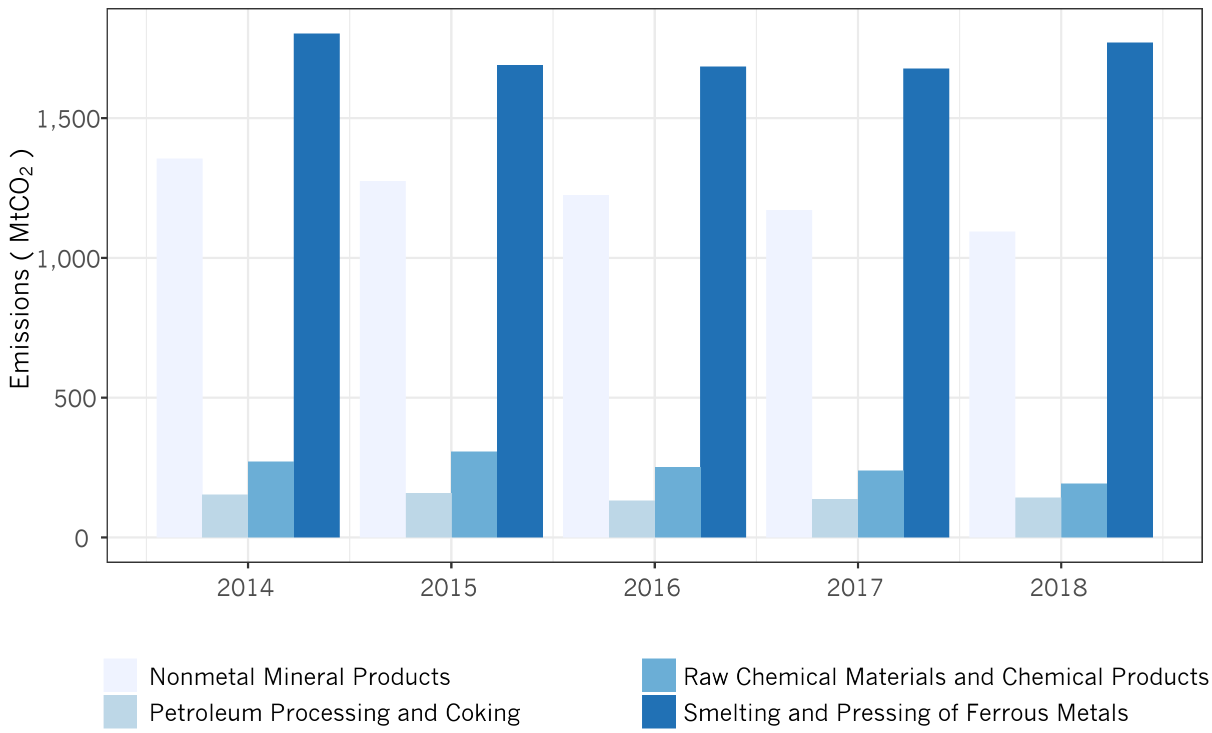
For some heavy industries, electrification rate in China currently is lower than other advanced economies' industries. In 2020, the portion of steel produced in China using an electric furnace was only about 9.2%, compared to 70.6% and 42.4% in the United States and the European Union, respectively (WSA, 2021a).

Rapid urbanization, infrastructure development, and increased consumption, domestically and globally, will likely continue growth of the industrial sector. Reducing CO_2 emissions in industry, while maintaining infrastructure growth, will be crucial to achieving carbon neutrality in China.

[14] Smelting and pressing ferrous metal mainly include ironmaking, steelmaking, steel and ferroalloy processing and manufacturing. Nonmetal mineral products mainly include the manufacture of cement, lime, gypsum, ceramics, etc. Raw chemical materials and chemical products mainly include the production of caustic soda and soda ash, the manufacture of fertilizers and pesticides, as well as the manufacture of synthetic rubber and industrial pigments. Petroleum processing and coking mainly refers to refining petroleum products from crude oil and converting coal into coke and chemical raw materials (like methanol and olefins).

FIGURE 6.1: CARBON EMISSIONS FROM CHINA'S MANUFACTURING SUBSECTORS IN 2014-2018

(Source: CEADs, 2021). In addition to combustion emissions, Nonmetal Mineral Products include process-related emissions, which are not found in other industries.



6.2 ROLE OF INDUSTRY ELECTRIFICATION IN CARBON NEUTRALITY

To achieve net-zero emission goals, industrial electrification will become one of the important and feasible solutions in China. Deep electrification, combined with power decarbonization, is a key element in achieving China's climate target.

Reducing emissions in the near-term, while accounting for sector growth is essential. Total industry demand is expected to increase through 2030/2035, and then decline from about 1,890-2,121 Mtce in 2020, to 1,075-1,832 Mtce in 2060 (Figure 6.2). Based on our results, the electrification rate of the industry sector should reach about 42-65% in 2050 and 58-69% in 2060. Our results suggest it is technologically feasible to electrify more than half of the industrial energy consumption, with electricity demand ranging from 672-1,100 Mtce in 2060 (Figure 6.3). Hydrogen share varies across models, with an anticipated share ranging from 1.7-12%, and a median share of 4.7%, by 2060 (Figure 6.4). Electricity share before 2040 varies across models, in part due to variations in forecasts of overall industry demand. Some models show declining total industrial final energy use after 2025, while others show continued growth through 2030. Models with continued growth assume a significant portion of increasing demand will be met with electricity production. Rapid fossil phase-down, starting in 2040, increases electricity share for models that project lower near-term electricity growth.

FIGURE 6.2: INDUSTRY FINAL ENERGY CONSUMPTION IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) TOTAL FINAL ENERGY, (B) FINAL ENERGY BY FUEL.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA).

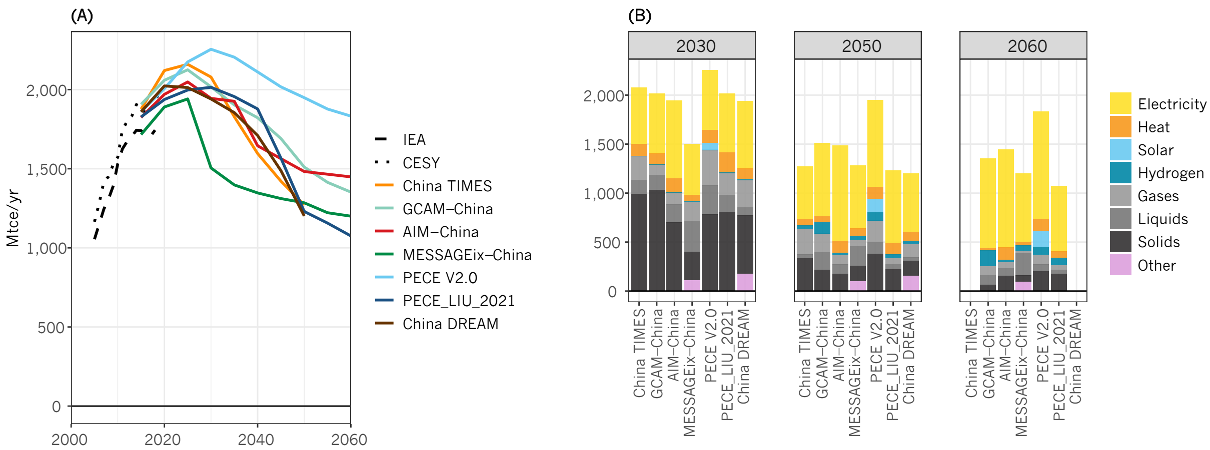


FIGURE 6.3: ELECTRIFICATION IN INDUSTRY SECTOR IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO. (A) ELECTRICITY DEMAND. (B) ELECTRIFICATION RATE.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA). The electrification rate of PECE V2.0 does not include the electricity from distributed PV in industry.

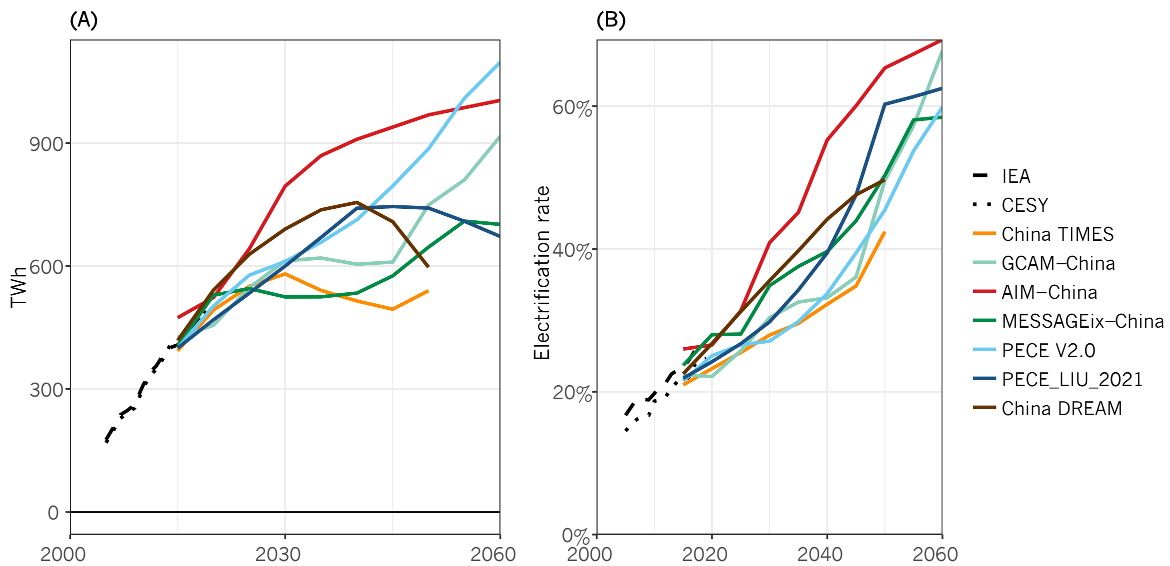
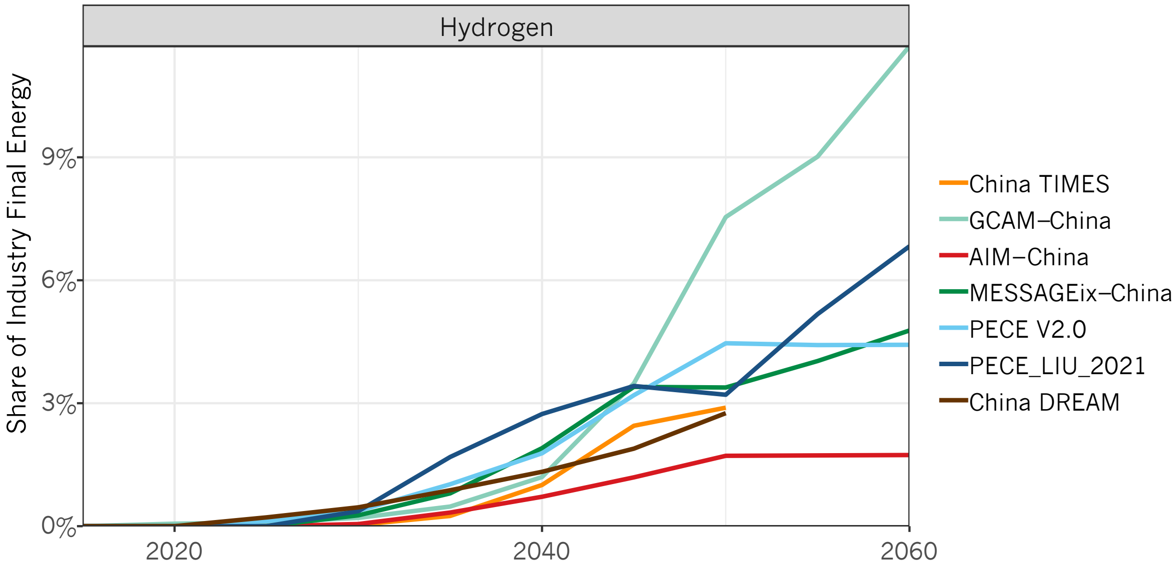


FIGURE 6.4: HYDROGEN SHARES IN INDUSTRY SECTOR IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.



The industrial sector comprises many sub-sectors whose energy needs and manufacturing processes vary greatly. Light industry provides products directly for residents' consumption, while heavy industry often provides materials for other industrial sectors, with larger equipment and more energy consumption. Electrification has been low in several heavy industries, including iron and steel, cement, petrochemical and chemical. However, some machinery and equipment manufacturing sectors currently have more than 40% electrification adoption (Deason et al., 2018). Given its limited reliance on high-heat, or other energy intensive infrastructure, light industry, including textile and pulp and paper, is the easiest sub-sector of industry to electrify.

Iron and steel production has higher electricity substitution compared to cement, petrochemical and chemical products (Figure 6.6). According to past steel capacity and consumption, there will be a significant increase in scrap resources in China. Enterprises in the iron and steel industry are larger and have abundant funds to replace equipment with electrified updates. Moreover, as a means of indirect electrification, green hydrogen could be applied in steel and chemical industries in the future.

While future demand for industrial products is uncertain and dependent on a range of factors, it is expected that the demand for steel, cement, electrolytic aluminum, and most petrochemical and chemical products will continue to grow in the short term. One model predicts that total industrial energy consumption will continue to grow until 2030, followed by a gradual decline due to the reduced demand for industrial products from decreased population and a slowdown in urbanization. Reductions in demand for steel and cement are the main drivers for the decline of energy consumption after 2030 (Figure 6.5).

FIGURE 6.5: ENERGY CONSUMPTION BY INDUSTRIAL SUBSECTOR IN THE PECE_LIU_2021 MODEL[15].

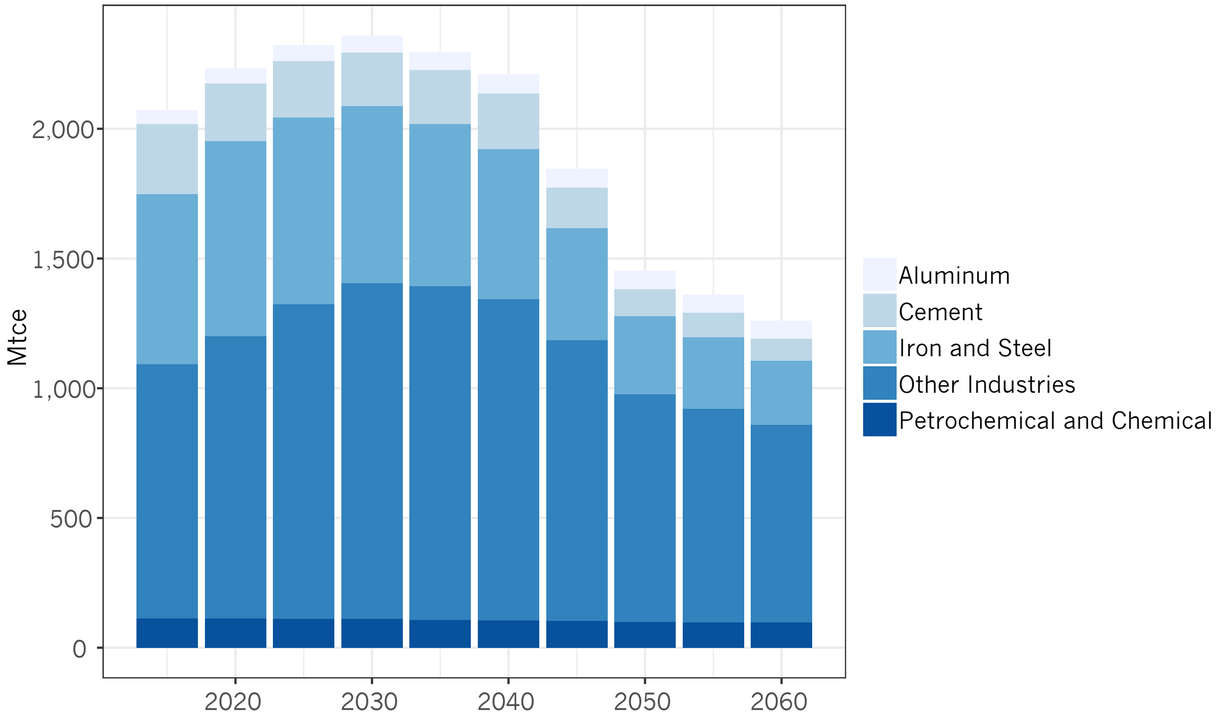


FIGURE 6.6: SHARE OF ENERGY CONSUMPTION BY INDUSTRIAL SUBSECTOR IN THE PECE_LIU_2021 MODEL.

Only green hydrogen produced via electrolysis is presented as hydrogen fuel in the figure. Other hydrogen produced from coal and natural gas are shown in the form of the original energy source.

[15] PECE_LIU_2021 is a national energy system model which focuses on China's long-term low carbon transition roadmap for climate targets (J. Liu et al., 2021). The scenario results have been updated to reflect China's carbon neutrality pathway in this report.

6.3 CHALLENGES AND OPPORTUNITIES

Industrial electrification is of great significance to industrial development, economic growth, energy conservation, and emission reduction. Increasing industrial electrification will require planning, outlining technical potential, and garnering support from policy makers and utilities. Industrial electrification offers several co-benefits, including improvements to health and safety, as well as to economic growth, but updating structures and processes built around fossil fuel consumption will be challenging.

Challenges

It is difficult to adjust the production process adapting electricity substitution due to the high integration of industrial equipment. Converting industrial equipment is not always as simple as swapping a coal-powered boiler for an electric one. A plant's circuits and electricity service need to be upgraded to power an enhanced electricity load. The ease of electric equipment integration varies across subsectors and manufacturing processes. Additionally, because upgrading to electrical equipment may require redesigning specific systems and manufacturing lines, the investment in related equipment upgrading is much more expensive than the one-time investment in purchasing equipment, as additional expenses will be incurred. Compared with the direct use of combustion fuel, the economics of electricity consumption is also a key factor for electrified equipment.

China's large traditional industry capacity and high cost for replacement make electrification challenging. In China, existing production capacity is relatively new, with an average age of around 15 years in the steel sector compared with around 35 years in the United States and over 40 years in much of Europe (Tong et al., 2019; Q. Zhang et al., 2021). For most equipment, there are limited operation and maintenance costs throughout the lifecycle, leaving little incentive to upgrade equipment before the end of useful life. Electricity equipment replacement before the end of the useful life leads to stranded assets. Blast furnaces are the main source of energy demand and carbon emissions in China's steel sector, comprising more than 0.8 billion tons of capacity, and replacement with electric blast furnaces poses a large stranded asset risk (WSA, 2021a; Zhou et al., 2020).

Electricity costs relative to direct use of combustion fuels are a critical factor for uptake of electric technologies. Electrification, if electricity prices are high, could have an adverse effect on industrial production costs and product price competitiveness. This can have a wide impact across industrial production, without considering carbon prices. For example, high scrap price for short-process electric furnace steelmaking can lower cost competitiveness for ground-source heat pumps compared to traditional heating by coal/natural gas boilers.

While costs are a key consideration for electrification of some industries, other industries have limited electrification equipment options. Some industrial processes are not currently designed to use electricity, because of the high temperature and high heat demand of energy intensive industries. Electrified alternatives are not currently available for many applications, including high temperature processes such as cement manufacturing (Deason et al., 2018). Heating equipment used for drying, curing, calcination and melting is difficult to achieve the transformation from fuel to electricity. Some technologies are not mature enough to be widely used and are still in the stage of commercial demonstration. Many industrial processes require high temperature electrification technology. Some technologies, such as electric boilers, hybrid boilers and low temperature industrial heat pumps, have been commercialized, but the costs are still prohibitively high.

TABLE 6.1: SELECTED INDUSTRIAL ELECTRIFICATION TECHNOLOGIES

(Source: IEA, 2021a).

Technology	Maturity	Timeframe
	Steel	
Electric tunnel kiln for steel	Demonstration	Started 2018
Direct reduced iron steelmaking with high shares of hydrogen blending	Demonstration	Started in 2020; commitments from major steel manufacturers to invest in and scale up direct reduced iron steelmaking with hydrogen between 2020 and 2030
Smelting reduction with hydrogen blending	Demonstration	Expected 2021
Blast furnace steelmaking with hydrogen blending	Concept	Started 2021
Other hydrogen-related	Concept	Started 2019
	Chemicals	
Methanol synthesis	Demonstration	Complete
BTX aromatics from methanol	Prototype	Started 2013

Opportunities

Industrial electrification will require updating sector transformation and upgrading of production processes and, potentially, even product structure. Some potential co-benefits from electrification include improved technical safety, manufacturing stability, and process optimization. According to the second national survey on pollution sources (MEE, 2020), industry contributed more than 75% of sulfur dioxide and particulate matter emissions in 2017, which are mainly caused by fossil fuel combustion. Reducing coal consumption in industry will likely increase the consumption of electric boilers. Electrically powered industry processes do not rely on combustion of fuels onsite, eliminating emissions from the end-use sector (Deason et al., 2018). With a decarbonized power sector, industrial electrification will greatly reduce pollutant emissions in the whole production process and upstream manufacturing. Electrification could indirectly reduce SO_2, NO_x, PM and CO_2 emissions compared to current level in 2014 by 19–25%, 4–28%, 20–29% and 11–12%, respectively, if the proportion of clean electricity in the power sector reaches 70% (Qian et al., 2021).

Although China is the largest manufacturing region, it's not the leader in high value-added industries, such as high-tech industries. With the advancement of electrification and expansion of China's domestic market, development of high value-added industries will continue to increase, as noted as an important policy in "Made in China 2025". Electrification, along with demand for new technologies and new products, will create industrial opportunities and new models for industrial processes. Overhauling existing processes and replacing infrastructure with electric alternatives also may offer the opportunity for increased efficiency throughout processes.

6.4 KEY AREAS FOR INDUSTRIAL ELECTRIFICATION

Industrial Restructure and Upgrade

Electrification is the conversion process of terminal energy demand from fossil fuels to electricity, with a significant impact on the change of industrial structure. Raw materials and accessories required for electrification equipment are no longer obtained from traditional upstream industries. Industries related to fossil energy and gas turbines are facing recession crisis, while battery, motor and other related industries are facing rapid development opportunities. Unlike the industrial chain of fossil fuel processing, such industries as battery and motor are horizontally distributed in the industrial chain.

Updating industrial processes for electrification is an essential step. As processes are adjusted and electric technology substituted for fossil-dependent infrastructure, developing strategic focuses within industry, particularly in high-value areas, as well as digital networks, will be key for creating efficient upgrades. Updating processing and manufacturing of different industries will face development opportunities and challenges. These updates need scientific and technological support to help engender new technologies, models for development, and more strategic emerging industries. Electrified applications can be equipped with smart controls, offering an advantage over traditional automation technology that has been unable to meet the development needs of modern industry. Electrification can reduce labor costs, operate power equipment more efficiently, and greatly improve the production quality of industrial enterprises. Electricity substitution usually offers digital control and improved manufacturing flexibility. Electrification and digitalization link more enterprises and technologies, which can provide an impetus for the industrial ecology and circular supply chain. Increasing material and energy efficiency can help to reduce emissions through retrofits and process redesign. Optimizing cement make-up can reduce emissions by 50% (Lovins, 2021).

Production Process Adjustment and Electric Substitution Technology

According to the statistics of World Steel Association, the proportion of short-process steelmaking in electric furnaces in China is only 10% (WSA, 2021b). The global proportion of electric furnace steel is about 28%; the average proportion of electric furnace steel in other countries outside China is close to 50% – 65% in the United States, 40% in the European Union, 30% in South Korea and about 25% in Japan (WSA, 2021a). In 2050, the proportion of electric furnace steel in China will increase to 45%, and the proportion of scrap in the total materials will rise from 25% in 2019 to more than 50% (IEA, 2020b). The electrification of the steel industry will bring about the adjustment of the overall production line.

Low, medium, and high temperature heat (<1000 degrees °C) electrification technologies are available today (Roelofsen et al., 2020). These processes include food preparation, evaporation, distilling and petrochemical reforming. Very high heat technologies, used for calcination of limestone in cement production, are still in the research or pilot phase (Roelofsen et al., 2020). Lower temperature heat could be substituted with electric technologies in food and beverage, plastic and rubber industries and some types of glass production (Wei et al., 2019).

Light industry has shifted from fossil fuel heating to industrial heat pumps and electric boilers required for medium and low temperature heating. Electrification potential of light industry is close to 100%, for production of products such as food, lime, pulp and paper (NBS, 2021). Light industry already meets its steam demand or temperature needs by electric boilers, electric furnaces, heat pumps, and electric cold storage. Identifying and converting as many light industries as possible to become nearly 100% electrified in the near term is critical for meeting industry-wide electrification targets.

Advanced Industrial Electrification Technology

The emerging technology of electric heating has high cost and needs to be improved in technical maturity. But it may have application potential in higher temperature fields or sterilization and curing needs, such as pulsed electric technology, ultrasound, ultraviolet electroslag, and plasma technology. The temperature required for the processing and manufacturing of building materials (such as cement, glass and ceramic.) is often about 1,500°C. It is difficult but feasible to electrify high temperature furnaces, like flat glass furnaces (1,600°C); cement dry kilns (1,500°C); and brick kilns (1,200°C) (Deason et al., 2018; Roelofsen et al., 2020). Electric tunnel kiln is an industrial kiln with electricity as energy, which could be widely used in the roasting production of building products. Purr et al.(Purr et al., 2014) describes the transition away from fossil fuel to a combination of electric furnaces and electrolysis production of hydrogen. In the field of building materials, developing electric heating furnaces for building materials such as cement electric kilns, glass electric melting furnaces, and ceramic electric kilns is needed for industrial process electrification.

Microwave heat technology for industrial production can not only effectively improve the reaction conversion and selectivity, but also reflect many advantages, such as energy saving and environmental protection. The processing of aluminate cement by microwave technology not only meets the processing temperature (1,000°C ~ 1,300°C), but also greatly speeds up the sintering reaction of the clinker. RD&D projects on microwave heat technology could be highly valuable to expand the application of microwave heating in the industries with drying, evaporation, melting, reacting, processing, and sterilization needs.

Indirect electrification pathways enable electricity to replace fossil fuel demand in industry, through hydrogen electrolysis production. Taking the iron and steel industry as an example, hydrogen energy can be applied to hydrogen-based DRI. This technology is theoretically zero-carbon with the realization of zero-carbon electricity in the future. Since the technology is not mature enough before 2030, hydrogen and coke can be mixed and added to the traditional DRI-EAF and BF-BOF as a transition choice (IEA, 2020b).

BOX 6.1 ELECTRIFYING PROCESS HEATING SYSTEMS IN CHINESE INDUSTRIES

What are process heating systems?

Process heating systems supply heat to materials for manufacturing purposes in furnaces, melters, heaters, kilns, ovens, lehrs, calciners, and other heating systems. These systems include a variety of heating processes, such as steam generation, fluid heating, calcining, drying, heat treating, metal treating, metal and non-metal melting, smelting, agglomeration, curing, and forming. Process heating temperatures can range from as low as 100°C to as high as 1,600°C. Process heating systems use many different types of energy sources to generate heat, such as fuels (e.g., coal, natural gas, biomass), electricity, steam, hot water, liquids (e.g., fuel oils), and others. Globally, process heating energy use accounts for about one third of all industrial energy use, about 80% of which is generated by fossil fuels (BloombergNEF & WBCSD, 2021).

Electrification of process heating systems

As the cost of renewable technologies continues to decline, and the power sector decarbonizes, electrification is an increasingly promising low-carbon option for industry. While decarbonizing high-temperature manufacturing processes will be challenging, increasing the rate of electrification using zero-carbon electricity is an important near-term strategy to decarbonize lower temperature industrial processes. In addition to reducing emissions of greenhouse gases (GHGs) and key air pollutants, the use of zero-carbon electricity has other non-energy benefits, such as increased productivity, improved product quality, enhanced operational and worker safety, increased manufacturing flexibility, reduced waste production, and reduced cost of environmental compliance (Rightor et al., 2020).

Key technologies to electrify process heating systems

A number of commercially available or emerging electrotechnologies are presented in Table 1 . Electric boilers, hybrid boilers, and low temperature industrial heat pumps are already commercially available and can be adopted in many industries that have steam demand. Higher-temperature industrial heat pumps are also emerging to further electrify process heat. Other commercially available electrotechnologies, such as infrared heating, induction heating, and resistance heating, can be used in industries with metal or chemical processing needs or processes with lower temperature demand (e.g., drying and evaporation). There are also many other emerging electrotechnologies with potential applications in industries such as primary metals, food, textiles, automotive manufacturing, and machinery.

TABLE B6.1: SELECTED ELECTROTECHNOLOGIES FOR PROCESS HEATING SYSTEMS

(Source: Deason et al., 2018; EECA, 2019; Jadun et al., 2017; Rightor et al., 2020).

Technology	Maturity	Cost	Industry applications
Electric boiler	Commercial	Low-Medium	Many industries, with steam demand
Hybrid boiler	Commercial	Medium	Many industries, with steam demand
Heat pump	<100°C: commercial 100-150°C: emerging >150°C: R&D	Low Medium High	Many industries with corresponding temperature needs
Infrared drying	Commercial	Low-Medium	Industries with drying, evaporation, melting, reacting, processing, mold forming needs
Resistance heating	Commercial	Low-Medium	Industries with metal, plastics, chemical processing needs
Extrusion porosification	Commercial	Low-Medium	Industries with melting, reacting, and processing needs

Technology	Maturity	Cost	Industry applications
Induction heating	Commercial	High	Industries with melting, reacting, and processing needs
Friction heating	Commercial	High	Industries with melting, reacting, and processing needs
Ohmic drying	Emerging	Medium	Industries with drying, evaporation, melting, reacting, processing, heat treating needs
Microwave, radiofrequency	Emerging	High	Industries with drying, evaporation, melting, reacting, processing, and sterilization needs
Pulsed electric field	Emerging	High	Industries with sterilization, melting, reacting, and processing needs
Ultrasound	Emerging	High	Industries with enhanced drying, sterilization needs
Pulsed light	Emerging	High	Industries with sterilization needs
Ultraviolet	Emerging	High	Industries with sterilization and curing needs
Electroslag, vacuum, plasma	Emerging	High	Industries with higher temperature needs

Current electrification potential in process heating systems in China

The top five energy-intensive sub-sectors in China's industry sector – iron and steel, chemicals, non-metallic minerals, petroleum refining and coking, and non-ferrous metals, which represent 83% of total manufacturing final energy use in China - are the largest users of process heating systems. Lu et al. (Lu et al., 2022) analyzed these top-five energy-intensive subsectors and found that process heating systems accounted for 24% to 84% of final energy demand in these industries. Specifically, process heating systems accounted for 84%, 79%, 78%, 54%, and 24% of the final energy demand in China's cement, iron and steel, petroleum refining, chemicals, and aluminum industries, respectively.

The electrification rate in China's heavy industry has been very low and was flat from 2000 to 2017 (NBS, various years). When including electricity used for both process heating systems and non-process heating systems (e.g., machine drive systems, process cooling and refrigeration, electro-chemical systems, facility HVAC, and facility lighting), electricity represented only 7% of total final energy use in the petroleum refining and coking industry; 10% in ferrous metals; 15% in non-metallic minerals subsector; and 16% in chemicals. Electricity penetration is higher in the non-ferrous metals subsector, reaching 66% (Lu et al., 2022).

By adopting today's commercially available electrotechnologies, such as electric boilers, hybrid boilers, industrial heat pumps, resistance heating, and induction heating, a portion of the current process heating energy demand can be electrified. This could be done either through electrifying steam production or replacing direct fossil fuel combustion with electrotechnologies. By combining electrification of steam and low temperature heat electrification, the average electrification penetration rate in process heating systems can be increased from 3.5% to 24% in these five energy-intensive industries (Lu et al., 2022).

Barriers to electrification and policy support

Increasing electrification faces a number of barriers. These include current low penetration of electricity in many of the key industries; higher electricity costs than fossil fuels; requirement for extremely reliable and constant energy supply; industry's aversion to any process disruption; long lifetime of industrial equipment; lack of credible information on electrotechnologies; complications and difficulties for integration of electrotechnologies in the existing production processes; lack of access to commercialized electrotechnologies; industry's preference for technologies or measures that have very short payback times; perceived and/or real high upfront costs; and financing challenges.

To pursue the decarbonization potential and non-energy benefits of using low-carbon electricity in industry, a number of policy tools and instruments could be considered (Shen et al., 2017), such as:

- Develop technology catalogs and guidebooks on electrotechnologies;
- Strengthen standardization and associated testing protocols on electrotechnologies;
- Provide incentives to encourage increased use of renewable electricity;
- Promote electrotechnologies in industry clusters that have access to low-carbon, low-cost electricity;
- Offer attractive green financing mechanisms to industries for low-carbon electrification, such as transition from supplying equipment to supplying steam or heat services;
- Accelerate R&D on emerging electrotechnologies;
- Develop public-private partnerships to pilot deployment programs to showcase innovative electrotechnologies;
- Strengthen regulatory enforcement and expand ultra-low emissions standards to process heating systems;
- Enhance technical support and capacity-building in process heating systems and electrification technologies for industry.

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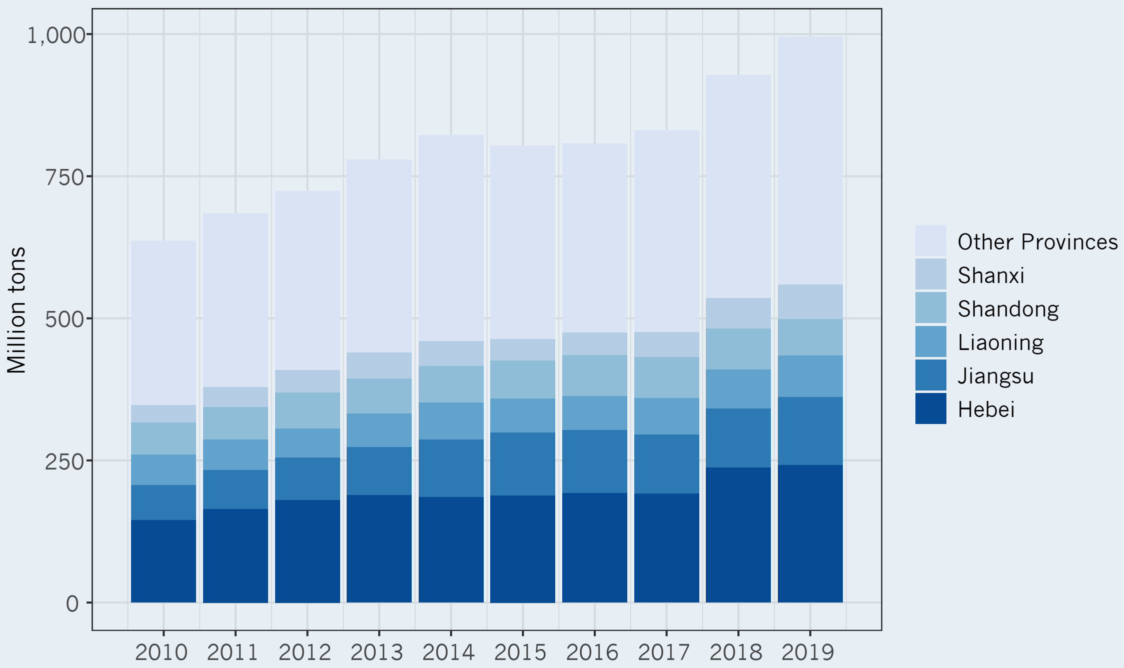
BOX 6.2: INDUSTRIAL ELECTRIFICATION IMPACT ON REGIONAL DISTRIBUTION OF STEEL CAPACITY: THE UNBALANCED PRODUCTIVITY OF IRON AND STEEL INDUSTRY IN CHINA

China has the largest steel production in the world – 1,053 million tons in 2020, accounting for 56.49% of the global production (WSA, 2021a). The layout of China's steel industry shows more production in northern and eastern China. In 2020, the crude steel production of Hebei, Jiangsu, Liaoning, Shandong and Shanxi provinces totaled 593 million tons, accounting for 56% of the country's total (NBS, 2021) (Figure B6.2). In 2019, Guangdong's steel output was only 33.82 million tons. This imbalance in production location means a large amount of steel needs to be transported over a long distance, from the north to the south, and/or imported from abroad. Steel is a resource-based industry, and China's iron and steel industry has been located near iron ore, resulting in scattered steel production that is also far away from the market. In 2020, the industry concentration of the top 10 steel enterprises (CR10) was only 39% (WSA, 2021b). Compared with other countries with high steel production, industry concentration of steel of the top three steel enterprises (CR3) in the United States, India and Japan reached 59%, 58% and 86% in 2020(WSA, 2021b). With the further promotion of joint restructuring, China's steel industry concentration (CR10) will become more than 60% by the end of the 14th FYP (MIIT, 2020), meaning steel may need to be transported over an even longer distance than today.

FIGURE B6.2: CRUDE STEEL PRODUCTION IN TOP 5 PROVINCES.

(Source: NBS, 2021).



The Ministry of Industry and Information Technology clearly puts forward that by 2025, the proportion of short process steel production in the total production of crude steel will be increased to more than 15%, with a possibility of reaching 20% (MIIT, 2020). This is a challenge for China's steel industry, because of the high cost of recycling and transporting scrap steel. Developing electric arc furnaces (EAFs) short process steel making based on scrap is not only an important way to achieve low emissions in China's iron and steel industry, but also an important part of the electrification process. There is a large amount of scrap and great potential for its use According to the China Association of Metalscrap Utilization, the total scrap steel was 240 million tons in 2019, an increase of more than 20 million tons compared with 2018 (Ren, 2020). Switching to the electrified steel-making furnace is also a major industry trend. Relocating steel enterprises and re-designing with all materials and processes in the supply-chain in consideration, including scrap recycling, transportation, production and supply, can help to reduce emissions. Many short process steel enterprises have emerged in Guangdong, Guangxi and Sichuan. Guangdong is an area with a developed urbanization process. Urban construction and renewal lead to rich local scrap resources. Southwest China has the advantages of regional electricity price and relatively convenient transportation. Developing short process steelmaking could produce construction steel to meet regional consumption characteristics. China Baowu has a production capacity of more than 100 million tons, ranking among the world's largest steel producers. Baowu has carried out industrial layout in Guangdong since 2020, developing short process steelmaking to handle scrap resources and meet regional steel demand. As the largest short process steelmaking group in China, Sichuan Metallurgical Control Group will reach 10.49 million tons of electric furnace steel and an annual output value of more than 100 billion yuan ($14.8 billion) by the end of 2021 (Sichuan Metallurgical Group, 2021). Redesigning the steel production supply chain can not only help to reduce direct emissions and increase electrification in the steel-making process, but also reduce indirect emissions from transportation and help develop a circular economy for local, scrap resources in urban areas.

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6.5 KEY POLICY APPROACHES

Challenges and opportunities coexist in industrial electrification. To achieve an ambitious carbon target, China's industrial electrification not only needs to achieve technological breakthroughs and incentives in technology, but also needs efforts from product innovation, industrial models, and platforms for demonstrating and training on new technologies.

Electrification is technologically feasible in many subsectors, but it faces implementation challenges. Comprehensive policies and incentives that will help overcome these barriers may be required. In moving forward to deeper electrification, a top-level framework design about cross-sectoral integration is necessary to strengthen policy coordination and cooperation. This policy framework needs to involve industrial policy, energy policy, environmental policy, carbon market policy, and financial support.

Current policy support for industrial electrification in China is quite limited. Existing industrial policies don’t offer electrification support systems, mechanisms, policies, and technical standards. Electrification needs more advanced services, advanced manufacturing, and high value-added products. New demands brought by electrification are driven by related technological innovation and industrial upgrading policies. Updating manufacturing upgrade policies will help industries with existing electric replacements swap their infrastructure to electric alternatives. Significant progress on electric technologies will be required, including direct electrification processes and indirect industry electrification through electrolytic production of hydrogen. Process development and redesign will be necessary in a wide variety of applications and industries. Research and development are necessary for both direct and indirect electrification to determine the best path forward in various industries and infrastructure needs.Equipment efficiency standards are set separately for electric and fueled devices. Adoption of one fuel efficiency standard may reduce the gap between electric and fossil-fueled devices deployment. Additionally, the latest double control policies, which are policies that target both energy consumption and intensity, mention that new renewable energy use is not included in the total energy consumption threshold. This means that industries can consume renewable energy beyond their traditional energy consumption limits through the adoption of electrification technologies. Additionally, developing green public and/or corporate procurement programs to increase demand on "low-carbon products” could help increase public demand for goods manufactured using electricity instead of fossil-fuel combustion, through public infrastructure projects, and development of certification standards to enhance transparency.

Electricity price is a key factor in stimulating industrial enterprises to carry out electrification substitution. Demand-response programs and electricity market design are essential. For example, time-varying pricing may encourage enterprises to avoid the peak period of power consumption, saving electricity charges to reduce production costs. Industrial subsectors that can be electrified with higher carbon reduction benefits do not have lower tariffs. Differential tariffs should be set based on consideration of comprehensive benefits. At present, high-energy and high-emission projects, such as electrolytic aluminum, no longer enjoy preferential tariffs. Industry electrification may work in combination with other policies and technologies, such as electricity price; product redesign and product recycling; innovation in basic material formulations, biomass-fuel utilization or bioenergy; and greater utilization of renewable energy for process heating.

Financial institutions are encouraged to expand green credit for electrification projects and reasonably reduce the cost of renovation. Electrification projects need to be given financial support, for example, encouraging eligible enterprises to issue medium- and long-term green bonds, and supporting enterprises to go public for financing and refinancing. Meanwhile, it is necessary for financial institutions to develop financial products for electrification transformation and technology promotion of key industries, such as iron and steel, petrochemical, and building materials. Financial product innovation could provide more transformation funds for these industries.

Including all industrial sectors in the carbon market is very important for promoting industrial electrification and low-carbon transition. China officially launched a national carbon trading market in 2021, but it only covers the thermal power industry. Several industrial subsectors, such as petrochemical, chemical, steel, and non-ferrous metals are actively promoting the relevant preparations for inclusion in the national carbon market. The diversity and complexity of industrial subsectors make it more difficult for them to participate in the carbon market, so the availability and reliability standards of industrial carbon emission data will become the first standards to be formulated. Carbon price and trading policies need to be further designed to accommodate industry participation.

TABLE 6.2: SUMMARY OF ACTIONS FOR ELECTRIFICATION IN THE INDUSTRIAL SECTOR.

Near-term Actions	Long-term Strategies

► Transition to industrial heat pumps and electric boilers for low and medium temperature heating needs in light industries.
► Deploy demand response programs and electricity market design, time-varying pricing, and other digital tools.
► Develop an industry electrification technology standard.
► Offer targeted transition finance products.
► Include all energy intensive industrial sectors in the carbon market ASAP.
	► Expand hydrogen use as a reduction agent in the steel industry and as a feedstock for ammonia and methanol production in the chemical industry for indirect electrification.
	► Increase production of steel from scrap in electric arc furnaces.
	► Develop industrial electric boilers, electric heating furnaces, electric metallurgical furnaces, and industrial heat pumps.
	► Promote and research advanced industrial electrification technology, including:
	  ► Induction or microwave heat technology for cement clinker production.
	  ► Direct reduced iron technology based on green hydrogen.
	  ► Infrared and ultraviolet heating technology for process heating: electronic heating technology, induction melting.
	► Establish transition finance mechanism, taking into account the demand for electrification funds and the function of risk management.

07 ELECTRIFICATION ROADMAP FOR TRANSPORTATION

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7.1 CURRENT STATUS

Of the different modes of transportation that include road, rail, aviation, and shipping, most of China's efforts to electrify have focused on the road sector, driven by expected growth in vehicles. China's passenger and freight vehicle stock increased significantly over the past two decades, growing from 20 million units in 2002 to more than 395 million units by 2021 (Xinhuanet, 2022). Passenger vehicles grew the most, increasing 18% per year on average, while freight vehicles grew 8% annually. In addition, the average vehicle lifetime is about 13 years for passenger vehicles (J. Zheng et al., 2019) and 10 years for freight vehicles (Moultak et al., 2017). The exponential increase in vehicle stock and the long lifetime of vehicles put significant environmental and energy security pressure on China. It is critical to identify pathways to mitigate these issues.

China takes the leading position in both consumption and manufacturing of New Energy Vehicle[16] (NEV), through broad policy support that includes financial incentives, municipal fleet electrification targets, non-financial incentives such as preferential licensing, and public and private investment in technology and infrastructure development. From 2011 to 2021, China's sales of NEVs increased more than 560 times, from 6,189 units sold in 2011 to about 3.52 million units in 2021 (MIIT, 2022). The market share of China's NEVs reached 13.4% in 2021, exceeding the global average of 8.57% (Paoli & Gül, 2022). Of the 3.52 million NEVs sold in China, more than 2.9 million NEVs were battery electric vehicles (BEVs), representing 83% of the NEVs sales in China. Other types of NEV vehicles include plug-in hybrid and fuel cell vehicles, selling 605,000 units in China in 2021 (MIIT, 2022). Globally, China alone accounted for more than half of global NEV sales (Paoli & Gül, 2022). Due to a number of factors, such as COVID-19 impacts, weaker economic growth, higher costs and expected decline in subsidies[17], the market share of NEVs in total truck sales decreased in recent years, dropping from 2.3% in 2018 to 0.9% in 2020. Total NEV trucks sold decreased from more than 85,000 in 2018 to a little more than 42,000 units in 2020, but increased to 47,534 units in 2021 (CAAM, 2021; OFweek, 2021).

By 2021, China's total NEV stock reached 7.84 million units (Xinhuanet, 2022). The share of NEVs in total vehicle stock has increased from 0.7% in 2017 to 2.6% in 2020. The vast majority of the NEV stock are BEVs, accounting for about 82% of all NEVs by 2021(Xinhuanet, 2022).

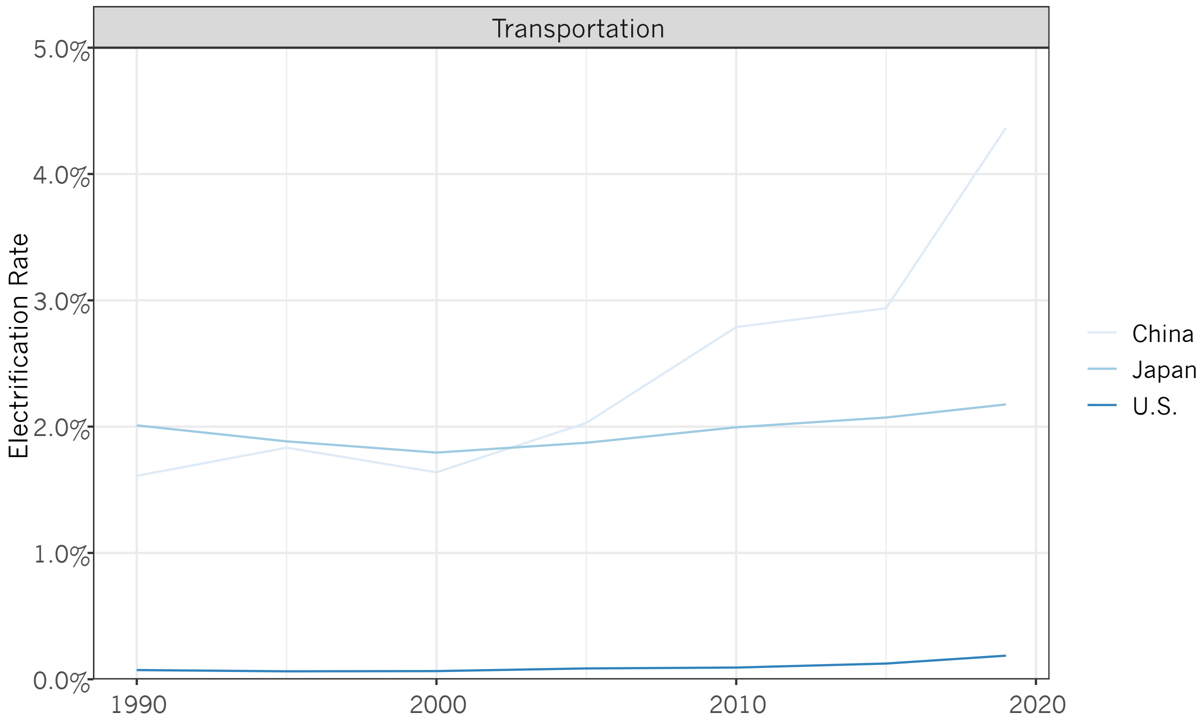
In terms of NEV infrastructure development, China represented 60% of installed public charging stations globally (McKerracher, 2021) while the United States only represented 6%. As of 2021, China had a total of 2.617 million charging stations, including 1.147 million public charging stations and 1.47 million private charging stations. Compared to the 2015 level, China's public and private charging stations have grown almost 20 and 184 times, respectively.

Transportation electrification in China has increased quite rapidly since 2000, and today is double, and almost quadruple, the electrification rates in Japan and the U.S., respectively (Figure 2). China has positioned itself as a leader in the electrification of transportation space, outpacing other countries, but continuing electrification expansion and targeting hard to abate sectors will be critical for climate change mitigation.

[16] NEVs include battery electric, plug-in electric and hydrogen fuel cell vehicles.
[17] In April 2020, the Chinese government announced that subsidies for purchasing NEVs will be extended through the end of 2022. Between 2020 and 2022, NEV subsidies will be gradually reduced by 10%, 20%, and 30% from the previous year. Overall NEV subsidies in 2022 will be reduced by 30% from the 2021 level. Subsidies for specialty vehicles (e.g., city buses, city logistics delivery vehicles, post delivery vehicles, city sanitation vehicles) in 2022 will be reduced by 20% from the 2021 level (MOF, 2021). Subsidies will end December 31, 2022.

FIGURE 7.1: HISTORICAL TREND OF SHARE OF ELECTRIFICATION IN THE TRANSPORTATION SECTOR OF CHINA, JAPAN AND THE U.S.

(Source: IEA, 2021d). Transportation includes all modes of mobile transport except for military fuel use. Electrification is defined as the share of total final energy supplied by electricity.



7.2 ROLE OF TRANSPORTATION ELECTRIFICATION IN CARBON NEUTRALITY

In addition to improvements in energy efficiency, electricity and other low-carbon fuels can help significantly decarbonize transport in the coming years. But, according to our modeling results, hard-to-decarbonize segments of aviation, shipping and heavy-duty freight continue to largely rely on different forms of oil products and natural gas, which still accounts for 14–31%[18] of transport energy consumption by 2050 in almost all models. Modeling assumptions about decarbonization across modes of transit vary. One model, AIM-China, found complete decarbonization of transport possible by 2050, as the hard-to-decarbonize segments are assumed to rely fully on a combination of electricity, hydrogen, biofuels, and methanol, and ammonia for shipping. Limited low-carbon options, combined with growing demand for mobility and transport energy services, present a challenge for emission reductions in freight transport across other models.

Most segments of passenger road transport can be rapidly and nearly fully electrified, as

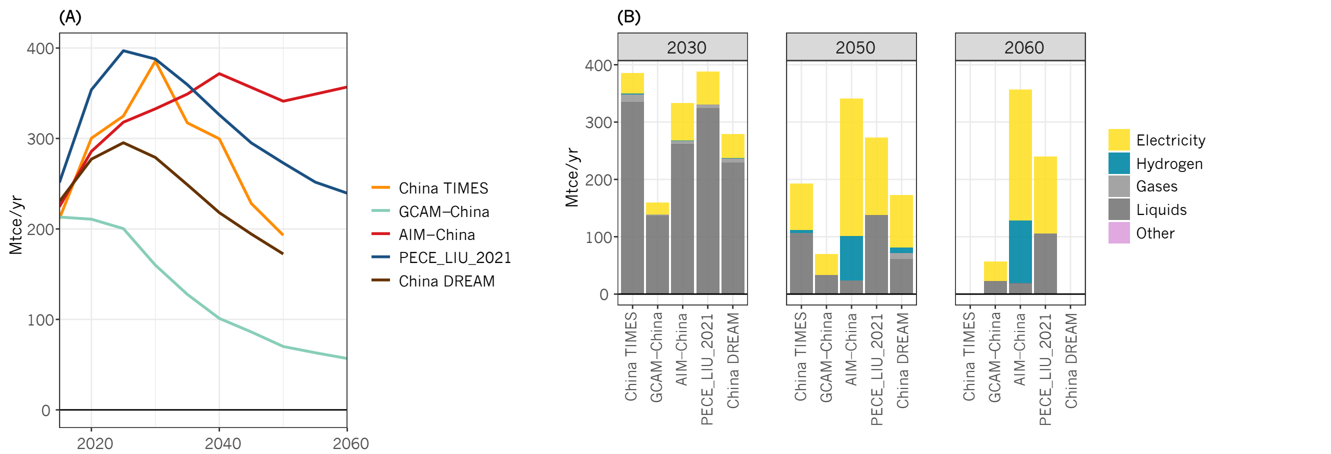
[18] This range excludes one model, AIM-China, that forecasts rapid oil phaseout of vehicles, and has only 0.3% of total final energy from transportation coming from oil in 2050.

demonstrated by the relatively high shares of 42–70% of electricity and 0–23% of hydrogen for overall passenger transport by 2050 (see Figure 7.2, 7.4, 7.5), but there is still aviation transport that is more difficult to electrify. The rapid rise in total sales and NEV market share in recent years and growing number of NEV models on the market for different vehicle classes, suggest light-duty and medium-duty passenger vehicles, including cars and buses, can be fully electrified relatively quickly. Heavy-duty passenger vehicles, such as larger, long-distance buses, may take longer to fully electrify, but China is already emerging as a leader and dominant player in global fuel cell bus production. However, the wide range in future electrification rates between different models and scenarios shown in Figure 7.4 highlight remaining uncertainties in the outlook for scaling up electric vehicle technologies across multiple classes of passenger vehicles, as well as uncertainty on alternative fuels such as biofuels.

Light- and medium- duty trucks are expected to be electrified rapidly with existing technologies and growing demand from intracity and logistics uses, while the electrification of heavy-duty trucks (HDTs) will depend on a mix of factors. These include the pace of NEV technological development, especially for hydrogen fuel cell technologies that can provide longer ranges; technologies for specific heavy-duty utility trucks; and declining battery costs. The slower and more uncertain expectations for electrifying freight is reflected in the overall lower rates and also in the wider range, of 19–30% in electricity share and 17–66% in hydrogen share for freight energy consumption, compared to passenger transport, by 2050 (see Figures 7.3, 7.4, 7.5). The wide range expected shares of both electricity and hydrogen reflects uncertainty in future technological development and deployment. However, the proportion of final energy in transportation that can be met by either hydrogen or electricity is fairly similar across most models (38–55% in 2050[19]).

FIGURE 7.2: PASSENGER TRANSPORTATION FINAL ENERGY CONSUMPTION IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) TOTAL FINAL ENERGY, (B) FINAL ENERGY BY FUEL.

Results shown include all modes of passenger transportation: road, rail and aviation. "Liquids" includes oil and biomass to liquid fuels. One model includes coal fuels.



[19] This range excludes one model, AIM-China, that forecasts rapid oil phaseout of vehicles, and has 94% of total final energy from transportation coming from electricity and hydrogen in 2050.

FIGURE 7.3: FREIGHT TRANSPORTATION FINAL ENERGY CONSUMPTION IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO: (A) TOTAL FINAL ENERGY, (B) FINAL ENERGY BY FUEL.

Results shown include all modes of freight transportation: road, rail and aviation. "Liquids" includes oil and biomass to liquid fuels. One model includes coal fuels.

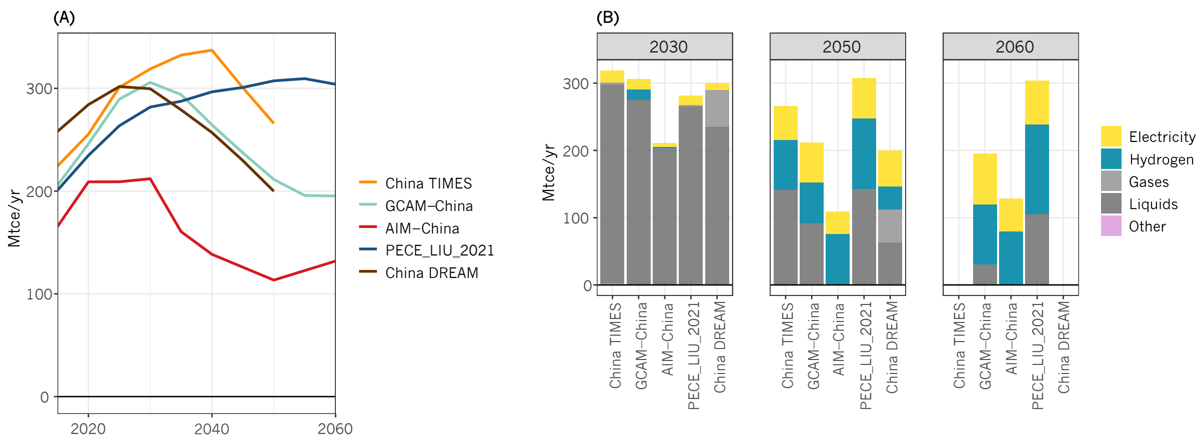


FIGURE 7.4: ELECTRIFICATION IN THE TRANSPORTATION SECTOR IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO. (A) ELECTRICITY DEMAND. (B) ELECTRIFICATION RATE.

Results shown include all modes of transportation: road, rail and aviation.

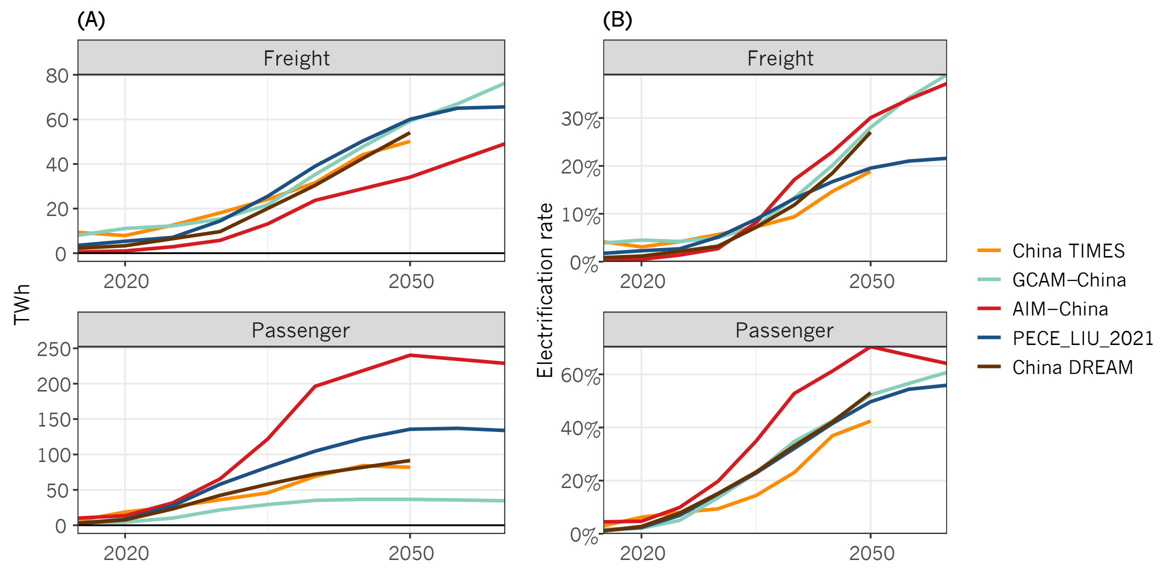
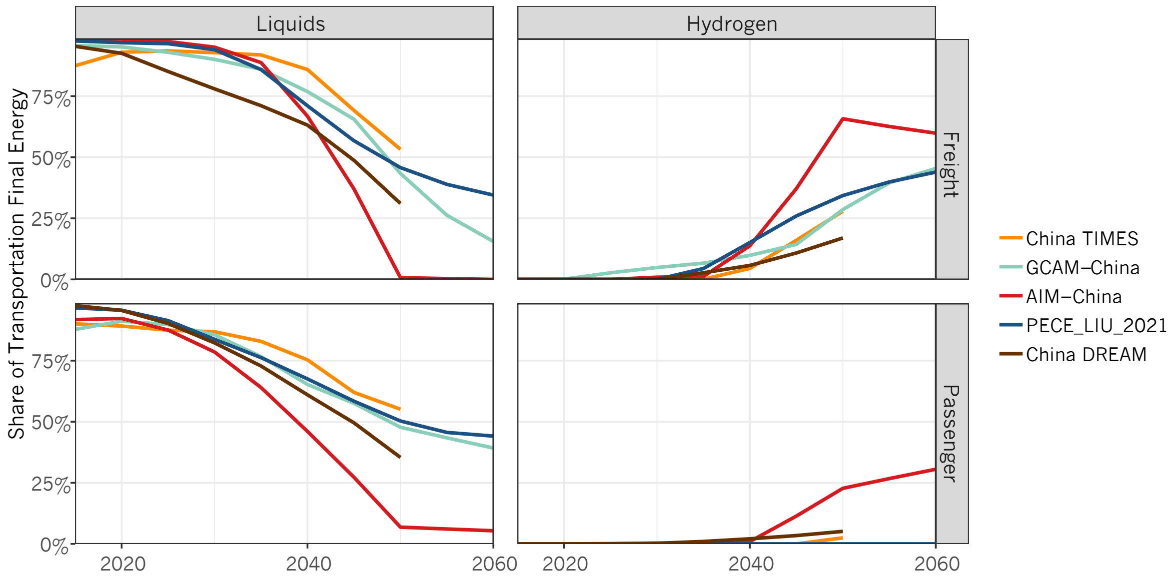


FIGURE 7.5: FUEL SHARES IN TRANSPORTATION SECTOR IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

Results shown include all modes of transportation: road, rail and aviation. "Liquids" includes oil and biomass to liquid fuels.



7.3 CHALLENGES AND OPPORTUNITIES

Challenges

The successful growth of NEV passenger vehicles and public charging infrastructure under existing policy support indicates that electrification will be less challenging for the passenger road sector. In particular, commercial and municipal fleet vehicles, such as taxis and buses, have electrified quickly in some cities with policy support. However, continued development of private charging infrastructure beyond just public chargers will be needed to support the quickly rising number of NEVs, particularly for private cars. The market's ability to sustain continued and rapid growth in private NEV vehicles sales after subsidies end will also determine the pace of passenger road transport electrification.

For freight, there are multiple technical, economic, and institutional challenges to fully electrifying road transport, particularly for the heavy-duty trucking segment. Although multiple battery electric HDT models are slated for commercial deployment with pilot production of fuel-cell HDTs expected in 2022, there is still no wide-scale production or deployment. The physical requirements for HDTs are much more challenging to electrify, including heavier weight, longer travel distances and operating times that require longer range and batteries with greater densities able to withstand more discharge cycles. Battery electric HDTs will also need fast chargers or face longer charging times for sufficient range. For hydrogen fuel-cell HDTs that could provide longer ranges, there are additional safety challenges for hydrogen transmission and distribution networks and need for large-scale "green hydrogen" production to support full decarbonization. From an economic perspective, while rapidly declining battery costs suggest electric HDTs could achieve cost parity with conventional diesel HDTs between 2025 and 2030 through fuel savings, hydrogen fuel-cell HDTs face much higher capital, fuel, and infrastructure costs, and a steeper learning curve that will delay cost parity until after 2030 (Mao et al., 2021). The current decentralized ownership and business model for heavy-duty freight and reliance on financing for new vehicle purchases also pose institutional challenges to electrification. In addition, competing demand for batteries for grid storage and limited raw material supply chains for batteries may increase future cost uncertainties and pose bottlenecks to full road transport electrification.

Infrastructure development for both battery electric vehicle charging and hydrogen transmission, distribution, and refueling is another area of challenge. To date, most of the electric charging infrastructure are public slow chargers intended for passenger vehicles, with about one-third as fast chargers and even fewer "megachargers" of greater than 1 megawatt capable of meeting HDT charging needs (IEA, 2021c). The current charging infrastructure also faces problems with: suboptimal distribution of charging stations, mismatch between demand and supply of electricity for charging, low utilization rates, compatibility issues among charging stations, parking difficulties, and long charging times (McLane & Liu, 2020). This suggests that operation and maintenance of existing charging piles will remain a challenge, as well as less certain business models for private charging infrastructure. Rapid road transport electrification will require an extensive network developed through coordination between public and private sectors, passenger and freight charging networks, and fast versus slow chargers. Development of next-generation charging infrastructure that can effectively integrate with the power grid and other land-use considerations (e.g. parking management) is also a challenge.

For air transport, where rapid demand growth is expected, electrification is technologically challenging, as there are very limited prototypes for electric aircrafts. Electrifying an aircraft with 600 miles range is currently very challenging, as it would require 4-5 times the specific energy of the current state-of-art battery technology (Gray et al., 2021).For hard-to-decarbonize modes of transport, bio-blend jet fuels, such as in the form of biojet, is a possible near-term "drop-in" alternative that does not require redesign and can replace existing technology without significant changes to plane engine or structure. But China faces limited overall bioenergy resources. Transition to synthetic fuels, such as combining hydrogen with captured CO_2, will be more difficult in the near term due to the long approval time needed for testing and certification of international jet standards (e.g. ASTM D7566) and high cost of synthetic fuels (Scheelhaase et al., 2019). Similarly, for shipping, blend walls limit the amount of biodiesel that can be used to substitute fuel oil. Alternative fuels, such as hydrogen fuel cells, can reduce cargo-carrying capacity and face refueling challenges, as hydrogen infrastructure at ports can be limited. Ammonia fuel cells are another option, but they have lower production efficiency than hydrogen (Gray et al., 2021).

Opportunities

Rapid subnational electrification of municipal fleets, as shown by Shenzhen's success in fully electrifying its taxi and bus fleets within four years, demonstrate significant opportunity for electrifying passenger road transport. Along with the largest number of EV models offered for different light-duty vehicle classes in the world, China has also seen the average BEV car price drop by 3% in 2020, with price parity with internal combustion vehicles expected by 2025 (IEA, 2021c). China is also the global leader in fuel cell buses production, with over 100 models of electric buses available (IEA, 2021c).

Electrification can also offer the opportunity for improved air quality. Local policies focused on reducing air pollution have helped increase the adoption of electric buses. For example, the ten designated cities and provinces for key air pollution controls in China accounted for half of the country's NEV buses. In these cities and provinces, NEV buses accounted for more than 70% of the market share of buses, versus much lower shares in other regions. The faster growth in electrifying the municipal bus fleet was supported through local policies, such as additional financial incentives, charging infrastructure development, and local targets for NEV shares for buses (CATARC, 2020). Similarly, national policies are also helping increase the market adoption of NEV trucks and setting NEV car targets of 50% by 2030 in key areas of air pollution control, such as the Beijing-Tianjin-Hebei area (MEE, 2022a).

Continued electrification of light-duty trucking is expected, with existing commercialized technologies for light-duty trucks and favorable economics expected for battery electric models. China has some models of medium-duty trucks on the market, but fewer models of HDTs, when compared to the U.S. and Europe (IEA, 2021c). However, key Chinese manufacturers, such as BYD and Geely, are introducing battery electric models of medium-duty and heavy-duty trucks, including drayage and regional haul trucks, and a semi-truck, to target both the Chinese and international markets (Kharpal, 2021). Growing policy support, including the introduction of new local subsidies for fuel cell vehicles, is also increasing the production capacity of China's hydrogen fuel cell vehicle manufacturers, including for Sky-well, Foshan Feichi, and Dayun truck manufacturers (FuelCellsWorks, 2022).

China is the global leader in the installation of publicly accessible chargers, with slow and fast charge installations increasing by 65% and 44% in 2020 relative to 2019 (IEA, 2021c). The successful growth in public chargers has reduced costs, with average charging prices dropping to 1 – 1.8 yuan/kWh ($0.15 – $0.27/kWh) in 2020 (McLane & Liu, 2021), providing affordability to urban NEV owners.

7.4 KEY AREAS FOR TRANSPORTATION ELECTRIFICATION

Electric Vehicle Manufacturing and Sales

There is growing support for passenger road electrification from both the vehicle manufacturing industry and subnational governments. Leading Chinese manufacturers are recognizing and tapping into the potential for domestic growth in the electric light-duty passenger vehicle market as well as opportunities to export to foreign markets. Major manufacturers, including Changan Automobile Group, Dongfeng Motor Co., and Volvo (Geely Group), have announced goals to increase the number of models sold or electric market share of total sales, while BYD has found success in export markets (IEA, 2021c).

With e-commerce as a key business driver, the private sector is also helping to drive light-duty road freight electrification with recent announcements by major Chinese retailers including JD, SF Express, and Suning, to use NEVs for their delivery and logistics fleets (IEA, 2021c). At the same time, cities are driving public bus fleet electrification efforts, with over 15 cities announcing electrification targets for urban bus fleet from 2019 – 2025 (IEA, 2021c), and major cities, such as Shanghai and Shenzhen, outpacing their initial municipal electrification goals.

In electrifying heavy-duty road freight, NEV HDT sales are growing relatively slowly in China, but there is growing interest and activity amongst domestic manufacturers. China's NEV HDT sales are dominated by a few leading domestic manufacturers, such as Dongfeng Motor, SINOMACH and Geely, but ranges and commercialization are still limited for specific subtypes (Mao & Rodríguez, 2021). For straight HDTs, Youngman Auto has emerged as a key player for hydrogen fuel cells, so there is market development. For battery electric and fuel cell heavy-duty utility vehicles, there is also strong competition among multiple manufacturers (Mao & Rodríguez, 2021), suggesting opportunity for growth.

Charging Station Deployment

For charging infrastructure, China has started anticipating the need for providing fast, high-powered chargers for HDT electrification, with the China Electricity Council working jointly with the CHAdeMO Association for fast, DC charging to develop ultra-high power charging standards for up to 900 kW and 1.8 MW megachargers (IEA, 2021c). Optimizing charging siting and user-focused charging infrastructure development can also help address very different charging demand patterns, such as between fast versus slow charging, charging proximity to home base, and time of charging, for individual segments within the broader EV market (McLane & Liu, 2020). Chinese manufacturers, such as Nio and Geely, have also developed business models for battery swapping. A national standard for battery swapping has been approved, which could also help address range constraints for heavy-duty vehicles.The existing electric vehicle charging stations are relatively concentrated in Beijing, Tianjin, Hebei, Shandong, Yangtze River Delta, and Pearl River Delta (China Automotive Research Center, 2021).

7.5 KEY POLICY APPROACHES

Based on international and China's own experiences, there are multiple policy options for accelerating passenger and freight road electrification (Table 1). For passenger road vehicles, where national NEV policies have already been introduced, subnational policies can help complement and further accelerate progress in electrification. These could include administrative policies such as licensing or traffic restrictions for conventional vehicles; target-setting for municipal fleets to drive the public passenger transport segments; and preferential policies and subsidies for zero-emission vehicles. For freight electrification, where existing policy actions have been limited, a mix of national policy options can help foster market growth through sales requirements or targets, low-carbon fuel standards, direct incentives or indirect incentives, such as weight exemptions for ZEVs, and investments in freight EV charging networks. In addition, subnational actions, such as pilot demonstrations for zero-emissions freight lanes or areas for medium and heavy-duty trucks, and zero-emission or ultra-low emission zones can accelerate local freight electrification.

To support the coordinated and effective development of charging infrastructure, targeting high-value, high-use charging segments, such as public and logistics fleets in public charging infrastructure roll-out, can help maximize charger utilization, which can help increase the profitability of charging investments (McLane & Liu, 2020). Priority permitting and guarantees of land, energy, and labor to help reduce regulatory and bureaucratic challenges to charging station siting and development can also help accelerate private charging infrastructure build-out.

To further decarbonize aviation and water transport, increased investments in researching and developing the processes needed for large-scale development and commercialization of synthetic fuels can help increase their technological feasibility. Additional policies, such as subsidies or government pilots, can help reduce the high costs of synthetic fuel production. Policies such as pricing carbon, increasing tax on conventional fuels, and compulsory blending quota can increase market adoption.

TABLE 7.1: SUMMARY OF ACTIONS FOR ELECTRIFICATION IN THE TRANSPORTATION SECTOR.

Near-term Actions	Long-term Strategies

▸ Electrify passenger light-duty and medium-duty vehicles including cars and buses, along with light and medium duty trucks faster, possibly through:
  ▸ NEV fleet-wide targets or sales bans on internal combustion engine (ICE) vehicles
  ▸ Incentives for early retirement of ICE vehicles
▸ Implement freight incentives and policies:
  ▸ Low carbon fuel standards for trucks
  ▸ Zero emission vehicle (ZEV) freight sales requirements/targets
  ▸ Pilots for zero-emission freight lanes/areas and zero emission zones
  ▸ Weight exemptions for ZEVs (heavy-duty vehicles)
  ▸ Direct incentives for ZEV purchases
  ▸ Direct and utility investments in EV charging
▸ Implement passenger incentives and policies:
  ▸ Car license plate restrictions, traffic restrictions
  ▸ Public or municipal fleet electrification targets
  ▸ Direct ZEV purchase subsidies and subsidized charging infrastructure use
  ▸ ZEV direct access, right-of-way and waivers for zero-emission zones
  ▸ Preferential parking policies for ZEVs
	▸ Develop hydrogen fuel cell technologies and advanced electrification technologies that can provide longer ranges for specifically heavy-duty utility trucks.
	  ▸ Expanded use of hydrogen and hydrogen-derived fuels produced by electrolysis.
	▸ Advance biojet/synthetic fuel development for air and water transport, potentially through:
	  ▸ Subsidies.
	  ▸ Government pilots.
	  ▸ Carbon pricing/taxes.
	  ▸ Compulsory blending quota for new fuels.
	▸ Promote the coordinated and effective expansion of charging infrastructure:
	  ▸ Public investment.
	  ▸ Priority permitting and guarantees of land.

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08 THE POWER SYSTEM AND ELECTRIFICATION

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8.1 CURRENT STATUS

Without significant power system changes to meet increasing demand and decarbonize power supply, end-use sector electrification will have a limited impact on achieving China's climate change mitigation goals. Today, combined heat and power plants and heat plants account for over 50% of combustion emissions (IEA, 2022b) and about 60% of power supply is from coal powered plants (CEC, 2021). Additional energy sector current trends and policies were discussed in chapters 2 and 4. Without taking any action, coal power capacity may grow by 158 GW through 2030 and may exceed 1230 GW during the 15^{th} FYP (Cui et al., 2022). Research suggests that decarbonization of the power system will be technologically feasible and economically beneficial (G. He et al., 2020), but how quickly the power system transitions away from fossil fuels depends on a variety of economic and policy factors, including technology costs and market conditions. Policies that increase power sector capacity, deploy additional distribution infrastructure, and promote the transition to renewable energy are critical for adapting to electrification and aligning with national climate targets.

8.2 TRANSITIONS IN THE ELECTRICITY SYSTEM

As sectors electrify, electricity demand will increase, with total electricity demand potentially reaching 12000-17000 TWhs in 2060 (Figure 8.1), compared to 8310 TWh (CEC, 2022b) currently. To meet this demand, our results suggest that by 2060 electricity generation is projected to double (Figure 8.1) and 5346-7445 GW of capacity will be installed (Figure 8.2). Emissions in the electricity sector likely need to be reduced 99-122% by 2050, requiring a transition from fossil fuels in the power sector to primarily non-fossil and renewable energy sources and increased adoption of negative emission sources, like biomass with CCUS. All models estimate a rapid decline of coal in electricity generation, from a share of 57-69% in 2020 to less than 6% of coal without CCUS by 2045 (Figure 8.3). By 2050, all models agree that coal with and without CCUS will contribute to only <7% and <1.5% of total generation, respectively.

FIGURE 8.1: ELECTRICITY SYSTEM TRANSITION IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO. (A) TOTAL ELECTRICITY GENERATION, (B) ELECTRIFICATION GENERATION BY TECHNOLOGY.

Historical data is from the Chinese Energy Statistical Yearbook (CESY) and the International Energy Agency (IEA).

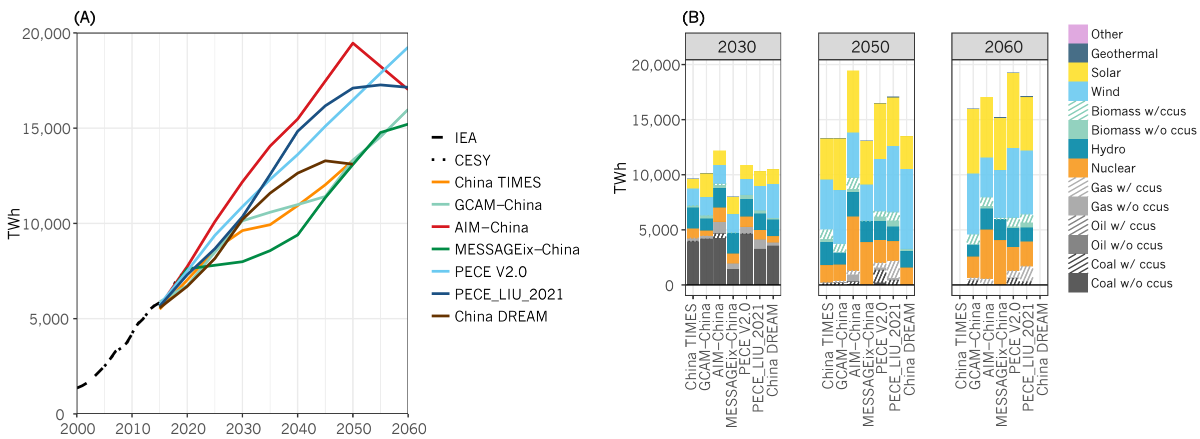


FIGURE 8.2: TOTAL ELECTRICITY CAPACITY BY TECHNOLOGY IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

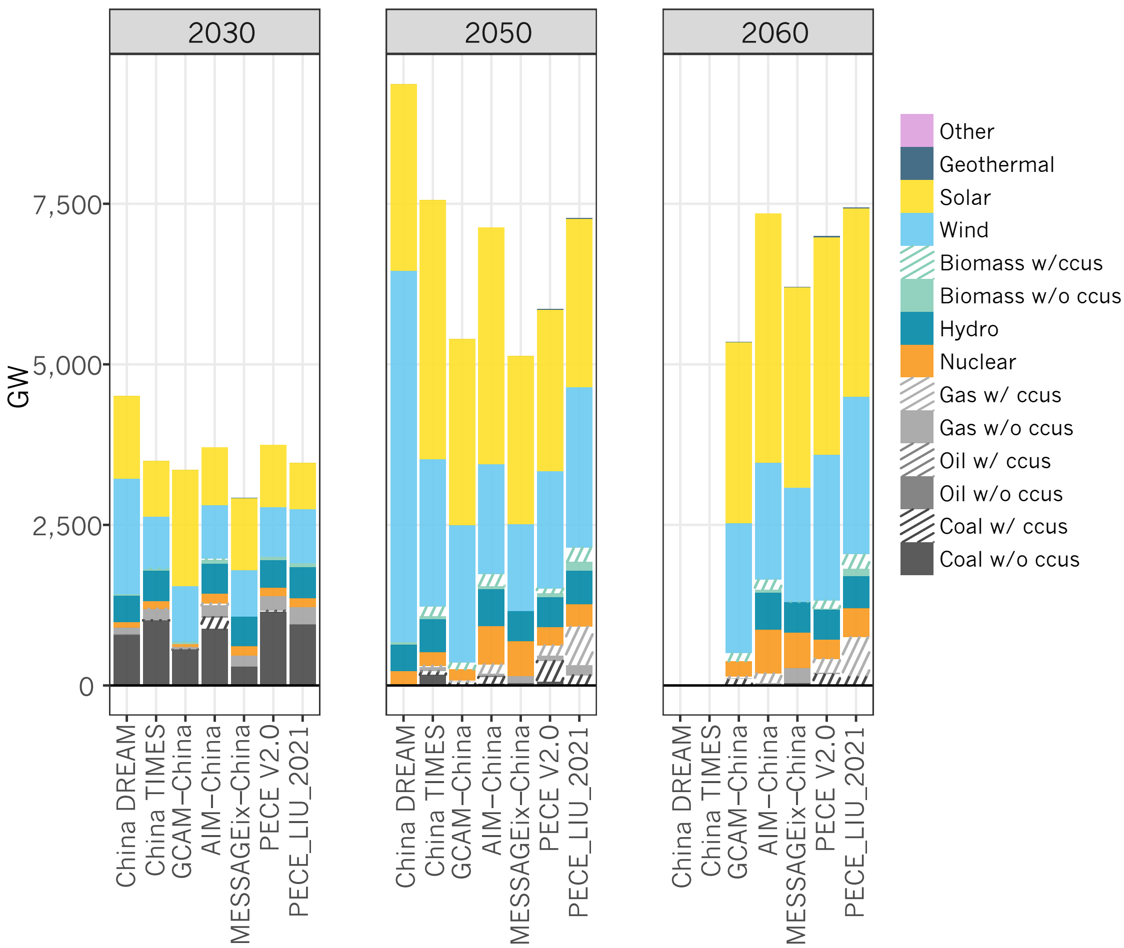
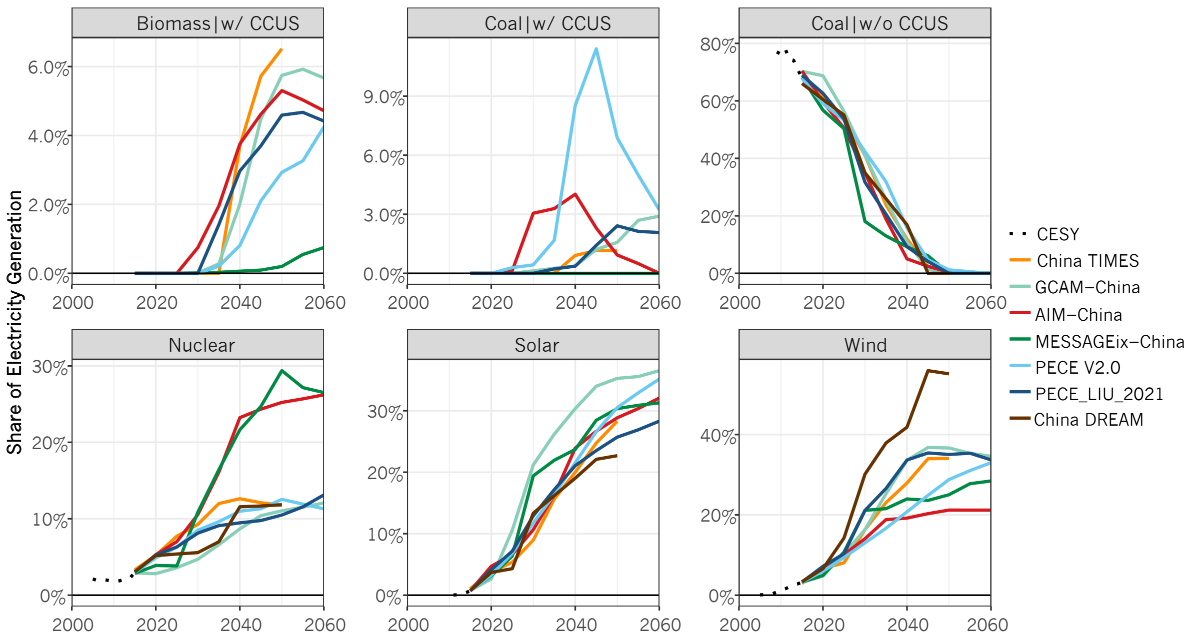


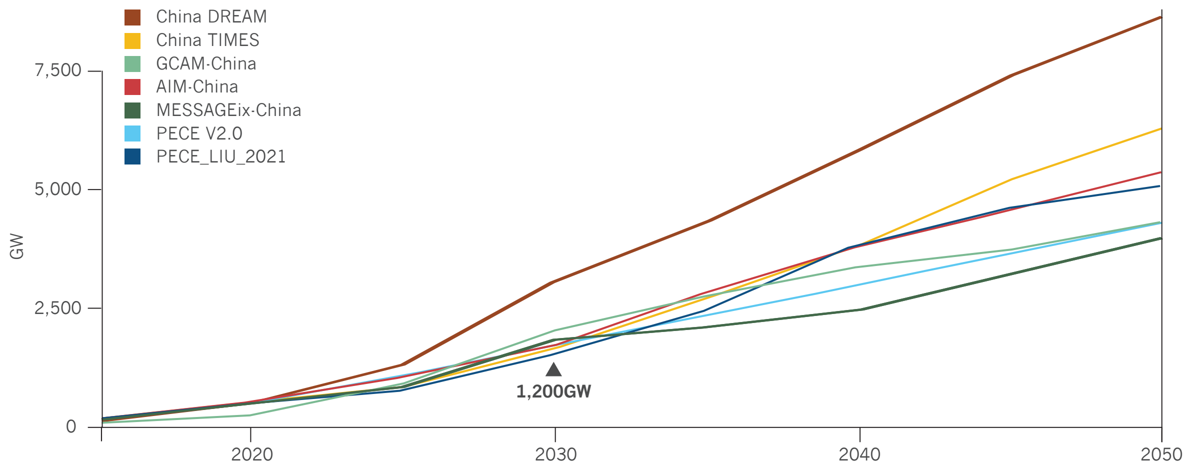
FIGURE 8.3: ELECTRICITY GENERATION SHARES IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.

Historical data is from the Chinese Energy Statistical Yearbook (CESY).



As renewable energy generation and total electricity demand continue to grow and coal-fired power generation is being phased-out, investments will be needed in non-fossil generation technologies, including wind, solar, nuclear, fossil with CCUS, and bioenergy with CCUS. Our results suggest that the bulk of generation will likely come from solar and wind, each making up 23-35% and 21-55% of electricity generation, respectively, by 2050 (Figure 8.3, Figure 8.4). Coal with CCUS, biomass with CCUS, and nuclear may play a significant role in ensuring grid reliability, in a power supply mix made up primarily of renewable energy. These three alternative technologies are projected to have a combined share of 19-31% of total generation in 2060 (Figure 8.3). In order for these technologies to play a significant role in the power market, policies to enhance CCUS in new power plants, add retrofits to existing facilities with CCUS, and expand nuclear projects where feasible, is critical. China's NDC target includes a commitment to installing over 1,200 GW of combined solar and wind capacity by 2030. All models exceed this target under the *Updated NDC to Carbon Neutrality* scenario, reaching 1,557-3,088 GW installed, suggesting room for higher ambition in this near-term target (Figure 8.4). China is already on a pathway to achieve this goal, as installed capacity of wind and solar reached 690 GW at the end of August 2022, with a 16.6% and 27.2% year-over-year growth in wind and solar capacity, respectively (NEA, 2022b).

FIGURE 8.4: SOLAR AND WIND CAPACITY IN THE *UPDATED NDC TO CARBON NEUTRALITY* SCENARIO.



BOX 8.1 EXPANSION OF NUCLEAR GENERATION IN CHINA

Unlike solar and wind, nuclear power is not weather intermittent, making it a potentially important tool for enhancing grid reliability. China's 14th Five-Year Plan set a target of reaching 70 GW of nuclear capacity by 2025. Our results suggest China will likely meet that goal, with capacity ranging from 20-90 GW, and a mean across models of 71 GW. Our results foresee nuclear power comprising about 10-13% of electricity generation by 2050, though two models project it could provide up to 25-29% of generation (Figure 8.3). Installed capacity ranges from 178 to 595GW in 2050 (Figure 8.2). The large variation in 2050 projections of nuclear energy across models reflects different assumptions for the key factors mentioned above. Additionally, nuclear deployment is partially dependent on the rate of coal phaseout and renewable deployment. Given the significant political and economic factors influencing nuclear power development, the role it will play in decarbonizing China's power system is unclear (S. Yu et al., 2020).

New technological developments may enhance the flexibility of nuclear power generation. Nuclear capacity is limited to coastal provinces, because water access is required for operation, putting these facilities at risk during extreme weather events and/or sea-level rise. However, new technologies with low water use are being developed, including third generation air cooling. Some fourth generation technologies may not need any water use, reducing future needs for coastal access (C. He, 2021). Third generation and fourth generation nuclear technologies are developing rapidly in China, with 14 units of third generation nuclear under construction. New nuclear energy utilization technologies for heat-supply pilot projects are being developed in several cities in China, for both space heating and heat supply for industry. Space heating by nuclear energy was promoted by the State Council (The State Council, 2021). It is expected that the cost of power generation will be lower than 0.3 yuan/kWh ($0.044/kWh) in the near future (Jiang, 2021), compared to a national average of 0.263 yuan/kWh ($0.039/kWh) for electricity produced by coal today (Renmin University of China and EFC, 2022). Space heating by nuclear energy may have a lower cost for heat supply than coal fired boilers and natural gas boilers (Jiang, 2022).

Political support for nuclear generation also may be changing. The government has expressed recent interest in promoting further development of nuclear energy (The State Council, 2020), which is regarded as a significant change from previous government policies on nuclear expansion. The development of nuclear energy was clearly mentioned in the new policies in the *Action Plan on Carbon Emission Peaking Before 2030* (The State Council, 2021). However, research suggests that there are a number of factors that can contribute to nuclear deployment, and that future expansion is dependent on electricity demand growth, technology costs, energy and climate policies, and increases in inland provinces with nuclear plants (S. Yu et al., 2020).

8.3 CHALLENGES AND OPPORTUNITIES

Challenges

In a highly electrified power system, the grid's proportion of renewable energy must be increased to meet climate change mitigation goals. However, wind and solar power, the two most important renewable energy resources, are highly intermittent and raise concerns about power system security and reliability. Enhancing grid flexibility, or the ability of the power system to balance supply and demand and maintain continuity (Impram et al., 2020), is critical for ensuring reliable, clean electricity access.

Increasing non-fossil energy sources in the power system will require adapting to existing geospatial discrepancies between power supply and demand across China. The three northern grid regions have high renewable energy potential and coal resources, while there is heavy electricity load in the South and East regions (W. Chen et al., 2010). Northern regions have a high wind potential, with around 80% of onshore wind capacity in the North, Northeast and Northwest regions (IRENA, 2014), but small demand (W. Liu et al., 2011). Research suggests that current geospatial differences in renewable generation will continue, as Yunnan, Hainan, Inner Mongolia, Xinjiang, and Qinghai are ranked as the top provinces for renewable share (without hydro) in both 2030 and 2060 (Lou et al., 2022) (Figure 8.5).

Large investments in renewable energy sources in Northern and Western regions without matching local demand or building sufficient transmission infrastructure to high population areas has led to curtailment, as high as 17% of all wind generation in 2012 (Dong et al., 2018). Expanding inter-provincial transmission can help to increase grid flexibility and distribute intermittent renewable energy across grid regions (Y. Li et al., 2016). But while inter-provincial transmission may play a role in meeting demand and mitigating load curve issues, there are potential barriers and risks. Long distances between renewable power plants and demand centers require efficient bulk energy transmission over long distances, from wind power plants in Northwestern China to Eastern regions (Alassi et al., 2019). Additional barriers include public opposition to overhead lines due to visual and environmental impacts; short-term faults in overhead wires; and differences in grid codes and grid voltage levels across grid regions, which can require additional transformers (Alassi et al., 2019). Construction of high voltage transmission lines helped to reduce wind curtailment to 7% by 2014 in China, but even after long-distance transmission development, wind curtailment increased to 17% again in 2016, due to changing local demand, decreased use of high voltage transmission lines (Dong et al., 2018), decentralization of coal power plant construction and coal overcapacity (Y. Feng et al., 2018), and increased local use of coal over imports of renewables from other provinces (Alassi et al., 2019). Consistency in standards and regulations across grid borders is needed for long distance high voltage transmission (Alassi et al., 2019). Development of additional infrastructure should reduce curtailment, but only if there is coordination between end users and energy exporters to prevent an energy importer from switching to a local energy generator after transmission lines are built. If regions change from an energy importer to exporter, it can lead to under-utilization of expensive transmission resources, congestion, and curtailment (Alassi et al., 2019).

Opportunities

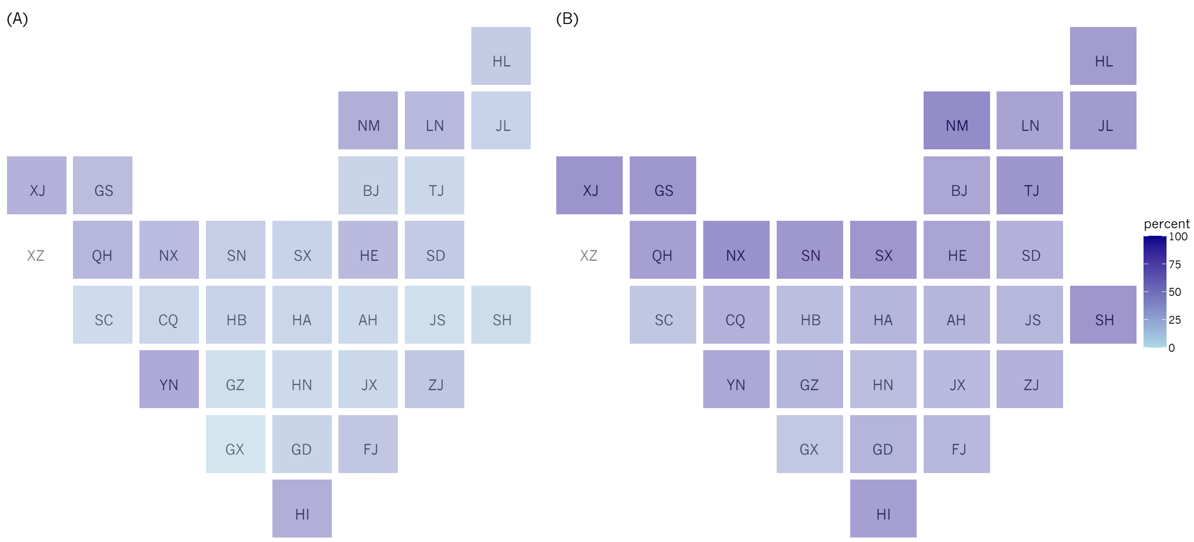
Investing in grid improvements seems to be a priority for China. Investments in the power grid and other related industries by State Grid are expected to exceed 6 trillion Yuan ($896 billion USD) in 2021-2025 (Reuters, 2020). Attempts to improve grid reliability include the development of ultra-high voltage power lines to improve long-distance transmission and efficiency. Several inter-provincial and inter-regional transmission lines have already been constructed in China (China Electric Power Planning and Engineering Institute, 2021a), and will likely need to be expanded to meet increasing demand in regions with limited renewable energy supply. These regional differences in renewable energy potential and electricity demand highlight the importance of expanded transmission connections across grid regions and power trading (IEA, 2019), especially when looking to the future. The adoption of one national electricity market could help promote inter-provincial electricity transmission, increase access to a wider variety of generation resources, and balance renewable generation and demand (Cui et al., 2022).

In addition to expanded inter-regional infrastructure, geospatial variations in supply and demand can be mitigated through large-scale wind and solar power bases with distributed power sources adapted to local conditions. Electrification may also help to integrate resources between regions in China, increasing the economic growth of power supply provinces in Central and Western China through the construction of many power storage and power transmission grids.

Renewable energy transitions can result in many broader benefits. Targeting the phaseout of plants strategically – considering existing policies on plant age, location and capacity – is not only critical for meeting climate goals, but can also have additional health and social benefits, including improving local air pollution emissions, water conservation, and potentially energy security (Cui et al., 2022). Although renewable sources of energy have intermittency and flexibility concerns, transitioning away from coal may improve energy security in the long-term, given the volatility of coal prices (Cui et al., 2022).

FIGURE 8.5: RENEWABLE ENERGY SHARE (%) OF TOTAL ELECTRICITY GENERATION IN (A) 2030 AND (B) 2060 IN MAINLAND PROVINCES.

Results based on the GCAM-China model. The darker the color, the higher the percentage of renewable energy share of the total electricity generation (Lou et al., 2022).



BOX 8.2 EXPANSION OF ELECTRICITY GENERATION CAPACITY AND IMPLICATIONS FOR UPSTREAM SECTORS

China's power system transformation will almost certainly include the expansion of renewable resources, especially solar and wind power. Some of the challenges presented by this transition include changes in land area needed for power generation and new materials and manufacturing processes required for renewable energy production.

Compared to fossil fuels, renewable energy may require more land area for energy production, including additional transmission infrastructure to accommodate a higher proportion of energy supply stemming from renewables (Saunders, 2020). Land-use changes from expanded solar development may indirectly result in a loss of natural land, depending on the region and land use prior to the conversion to solar (van de Ven et al., 2021). These impacts can be mitigated through increased technology efficiency to reduce the area of land needed for renewable developments (Zalk & Behrens, 2018) and by focusing on technologies with higher power density (such as Concentrated Solar Power or PV) (Zalk & Behrens, 2018). Additionally, land-use impact can be mitigated by installing renewables on land with multiple purposes, including residential solar (Zalk & Behrens, 2018) or pastures with grazing livestock (Zalk & Behrens, 2018). Adoption of permitting policies that limit competition between renewable development and agriculture and that incentivize development in non-arable land can also reduce land use changes (Zalk & Behrens, 2018). Additionally, altering conservation siting requirements to increase adoption of renewables on conserved land can increase land area available for renewable development (Saunders, 2020).

Though efficiency and material upgrades are improving over time, renewables also may have additional material requirements compared to fossil-fuel energy production, including increased reliance on concrete, cement, glass and steel (DOE, 2015). While the global warming potential of PV production has declined from 2005 to 2015, largely through improvements in the silicon manufacturing process, the energy make-up of the manufacturing region and industrial sector plays a significant role in environmental impacts from renewables (Stamford & Azapagic, 2018). Given the increasing reliance of manufacturing on electricity and hydrogen moving forward, cleaning upstream production is critical for reducing emissions during the renewable manufacturing process (S. Yu et al., 2021).

8.4 KEY AREAS AND POTENTIAL OF ELECTRIFICATION

In a power grid composed of more solar and wind power, it is necessary to consider multiple mechanisms for improving power system flexibility, resilience, and reliability, which can come from the power supply side, grid side, and load side.

Supply Side Flexibility

Enhanced Adjustable Power. Conventional generation units may struggle to accommodate new renewable sources of energy due to the variable nature of renewables, which is challenging for base-load power plants with long ramp up and down times (Impram et al., 2020). Developing flexible, baseload power to support renewable deployment is critical for maintaining a reliable grid. At present, existing adjustable power in China includes thermal power, hydropower and pumped storage hydropower, Concentrated Solar Power (CSP), and others, of which thermal power accounts for the highest proportion. The role of thermal power is mainly to provide base-load power generation and transmission and some heating. In the future, thermal power may offer regulation capacity for the power system and provide base-load support to the power grid (NDRC & NEA, 2016b). Pumped storage hydropower and adjustable coal-fired power may become profitable after 2021 policy enactments (NDRC, 2021a). China has targets for pumped hydro storage, reaching 62 and 120 GW by 2025 and 2030, respectively (NEA, 2021).

Wind and PV Optimization. Advancements in wind and solar technologies are needed to improve integration into the power system. More refined design and optimized operation of wind power and PV technology are needed to enhance its integration into the power system. For example, wind turbines have a small amount of power storage, which can provide some support to the power grid, especially when combined with other turbines in a larger wind farm or wind base (Wind Machinery Branch of China Agricultural Machinery Industry Association, 2021). PV generation can better match load curves though the change of bracket inclination or adjustment mode (China Photovoltaic Industry Association, 2020).

Consider Local Conditions. In remote areas with weak power grids, a micro-grid can strengthen the main grid, and its cost may be comparable to a main grid extension (OFweek, 2018). For wind and PV, which don't have the capability of independent regulation, power storage facilities are needed to form an integrated power supply point of comprehensive dispatching, potentially as virtual power plants (Development Research Center of the State Council, 2021). Combined with pumped storage, battery storage, and grid dispatching, renewable generation can be smoothed and grid stability improved (S. Ma & Zhou, 2021). Additionally, imposing more restrictions on local coal consumption, improved coordination between provinces exporting renewable energy and demand centers, and combining multiple renewable energy sources (RES) in high voltage transmission lines can reduce intermittency (Alassi et al., 2019).

Load Side Flexibility

Deployment of Electric Vehicles. Electric vehicles can act as controllable loads or energy storage devices, providing flexibility to the grid, but they can also increase peak load if charging doesn't take into account other energy demands. To maximize the impact of EVs used to regulate the load curve, orderly charging is important for improving efficiency while meeting consumer needs (Hou et al., 2020). Operational costs for microgrids decline when modeled users only charge their vehicles when solar output exceeds the load (Hou et al., 2020). Time of use pricing and other demand response strategies can help encourage EV charging at off-peak times, increasing the beneficial impact of EVs on load regulation (Goh et al., 2022). Not only can EVs operate as a transferable load, but with vehicle-to-grid (V2G) technology, there can be a bidirectional flow of energy between the EV and the grid, which can reduce system fluctuation (H. Liu et al., 2013). By adjusting the demand-side load, through implementing an electric vehicle charging time control, the demand-side load curve can be effectively smoothed (J. Sun et al., 2014). Grid-integrated and managed smart charging capabilities can also allow NEVs to help improve grid flexibility by more effectively utilizing variable renewable generation and helping to shave peak electricity demand (NREL, 2022).

Demand-side Adjustments. Demand response programs can help shift load to different times of day, reduce peak load, or increase demand during off-hours (Lund et al., 2015). Adoption of market-based pricing would help shift load from peak times, by incentivizing end-users to consume at off-peak times (Cui et al., 2022). Large power users can reduce their load in a specific period of time, or operate beyond the rated power within the bearable range of the equipment, to optimize the benefit from demand-side incentives. In addition, the difficulty of technology realization and the uncertainty of investment income increase. Increasing energy efficiency across end-use sectors can help to limit growing electricity demand and maximize emissions reduction impacts from electrification and decarbonization of the energy sector.

Adjustments can also include altering energy consumption intensity or time period for all energy users. Increasing power storage facilities on the load side and actively adjusting the energy consumption curve in combination with spot-market or guidance mechanisms could reduce the regulation pressure and supply side costs (China Electric Power Planning and Engineering Institute, 2021b; Sun Y. et al., 2022).

Grid Side Flexibility

Enhance Inter-network Interaction. At present, the country has formed six regional power grids in Northeast, North, Northwest, East, Central and Southern China, and has built a number of inter-provincial and inter-regional transmission lines. In the future, with further electrification, it is expected that the power grid will extend further to remote areas, and the structure in the main network will be stronger, increasing power system stability and reliability in different regions(China Electric Power Planning and Engineering Institute, 2021a).

Expansion of Energy Storage and Optimizing Grid Management. At relatively weak nodes of grid structure, energy storage can be added to fit the utilization needs of distributed energy. While correspondingly accelerating the construction of distribution infrastructure, it can enhance the safe and stable operation of the new power system with high renewable penetration and increasing end-use electrification (Rong et al., 2021).

As the location of hydropower and pumped storage mainly depends on geological resource conditions, it is necessary to consider local power grid conditions to provide support for the power system by optimizing dispatching operation mode as far as possible. While volatility of renewables is a concern, current wind power curtailment issues are more likely the results of inadequate grid management policies that account for renewables intermittency (Luo et al., 2016), including concentrated wind sources far from load centers, a large proportion of coal power plants, limited feed-in-tariffs, lack of wind-specific grid codes, and poor forecast accuracy have all contributed to high wind curtailment in China (Impram et al., 2020; C. Li et al., 2015).

Additional Operation Dispatching Technology. At present, China's power grid is becoming more digital and intelligent. For example, China Southern Power Grid has issued the White Paper on Digital Power Grid, which points out that digitalization could help the power grid become more intelligent, safe, reliable, and green with a series of technologies including cloud computing, big data, Internet of Things, mobile Internet, artificial intelligence, blockchain, and other new digital generation technologies (CSG, 2020). With the increasing proportion of electrification in the future, it also involves the support of basic and comprehensive technologies, such as IOT and 5G technology, for the processing needs of a large number of data and information flows in the new power system.

8.5 KEY POLICY APPROACHES

At present, the Chinese government has formed a relatively complete policy system to support energy transformation, including guidance and support for low-carbon technology, restriction and optimization guidance for high energy consuming industries or high carbon emission industries, power generation, transmission and distribution price mechanism, and market-oriented construction mechanism, all providing a good foundation for moving towards high-scale electrification.

In order to achieve the neutrality target, some policy solutions to further accelerate the pace of energy transformation include:

(1) Reducing the cost of renewable energy sources. Improving the flexibility of the power system requires capital investment, likely leading to an increase in the cost of electricity. In order for China to maintain a stable average price of electricity, wind power and PV will need to play a key role in reducing the cost of electricity. To provide endogenous power and a continuous decline of cost, China needs to continue to support wind power and PV essential technology capability improvement. Other renewable energy applications, such as CSP, can accelerate technology iteration and provide low-cost renewable power with regulation capability technology reserves (Development Research Center of the State Council, 2021).

(2) Using price mechanisms to reduce energy costs. At present, China is gradually transforming from governmental pricing to market-oriented pricing. During this process, it is first necessary to coordinate the cost composition of both the power generation side and power consumption side. Second, it is necessary to consider the differences in the price settlement methods of multiple types of users (such as power spot market and medium- and long-term transactions, peak valley time-sharing / step price, etc.). Third, it is necessary to comprehensively consider the cost, price, and price mechanism (ancillary service market) of power, energy, and system stability aspects. And fourth, the carbon emission level per kWh of the power system needs to be considered (Lin, 2021). In this process, multiple government departments need to work together on a series of policies.

For example, green power hydrogen production is beneficial in reducing carbon emissions from hydrogen production, providing load side regulation capacity for power systems and increasing electricity demand (NDRC & NEA, 2022b). In developing hydrogen energy, it is necessary to: cooperate with industrial departments in hydrogen demand; cooperate with power departments and price departments to consider green power supply scale, supply stability and economy; and cooperate with hydrogen production enterprises and price departments to consider the benefits of hydrogen production system support for power system stability (Jiang & Xiang, 2021).

Power market reforms, like phasing out fossil-fuel subsidies and adopting time-of-use rates, can increase adoption of renewable energy and other technology, such as EVs and battery storage. Implementing the least-marginal cost dispatch across interprovincial markets can reduce power-sector emissions and operating costs (IEA, 2021a). Expanding existing pilot provincial electricity markets to an inter-regional market, or even a national power market, can help to increase resiliency and reliability of the grid and reduce renewable curtailment.

Expanding the national emissions trading scheme (ETS) to include the industry sector as well as the electricity sector will help to reduce emissions and standardize mechanisms for reductions across sectors (Busch et al., 2022). Increasing the carbon price, reducing carbon permits issuance (Wu & Zhu, 2021), and increasing transparency of trading information disclosure (X. Wang et al., 2022) can also help to improve the ETS ability to reduce emissions in power and end-use sectors.

(3) Increasing policy and technology coordination between the energy sector and other industries. The carbon neutrality goal is connected to the whole of society. It needs to be closely connected with the development needs and speed of industry, construction, transportation, and other fields. A technical coordination system for the integrated development of various industries and energy, including technical standards and specifications, is needed (Energy and Environmental Policy Research Center of Beijing Institute of Technology, 2021). In the overall arrangement of major national strategies and major projects, such as the integration of energy and national infrastructure, cooperation across multiple fields is critical for meeting emission targets cost-effectively.

(4) Increasing coordination among national and subnational governments. Coordination among provinces, grid regions, and the national government is critical for ensuring a smooth transition. Regional power transition, grid integration, and the development of a single national market can help provinces reduce reliance on coal, improve RES curtailment rates, and facilitate renewable energy consumption across regions. Coal retirements should be coordinated with a broader strategy that considers renewable energy development, load balancing and power transmission, to ensure supply continues to meet demand (Cui et al., 2022). Increasing transmission infrastructure alone is not enough to prevent curtailment of renewable resources. Ensuring that energy recipients are willing and able to accept long-distance renewable generation over local generation is needed to reduce curtailment (Dong et al., 2018).

TABLE 8.1: SUMMARY OF ACTIONS FOR POWER SECTOR.

Near-term Actions	Long-term Strategies
► Encourage increase in renewable generation, along with other flexible low-carbon power sources (nuclear, carbon capture, utilization and storage) ► Adjust energy consumption intensity and time periods through market mechanisms ► Increase digitalization of the grid and demand response programs to reduce consumption ► Policy and technology coordination between energy sector and other sectors to integrate energy infrastructure, including removing some obstacles for construction of renewable energy projects, such as land supply constraints	► Further increase the adjustable power sources (thermal, hydropower, gas, and Concentrated Solar Power). ► Increase use of micro-grids in areas with weaker power grids. ► Promote smart demand side response management, such as smart charging, vehicle-to-grid, and virtual power plants, to reduce peak-load grid costs and avoid excessive new investment in power distribution. ► Increase inter-network interaction between grid regions. ► Expand the energy storage capacity (especially long-term and seasonal storage) and improve ancillary services market design to support energy storage development. ► Strengthen electricity market reform to support renewable development and significantly increase the integration of renewables into the grid.

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09 CONCLUSIONS

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9.1 ELECTRIFICATION IN MEETING CHINA'S CARBON NEUTRALITY TARGET

Our results suggest that electrification of end-use sectors, combined with decarbonization of the power sector, is a key strategy for meeting China's carbon neutrality target. All seven multi-models project rapid increases in electricity demand, generation, and capacity by mid-century. Results suggest coal without carbon capture, utilization and storage (CCUS) is essentially phased out of electricity generation after 2045, and solar and wind ramp up between 2025–2050. If emissions peak between 2025–2030, models exceed near-term policy targets for solar and wind capacity, emissions intensity reduction, and non-fossil share in primary energy. When emissions are modeled to peak in 2030, not all models meet the near-term targets, suggesting peaking before 2030 is important for aligning with near-term policy goals and meeting long-term targets.

Our analyses indicate an average of 80% electrification rate in buildings, and about 65% and 60% direct electrification in industry and passenger transportation, respectively, by 2060, suggesting that electricity becomes the dominant fuel source in these three sectors. The freight transportation sector reaches an average of only 35% electrification. This sector, along with passenger aviation and high temperature heat in heavy industries, needs further research and development to understand how alternative fuels, such as hydrogen and synthetic fuels, can help these sectors indirectly electrify and reduce emissions.

To meet increasing electricity demand, which increases by an average of 125% across models, almost 5,000 GW of capacity needs to be installed between 2020 and 2060. Our analyses suggest electricity capacity and generation will need to at least double compared to 2020. Rapid capacity expansion is accompanied by accelerated fuel switching, i.e., phasing out unabated coal use by 2050 or earlier while increasing the deployment of solar, wind, nuclear, and CCUS technologies. As a result, the power sector will see significant emissions reduction and reach zero or even negative emissions by 2050. While all models are in agreement on significant emissions reduction and coal phaseout, the pathways getting there are different. All models agree on the expansion of solar and wind generation, but contributions from other energy sources, such as biomass with CCUS, fossil fuel generation with CCUS, natural gas, and nuclear, vary across models. Future power sector portfolios will be the reflection of policy choices, technology availability, and economic costs.

Ensuring that supply equals demand, and vice versa, is a constant challenge for the power grid. The low-carbon transition will place additional constraints and opportunities for the power sector in this balancing act. Meeting increasing demand with intermittent renewable resources, adjusting manufacturing supply chains, and replacing existing infrastructure pose grid instability risks. However, EVs, battery storage, and consumer behavior programs can help reduce peak load; micro-grids and small-scale renewable energy systems can help provide electricity access in remote locations; and expanding grid infrastructure can help increase power supply diversity and improve overall reliability.

Simultaneously building out capacity for low-carbon fuels, phasing down unabated coal use, and increasing electrification across all three end-use sectors will require high levels of inter-sectoral coordination. Often, policies in one sector are connected to another sector, so sectoral coordination is needed. For example, the benefits of distributed PV systems are maximized when combined with smart vehicle charging stations. Emissions reduction in the industrial manufacturing sector that produces solar and wind technology is dependent on decarbonization in the power sector. Cross-sectoral policy could link electrification targets across end-use sectors to carbon neutrality goals, along with other key initiatives, such as social and economic development. This will help to ensure an approach that enables multiple transitions to occur simultaneously. Including power system planning in the electrification policy-making process at both the provincial and sectoral levels could potentially help to reduce curtailment, improve demand forecasting, and inform energy dispatching. This report outlines several near- and long-term sectoral options to decarbonize China through accelerated electrification and power system transition. Further actions that can promote electrification, such as offering financial incentives for replacing end-use infrastructure with market-available electric options; expanding research and development in end-uses that don't have an existing, feasible electric alternative; updating power grid market mechanisms; improving transmission and distribution capabilities across provinces; and developing cross-sectoral electrification policy.

9.2 AREAS OF FUTURE RESEARCH

While conducting this research, several key issues were identified, but were beyond the scope of this report. These issues can be further explored in future reports to provide a more comprehensive understanding of China's carbon neutrality transition.

Most models utilize technology costs as a key driver of determining future pathways. Future energy costs are difficult to determine, given that they will be reflective of a variety of economic, policy and social factors, including the rate of energy transition (Way et al., 2021). Different modeling assumptions for technology costs across models were not fully evaluated or standardized across models in this report, but future research could analyze some of these underlying modeling differences, to better understand model behavior.

Future research also needs to provide more granular technology or sectoral information and evaluate technology options. For example, future research can further disaggregate wind technologies into onshore and offshore wind and evaluate the trends of these technologies separately to better understand renewable deployment in China. Moreover, not all models could report detailed sector or subsector information, such as industry subsectors or modes of transportation. Policy recommendations and future projected fuel use will likely vary significantly across industry and mode of transport. This can be improved as model capabilities advance. Additionally, more research should further evaluate the role of energy storage in China's energy transition, and what technologies will be used in addition to batteries, such as seasonal storage, and pumped hydro storage, flow batteries, or compressed air and liquid air. This research did not evaluate investment needs of technologies referenced in the report, or model the energy demand associated with manufacturing technologies, such as solar panels or heat pumps. Other alternatives for decarbonization for road transit were not included in this report. Facilitating the use of alternative forms of transit , such as bicycles, can avoid light-duty vehicle use.

Ensuring a just, low-carbon transition is critical to achieving carbon neutrality and needs to be further studied. Increasing energy affordability is critical for a just, low-carbon transition. This study did not evaluate electricity pricing changes over time, which is an important component of energy planning and accessibility. Another factor in electricity affordability is GDP growth, which was not compared in great detail across models. Most models showed a similar trend of linear increase in GDP per capita through 2040, with one model showing a slight decline in GDP growth. As this is a significant driver of decision-making across most models, further evaluation could illuminate insights about meeting near-term targets or projecting electrification demand. Other fiscal implications from the transition, including investment needs, employment changes, or distributional variation across households, were not included in this report. Future research should evaluate distributional variation in effects from the low-carbon transition across socioeconomic variables, including geographies, income, and race.

Evaluating economic transitions, such as electricity pricing structure, and carbon market development is needed to evaluate energy transition pathways. Future research should evaluate the economic investments needed, as well as other important potential areas of interconnection across sectors, such as the circular economy and material efficiency. Critical for evaluating both economic and energy implications are projections of demand for goods and services in the future. This is especially important for the industrial sector, as future demand is unclear, given potential changes in consumer behavior, urbanization, population growth and technology.

Hydrogen is a key technology in achieving deep decarbonization. This report focused on direct electrification, not hydrogen production through indirect electrolysis. Hydrogen production and consumption in end-use sectors was included as a modeled technology in this report, but discussion was limited, as it is a significant area for the energy transition. Future research should evaluate hydrogen production, end-use opportunities, and key policy and economic barriers to full-scale implementation, as both electrification of end-use sectors and development of hydrogen technologies and scaling up of hydrogen production is needed for a low-carbon transition. Additionally, future research should evaluate the implications of increasing electricity demand from both end-use sectors and hydrogen production through electrolysis.

This analysis focused primarily on CO_2 emissions, given the significant share of total greenhouse gases (GHG) that come from CO_2 in China. We asked models to have net-zero GHGs in 2060 to align with the carbon neutrality goal, but did not evaluate abatement assumptions across models, or compare non-CO_2 mitigation across sectors. Given the significant warming effect of non-CO_2s, future research should evaluate emission pathways, technologies, and policy options for mitigation.

Future research should also evaluate the barriers to, opportunities for, and key government entities needed for an intersectoral electrification policy. Integrating sectoral policies and ensuring adequate communication and alignment across sectors could help to balance energy supply and demand efficiently and cost effectively.

REFERENCES

1. Ahmadi, M. H., Ahmadi, M. A., Sadaghiani, M. S., Ghazvini, M., Shahriar, S., & Alhuyi Nazari, M. (2017). Ground Source Heat Pump Carbon Emissions and Ground-Source Heat Pump Systems for Heating and Cooling of Buildings: A review. *Environmental Progress & Sustainable Energy*, *37*(4), 1241–1265. https://doi.org/10.1002/ep.12802

2. Alassi, A., Bañales, S., Ellabban, O., Adam, G., & MacIver, C. (2019). HVDC Transmission: Technology Review, Market Trends and Future Outlook. *Renewable and Sustainable Energy Reviews*, *112*, 530–554. https://doi.org/10.1016/j.rser.2019.04.062

3. Asian Development Bank (ADB). (2019). *Solar District Heating in the People's Republic of China Status and Development Potential* (China, People's Republic of). Asian Development Bank. http://dx.doi.org/10.22617/TCS190028-2

4. Bloomberg News. (2022, January 26). *Xi Jinping Says China Green Goals Can't Compromise Energy Security*. Bloomberg.Com. https://www.bloomberg.com/news/articles/2022-01-26/xi-jinping-says-climate-targets-can-t-compromise-energy-security

5. BloombergNEF, & World Business Council on Sustainable Development (WBCSD). (2021). *Hot Spots for Renewable Heat: Decarbonizing Low- to Medium-Temperature Industrial Heat Across the G-20*. BloombergNEF & WBCSD. https://www.wbcsd.org/contentwbc/download/12957/190622/1

6. Boer, D. de. (2022, March 4). *Leaders Group on Climate Change Meets Before Two Sessions*. CCICED. https://cciced.eco/ecological-progress/leaders-group-on-climate-change-meets-before-two-sessions/

7. Building Energy Research Center (BERC) of Tsinghua University. (2015). *2015 Annual Report on China Building Energy Efficiency*.

8. BERC. (2016). *2016 Annual Report on China Building Energy Efficiency*.

9. BERC. (2017). *2017 Annual Report on China Building Energy Efficiency*.

10. BERC. (2019). *2019 Annual Report on China Building Energy Efficiency*.

11. BERC. (2021). *2021 Annual Report on China Building Energy Efficiency*.

12. BERC. (2022). *2022 Annual Report on China Building Energy Efficiency*.

13. Busch, C., Hu, M., & Chen, M. (2022). *Next Steps for China's Carbon Emissions Trading System to Improve Efficiency, Achieve Climate Goals*. https://energyinnovation.org/wp-content/uploads/2022/04/Next-Steps-For-Chinas-Emissions-Trading-System.pdf

14. Carbon Emission Accounts & Datasets (CEADs). (2021). *China CO2 Inventory 1997-2019 (IPCC Sectoral Emissions)*. https://www.ceads.net.cn/data/nation/

15. Caijing. (2021, October 26). *It Is Necessary to Establish Carbon as a Production Element and to Develop Carbon Market as a Major Production Factor Market*. http://m.caijing.com.cn/article/235180?target=blank

16. Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R. Y., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S. J., Snyder, A., ... Wise, M. (2019). GCAM v5.1: Representing the Linkages Between Energy, Water, Land, Climate, and Economic Systems. *Geoscientific Model Development*, *12*(2), 677–698. https://doi.org/10.5194/gmd-12-677-2019

17. Cazorla-Marín, A. (2019). *Modelling and Experimental Validation of an Innovative Coaxial Helical Borehole Heat Exchanger for a Dual Source Heat Pump System*. https://www.researchgate.net/publication/334736444_Modelling_and_experimental_validation_of_an_innovative_coaxial_helical_borehole_heat_exchanger_for_a_dual_source_heat_pump_system
18. Chaoyang District Government. (2022, April 14). *Population in Chaoyang District*. http://www.bjchy.gov.cn/chaoyang/cygk/rkqk/
19. Chen, W., Li, H., & Wu, Z. (2010). Western China Energy Development and West to East Energy Transfer: Application of the Western China Sustainable Energy Development Model. *Energy Policy*, *38*(11), 7106–7120. https://doi.org/10.1016/j.enpol.2010.07.029
20. Chen, Y., Ebenstein, A., Greenstone, M., & Li, H. (2013). Evidence on the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China's Huai River Policy. *Proceedings of the National Academy of Sciences*, *110*(32), 12936–12941. https://doi.org/10.1073/pnas.1300018110
21. China Academy of Information and Communications Technology (CAICT). (2022). *New Energy Vehicle Industry Operation Report in the First Half of 2022*. http://www.caict.ac.cn/kxyj/qwfb/qwsj/202207/P020220727606061522187.pdf
22. China Architecture & Building Press (CABP). (2021). *General Code for Energy Efficiency and Renewable Energy Application in Buildings (GB 55015-2021)*. https://library.gbpn.org/library/bc-detail-pages/china-severe-cold
23. China Association of Automobile Manufacturers (CAAM). (2021). *2020 China Automobile Industry Economic and Operation Report*. China Association of Automobile Manufacturers. http://lwzb.stats.gov.cn/pub/lwzb/zxgg/202107/W020210723348607396983.pdf
24. China Automotive Research Center. (2021). *China Automotive Industry Yearbook 2021*. https://chinabookshop.net/shop/ols/products/china-automotive-industry-yearbook-2020
25. China Automotive Technology and Research Center Ltd. Co. (CATARC). (2020). *New Energy Buses in China: Overview on Policies and Impact*. https://www.changing-transport.org/wp-content/uploads/2020_GIZ_New-Energy-Buses-in-China.pdf
26. China Daily. (2022). *Rooftop Solar Energy to Power Nation's Green Development*. https://global.chinadaily.com.cn/a/202203/30/WS6243b41aa310fd2b29e5416d.html
27. China Economic Net. (2022). *Ten directors of the National Bureau of Statistics Interpreted the 2022 "Half-yearly report."* http://www.ce.cn/xwzx/gnsz/gdxw/202207/15/t20220715_37873930.shtml
28. China Electric Power Planning and Engineering Institute. (2021a). *China Electric Power Development Report*.
29. China Electric Power Planning and Engineering Institute. (2021b). *Report on China Electric Power Development 2021*.
30. China Electricity Council (CEC). (2020). *China Electrification Report 2019*. https://www.cec.org.cn/upload/zt/2019report/
31. CEC. (2021). *Analysis and Forecast of China Power Demand-Supply Situation 2020-2021*. https://english.cec.org.cn/detail/index.html?3-1128
32. CEC. (2022a). *Analysis and Forecast of National Power Supply and Demand from 2021 to 2022*. https://cec.org.cn/detail/index.html?3-306241
33. CEC. (2022b, January 27). *China Electricity Council Released the "2021-2022 National Electricity Supply and Demand Situation Analysis and Forecast Report."* China Electricity Council. https://cec.org.cn/detail/index.html?3-306171
34. CEC. (2022c, July 20). *Brief Introduction on The Operation of the Power Industry from January to June 2022*. https://cec.org.cn/detail/index.html?3-311529

35. China Hydrogen Alliance (CHA). (2020). *White Paper on China's Hydrogen and Fuel Cell (2019).* http://www.zg-kg.com/files/%E3%80%8A%E4%B8%AD%E5%9B%BD%E6%B0%A2%E8%83%BD%E6%BA%90%E5%8F%8A%E7%87%83%E6%96%99%E7%94%B5%E6%B1%A0%E4%BA%A7%E4%B8%9A%E7%99%BD%E7%9A%AE%E4%B9%A6%E3%80%8B.pdf

36. China Photovoltaic Industry Association. (2020). *China Photovoltaic Industry Development Research Report*. http://www.chinapv.org.cn/annual_report/821.html

37. China Power News Net (CPNN). (2022). *China's Newly Installed Generation Capacity of Wind and PV Exceeded 100 million Kilowatts in 2021*. http://www.cpnn.com.cn/news/xwtopb/202201/t20220126_1478906.html

38. China Southern Power Grid (CSG). (2020). *Digital Power Grid White Paper*. http://eng.csg.cn/Press_release/News_2020/202011/t20201126_315793.html

39. Cui, R., Cui, X., Cui, D., Song, J., Zhang, X., Dai, F., Gordon, J., Chen, Z., Hultman, N., & Kammen, D. (2022). *A Decade of Action: A Strategic Approach to Coal Phase-Down for China Environmental and Socio-economic Benefits of Targeted Coal Retirements in China's 14th and 15th Five-Year Plans*. https://cgs.umd.edu/sites/default/files/2022-03/A%20Decade%20to%20Act-Main%20Report-March%202022.pdf

40. Deason, J., Wei, M., Leventis, G., Smith, S., & Schwartz, L. C. (2018). *Electrification of Buildings and Industry in the United States: Drivers, Barriers, Prospects, and Policy Approaches*. Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States). https://doi.org/10.2172/1430688

41. Department of Energy (DOE). (2015). *Quadrennial Technology Review an Assessment of Energy Technologies and Research Opportunity*. Department of Energy. https://www.energy.gov/sites/prod/files/2017/03/f34/quadrennial-technology-review-2015_1.pdf

42. Development Research Center of the State Council. (2021). *Development Trend and Prospect of New Power System*. https://guangfu.bjx.com.cn/news/20210923/1178275.shtml

43. Dong, C., Qi, Y., Dong, W., Lu, X., Liu, T., & Qian, S. (2018). Decomposing Driving Factors for Wind Curtailment Under Economic New Normal in China. *Applied Energy*, *217*, 178–188. https://doi.org/10.1016/j.apenergy.2018.01.040

44. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J. C., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Stechow, C. von, & Zwickel, T. (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf

45. Energy and Environmental Policy Research Center of Beijing Institute of Technology. (2021). *Global Climate Governance Strategy and China's Carbon Neutral Path Outlook*. https://ceep.bit.edu.cn/docs/2021-01/d714a0f1049d4ed79c881150abfbdc83.pdf

46. Energy Efficiency & Conservation Authority (EECA). (2019). *International Technology Scan—Alternative Technologies for Process Heat*. https://www.eeca.govt.nz/insights/eeca-insights/international-tech-scan/

47. Energy Foundation China (EFC). (2016). *Best Practices of Energy Efficiency Projects in the Buildings Sector*.

48. EFC. (2020). *China's New Growth Pathway: From the 14th Five-Year Plan to Carbon Neutrality*. https://www.efchina.org/Reports-en/report-lceg-20201210-en

49. Feng, W., Zhou, N., Wang, W., Khanna, N., Liu, X., & Hou, J. (2021). *Pathways for Accelerating Maximum Electrification of Direct Fuel Use in China's Building Sector*. https://eta-publications.lbl.gov/sites/default/files/electrification_of_buildings_in_china_v2_clean_edited92821.pdf

50. Feng, Y., Wang, S., Sha, Y., Ding, Q., Yuan, J., & Guo, X. (2018). Coal Power Overcapacity in China: Province-Level Estimates and Policy Implications. *Resources, Conservation and Recycling*, *137*, 89–100. https://doi.org/10.1016/j.resconrec.2018.05.019

51. Forsell, N., Turkovska, O., Gusti, M., Obersteiner, M., Elzen, M. den, & Havlik, P. (2016). Assessing the INDCs' Land Use, Land Use Change, and Forest Emission Projections. *Carbon Balance and Management*, *11*(1), 26. https://doi.org/10.1186/s13021-016-0068-3

52. Fragkos, P., Laura van Soest, H., Schaeffer, R., Reedman, L., Köberle, A. C., Macaluso, N., Evangelopoulou, S., De Vita, A., Sha, F., Qimin, C., Kejun, J., Mathur, R., Shekhar, S., Dewi, R. G., Diego, S. H., Oshiro, K., Fujimori, S., Park, C., Safonov, G., & Iyer, G. (2021). Energy System Transitions and Low-Carbon Pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. *Energy*, *216*(C). https://ideas.repec.org/a/eee/energy/v216y2021ics0360544220324920.html

53. FuelCellsWorks. (2022). *Buses And Trucks Accelerate as Chinese FCEV Vehicles Hit Overdrive*. https://fuelcellsworks.com/news/buses-and-trucks-accelerate-as-chinese-fcev-vehicles-hit-overdrive/

54. Gao, B. (2020, July 2). 'China Should Set Up a Carbon Cap' – Zou Ji on China's Energy Targets. *China Dialogue*. https://chinadialogue.net/en/energy/china-should-set-up-a-carbon-cap-zou-ji-on-the-next-national-energy-targets/

55. GCAM. (2022). *GCAM v6 Documentation: GCAM Model Overview*. https://jgcri.github.io/gcam-doc/overview.html

56. General Office of the State Council. (2020). *New Energy Vehicle Industry Development Plan (2021-2035)*. http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm

57. Global Times. (2022). *Xi Stresses Energy Security When Carrying Out Carbon Reductions*. https://www.globaltimes.cn/page/202203/1254108.shtml

58. Goh, H. H., Zong, L., Zhang, D., Dai, W., Lim, C. S., Kurniawan, T. A., & Goh, K. C. (2022). Orderly Charging Strategy Based on Optimal Time of Use Price Demand Response of Electric Vehicles in Distribution Network. *Energies*, *15*(5), Article 5. https://doi.org/10.3390/en15051869

59. Gray, N., McDonagh, S., O'Shea, R., Smyth, B., & Murphy, J. D. (2021). Decarbonising Ships, Planes and Trucks: An Analysis of Suitable Low-Carbon Fuels for the Maritime, Aviation and Haulage Sectors. *Advances in Applied Energy*, *1*, 100008. https://doi.org/10.1016/j.adapen.2021.100008

60. He, C. (2021). *Research on the Ancillary Effects of Climate Change Mitigation: A Case Study of China's Energy Transition and Water Demand* [Doctor thesis]. Peking University.

61. He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020). Rapid Cost Decrease of Renewables and Storage Accelerates the Decarbonization of China's Power System. *Nature Communications*, *11*(1), 2486. https://doi.org/10.1038/s41467-020-16184-x

62. Hou, H., Xue, M., Xu, Y., Xiao, Z., Deng, X., Xu, T., Liu, P., & Cui, R. (2020). Multi-objective Economic Dispatch of a Microgrid Considering Electric Vehicle and Transferable Load. *Applied Energy*, *262*, 114489. https://doi.org/10.1016/j.apenergy.2020.114489

63. Hsu, A. (2021, November 7). Opinion | Don't Be So Quick to Doubt China's Climate Change Dedication. *The New York Times*. https://www.nytimes.com/2021/11/07/opinion/cop26-china-climate.html

64. Huppmann, D., Gidden, M., Fricko, O., Kolp, P., Orthofer, C., Pimmer, M., Kushin, N., Vinca, A., Mastrucci, A., Riahi, K., & Krey, V. (2019). The MESSAGEix Integrated Assessment Model and the ix Modeling Platform (ixmp): An Open Framework for Integrated and Cross-Cutting Analysis of Energy, Climate, the Environment, and Sustainable Development. *Environmental Modelling & Software*, *112*, 143–156. https://doi.org/10.1016/j.envsoft.2018.11.012

65. Impram, S., Varbak Nese, S., & Oral, B. (2020). Challenges of Renewable Energy Penetration on Power System Flexibility: A survey. *Energy Strategy Reviews*, *31*, 100539. https://doi.org/10.1016/j.esr.2020.100539

66. Integrated Energy and Environment Policy Assessment Model for China (IPAC). (2020). *IPAC-AIM/Technology*. http://www.ipac-model.org.cn/

67. International Energy Agency (IEA). (2019). *China Power System Transformation—Assessing the Benefits of Optimised Operations and Advanced Flexibility Options*. https://iea.blob.core.windows.net/assets/fd886bb9-27d8-4d5d-a03f-38cb34b77ed7/China_Power_System_Transformation.pdf

68. IEA. (2020a). *Energy Technology Perspectives 2020 – Analysis*. https://www.iea.org/reports/energy-technology-perspectives-2020

69. IEA. (2020b). *Iron and Steel Technology Roadmap*. https://www.iea.org/reports/iron-and-steel-technology-roadmap

70. IEA. (2021a). *An Energy Sector Roadmap to Carbon Neutrality in China – Analysis*. https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china

71. IEA. (2021b). *CO2 Emissions from Fuel Combustion*. https://www.iea.org/data-and-statistics/data-browser

72. IEA. (2021c). *Global EV Outlook 2021*. https://www.iea.org/reports/global-ev-outlook-2021

73. IEA. (2021d). *IEA Online Database*. https://www.iea.org/data-and-statistics

74. IEA. (2022a). *Global Energy Review: CO2 Emissions in 2021*. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

75. IEA. (2022b). *Greenhouse Gas Emissions from Energy—Data product*. IEA. https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy

76. IEA, & Tsinghua University. (2018). *District Energy Systems in China Options for Optimisation and Diversification*. https://iea.blob.core.windows.net/assets/590cc681-349a-4a55-9d3f-609eff6cde0b/District_Energy_Systems_in_China_Chinese_version.pdf

77. International Institute for Applied Systems Analysis (IIASA). (2021). *The MESSAGEix framework*. https://docs.messageix.org/en/stable/

78. International Renewable Energy Agency (IRENA). (2014). *Renewable Energy Prospects: China*. https://www.irena.org/publications/2014/Nov/Renewable-Energy-Prospects-China

79. IRENA. (2019). *Global Energy Transformation: A Roadmap to 2050 (2019 edition)*. https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition

80. IRENA, & International Labor Organization (ILO). (2022). *Renewable Energy and Jobs: Annual Review 2022*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Sep/IRENA_Renewable_energy_and_jobs_2022.pdf

81. Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., & Mai, T. (2017). *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050* (NREL/TP-6A20-70485). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1416113

82. Jiang, K. (2021). High Security Energy Supply System in the Carbon Neutrality Target. *China Power Enterprise Management*, *7*, 2–4. https://mall.cnki.net/magazine/article/ZGDQ202107008.htm

83. Jiang, K. (2022). Energy and Economic Transition with Multiple Targets. *Yuejiang Academic Journal*, *14*(1), 34-43+172. http://www.yjxk.cbpt.cnki.net/wkg/WebPublication/paperDigest.aspx?paperID=-05c4a5aa-f0bc-43b6-ba45-2ab53d23546f

84. Jiang, K., & Xiang, P. (2021). *Impact Analysis of Zero Carbon Emission Power Generation on China's Industrial Sector Distribution*. https://www.gei-journal.com/cn/upload/files/2021/1/issn2096-5125202101002.pdf

85. Jiang, Y. (2021). Develop PEDF solution to facilitate net-zero carbon power system. Presentation at 2021 China Electricity Distribution Summit Forum.

86. Keramidas, K., Diaz Vazquez, A., Weitzel, M., Vandyck, T., Tamba, M., Tchung-Ming, S., Soria Ramirez, A., Krause, J., van Dingenen, R., So Chai, Q., Fu, S., & Wen, X. (2020). *Global Energy and Climate Outlook 2019: Electrification for the Low-Carbon Transition* (JRC Research Reports No. JRC119619). Joint Research Centre (Seville site). https://econpapers.repec.org/paper/iptiptwpa/jrc119619.htm

87. Kharpal, A. (2021, November 8). *Chinese Auto Giant Geely Launches Electric Truck, Its Rival to Tesla's Semi*. CNBC. https://www.cnbc.com/2021/11/08/chinas-geely-launches-electric-truck-its-rival-to-teslas-semi.html

88. Lawrence Berkeley National Laboratory (LBNL). (2022). *Energy Modeling and Pathways-China DREAM*. https://international.lbl.gov/energy-modeling-pathways

89. Li, C., Shi, H., Cao, Y., Wang, J., Kuang, Y., Tan, Y., & Wei, J. (2015). Comprehensive Review of Renewable Energy Curtailment and Avoidance: A Specific Example in China. *Renewable and Sustainable Energy Reviews*, *41*, 1067–1079. https://doi.org/10.1016/j.rser.2014.09.009

90. Li, J., Chen, C., & Liu, H. (2019). Transition from Non-Commercial to Commercial Energy in Rural China: Insights from the Accessibility and Affordability. *Energy Policy*, *127*, 392–403. https://doi.org/10.1016/j.enpol.2018.12.022

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

92. Lin, B. (2021). *Report on China Energy Development 2021*. Science Press. https://item.jd.com/10046299544738.html

93. Liu, H., Hu, Z., Song, Y., & Lin, J. (2013). Decentralized Vehicle-to-Grid Control for Primary Frequency Regulation Considering Charging Demands. *IEEE Transactions on Power Systems*, *28*(3), 3480–3489. https://doi.org/10.1109/TPWRS.2013.2252029

94. Liu, J., Yin, M., Xia-Hou, Q., Wang, K., & Zou, J. (2021). Comparison of Sectoral Low-Carbon Transition Pathways in China Under the Nationally Determined Contribution and 2 °C Targets. *Renewable and Sustainable Energy Reviews*, *149*, 111336. https://doi.org/10.1016/j.rser.2021.111336

95. Liu, W., Lund, H., Mathiesen, B. V., & Zhang, X. (2011). Potential of Renewable Energy Systems in China. *Applied Energy*, *88*(2), 518–525. https://doi.org/10.1016/j.apenergy.2010.07.014

96. Liu, Z., Xu, W., Qian, C., Chen, X., & Jin, G. (2015). Investigation on the Feasibility and Performance of Ground Source Heat Pump (GSHP) in Three Cities in Cold Climate Zone China. *Renewable Energy*, *84*, 89–96. https://doi.org/10.1016/j.renene.2015.06.019

97. Lou, J., Yu, S., & Adofoli, V. (2022). *On the Road to Carbon Neutrality: Green Investment Needs in China*. Center for Global Sustainability, University of Maryland, College Park. https://cgs.umd.edu/sites/default/files/2022-05/%E6%8E%92%E7%89%888%E7%A8%BF05062022_Green%20Investment%20Needs%20in%20China.pdf

98. Lovins, A. B. (2021). *Profitably Decarbonizing Heavy Transport and Industrial Heat: Transforming These "Harder-to-Abate" Sectors Is Not Uniquely Hard and Can Be Lucrative*. https://rmi.org/wp-content/uploads/2021/07/rmi_profitable_decarb.pdf

99. Lu, H., Price, L., Fridley, D., & Zhou, N. (2022). *Quantifying Electrification Potential in Process Heating Systems in China*.

100. Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of Energy System Flexibility Measures to Enable High Levels of Variable Renewable Electricity. *Renewable and Sustainable Energy Reviews*, *45*, 785–807. https://doi.org/10.1016/j.rser.2015.01.057

101. Luo, G., Li, Y., Tang, W., & Wei, X. (2016). Wind Curtailment of China's Wind Power Operation: Evolution, Causes and Solutions. *Renewable and Sustainable Energy Reviews*, *53*, 1190–1201. https://doi.org/10.1016/j.rser.2015.09.075

102. Ma, S., & Zhou, B. (2021, October 26). *Synergistic Configuration of Pumped Storage and Battery Storage to Facilitate the Construction of New Power Systems*. State Grid News. https://news.solarbe.com/202110/26/345504.html

103. Ma, T. (2020, October 13). Researchers Unveil Roadmap for a Carbon Neutral China by 2060. *China Dialogue*. https://chinadialogue.net/en/climate/researchers-unveil-roadmap-for-a-carbon-neutral-china-by-2060/

104. Mao, S., Basma, H., Ragon, P.-L., Zhou, Y., & Rodríguez, F. (2021, November 16). Total Cost of Ownership for Heavy Trucks in China: Battery Electric, Fuel Cell, and Diesel Trucks. *International Council on Clean Transportation*. https://theicct.org/publication/total-cost-of-ownership-for-heavy-trucks-in-china-battery-electric-fuel-cell-and-diesel-trucks/

105. Mao, S., & Rodríguez, F. (2021). *Race to Zero: How Manufacturers are Positioned for Zero-Emission Commercial Trucks and Buses in China*. https://theicct.org/publications/china-race-to-zero-aug2021

106. McKerracher, C. (2021). *EV Charging Data Shows a Widely Divergent Global Path*. https://www.bloomberg.com/news/articles/2021-03-23/ev-charging-data-shows-a-widely-divergent-global-path

107. McLane, R., & Liu, Q. (2020). *China's Timely Charging Infrastructure Plan*. https://rmi.org/chinas-timely-charging-infrastructure-plan/

108. McLane, R., & Liu, Q. (2021). *What China Can Teach the U.S. about EV Fast-Charging Rollouts*. https://www.greenbiz.com/article/what-china-can-teach-us-about-ev-fast-charging-rollouts

109. Ministry of Ecology and Environment (MEE). (2020, June 9). *Bulletin on the Second National General Survey of Pollution Sources*. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202006/t20200610_783547.html

110. MEE. (2021a, January 5). *Measures for the Administration of Carbon Emissions Trading*. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk02/202101/t20210105_816131.html

111. MEE. (2021b, March 29). *Greenhouse Gas Emission MRV Guidelines for Enterprises*. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202103/t20210329_826480.html

112. MEE. (2021c, October 12). *China to Release Implementation Plans to Achieve Carbon Goals: Xi*. https://english.mee.gov.cn/News_service/media_news/202110/t20211012_956262.shtml

113. MEE. (2022a, June 13). *Implementation Plan for Synergistic Efficiency of Pollution Reduction and Carbon Reduction*. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202206/t20220617_985879.html

114. MEE. (2022b, July 21). *July Press Conference of the Ministry of Ecology and Environment*. https://www.mee.gov.cn/ywdt/zbft/202207/t20220721_989385.shtml

115. Ministry of Finance (MOF). (2021). *Notice on the Promotion and Application of Financial Subsidy Policies for New Energy Vehicles in 2022*. http://jjs.mof.gov.cn/zhengcefagui/202112/t20211231_3780322.htm

116. Ministry of Industry and Information Technology (MIIT). (2020, December 31). *Guidance on Promoting High-Quality Development of Iron and Steel Industry (Draft for Comments)*. https://wap.miit.gov.cn/jgsj/ycls/gzdt/art/2020/art_8fc2875eb24744f591bfd946c126561f.html

117. MIIT. (2022). *Press Conference on the Development of the Automobile Industry*. http://mp.weixin.qq.com/s?__biz=MjM5OTUwMTc2OA==&mid=2650854434&idx=1&sn=400fde0bad77237af752fa0a25ec4e81&chksm=bccefe858bb97793d1b5208f95182044eddbe7855d1947a8276ca94f39c91d489b7948453c45#rd

118. Moultak, M., Lutsey, N., & Hall, D. (2017). *Transitioning to Zero-Emission Heavy-Duty Freight Vehicles*. https://theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf

119. National Bureau of Statistics (NBS). (2017). *China Energy Statistical Yearbook 2017*. https://data.cnki.net/trade/Yearbook/Single/N2018070147?zcode=Z023

120. NBS. (2021). *China Energy Statistical Yearbook 2020*. https://data.cnki.net/Trade/yearbook/single/N2021050066?zcode=Z023

121. NBS. (2022a). *Energy Production in December 2021*. http://www.stats.gov.cn/tjsj/zxfb/202201/t20220117_1826406.html

122. NBS. (2022b). *Preliminary GDP Results for the Second Quarter and the First Half of 2022*. http://www.stats.gov.cn/tjsj/zxfb/202207/t20220715_1886607.html

123. NBS. (2022c). *Statistical Communique of the People's Republic of China on the 2021 National Economic and Social Development*. http://www.stats.gov.cn/tjsj/zxfb/202202/t20220227_1827960.html

124. National Development and Reform Commission (NDRC). (2021a, July 26). *The National Development and Reform Commission's Notice on Further Improvement of the Time-Of-Use (TOU) Power Pricing Mechanism*. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202107/t20210729_1292067.html?code=&state=123

125. NDRC. (2021b, November 16). *November Press Conference of National Development and Reform Commission*. https://www.ndrc.gov.cn/xwdt/wszb/novfbh/wap_index.html

126. NDRC, & National Energy Administration (NEA). (2016a). *Guiding Opinions on Advancing the Replacement by Electricity*. National Development and Reform Commission. https://www.ndrc.gov.cn/xxgk/zcfb/tz/201605/t20160524_963071.html?code=&state=123

127. NDRC, & NEA. (2016b). *The 13th Five-Year Plan for Electrification Development*. https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/201612/P020190905497888172833.pdf

128. NDRC, & NEA. (2017). *Clean Heating Plan for Northern China in Winter (2017-21)*. http://www.nea.gov.cn/2017-12/27/c_136854721.htm

129. NDRC, & NEA. (2022a). *Guiding Opinions on Further Advancing the Replacement by Electricity*. https://www.eqxun.com/news/16846.html

130. NDRC, & NEA. (2022b). *Medium- and Long-Term Plan for The Development of Hydrogen Energy Industry (2021-2035)*. NDRC & National Energy Administration. http://zfxxgk.nea.gov.cn/1310525630_16479984022991n.pdf

131. National Energy Administration (NEA). (2014). *PV Village in Jiangsu Province Connected to Grids*. http://www.nea.gov.cn/2014-01/09/c_133031324.htm

132. NEA. (2021). *Medium- and Long-Term Development Plan for Pumped Storage (2021-2035)*. http://zfxxgk.nea.gov.cn/1310193456_16318589869941n.pdf

133. NEA. (2022a, August 2). *Transcript of NEA's Third Quarter Online Press Conference in 2022*. http://www.nea.gov.cn/2022-08/02/c_1310648934.htm

134. NEA. (2022b, September 21). *The National Energy Administration Released the National Power Industry Statistics from January to August*. http://www.nea.gov.cn/2022-09/21/c_1310664624.htm

135. National New Energy Consumption Monitoring and Early Warning Center (NNECM). (2022). *Evaluation And Analysis of National New Energy Power Consumption in the Fourth Quarter of 2021*. National New Energy Consumption Monitoring and Early Warning Center (NNECM). http://mp.weixin.qq.com/s?__biz=MzU5NDg1OTc5MQ==&mid=2247484277&idx=1&sn=408fa1722d13fbd644a28bc3fa5e83d5&chksm=fe7b8115c90c0803b8c039c203a78ab4f57f3696a1098be1920fd1969d6efd6fedd5a916ab53#rd

136. National Renewable Energy Laboratory (NREL). (2022). *Electric Vehicle Smart Charging at Scale*. https://www.nrel.gov/transportation/managed-electric-vehicle-charging.html

137. OFweek. (2018, January 18). *Application Scenarios of Microgrids and Distributed Energy Resources*. https://solar.ofweek.com/2018-01/ART-260006-8420-30190430.html

138. OFweek. (2021, January 15). *2020 New Energy Commercial Vehicles Data Declined*. https://nev.ofweek.com/2021-01/ART-71011-8500-30481068.html

139. Paoli, L., & Gül, T. (2022, January 30). *Electric Cars Fend off Supply Challenges to More Than Double Global Sales*. IEA. https://www.iea.org/commentaries/electric-cars-fend-off-supply-challenges-to-more-than-double-global-sales

140. People's Government of Guangdong Province. (2022, July 13). *Implementation Plans for the Development of Green Finance to Support Carbon Peaking.* http://www.gd.gov.cn/zwgk/wjk/qbwj/ybh/content/post_3972447.html

141. Purr, K., Strenge, U., Werner, K., Nissler, D., Will, M., Knoche, G., & Volkens, A. (2014). *Germany in 2050—A Greenhouse—Neutral Country*. http://www.yjxk.cbpt.cnki.net/wkg/WebPublication/paperDigest.aspx?paperID=05c4a5aa-f0bc-43b6-ba45-2ab53d23546f

142. Qian, H., Xu, S., Cao, J., Ren, F., Wei, W., Meng, J., & Wu, L. (2021). Air Pollution Reduction and Climate Co-Benefits in China's Industries. *Nature Sustainability*, *4*(5), 417–425. https://doi.org/10.1038/s41893-020-00669-0

143. Ren, J. (2020). *Analysis on the Current Situation and Development Trend of Waste Iron and Steel Industry in China*. https://www.sohu.com/a/www.sohu.com/a/371392978_313737

144. Renmin University of China, & EFC. (2022). *Cost Analysis and Risk Assessment of Coal-Fired Plants in China*. https://www.efchina.org/Attachments/Report/report-lceg-20211020/%E4%B8%AD%E5%9B%BD%E7%85%A4%E7%94%B5%E6%88%90%E6%9C%AC%E4%B8%8E%E9%A3%8E%E9%99%A9%E5%88%86%E6%9E%90.pdf

145. Reuters, S. (2020). *China to Invest Nearly $900 Billion in Power Grids: State Media*. https://www.reuters.com/article/china-electricity/china-to-invest-nearly-900-billion-in-power-grids-state-media-idUSKBN26V0MO

146. Rightor, E., Whitlock, A., & Elliott, R. N. (2020). *Beneficial Electrification Industry. Research Report.* American Council for an Energy-Efficient Economy (ACEEE). https://www.aceee.org/sites/default/files/pdfs/ie2002.pdf

147. Roelofsen, O., Somers, K., Speelman, E., & Witteveen, M. (2020). *Plugging in: What Electrification Can Do for Industry*. https://www.mckinsey.com/~/media/McKinsey/Industries/Electric%20Power%20and%20Natural%20Gas/Our%20Insights/Plugging%20in%20What%20electrification%20can%20do%20for%20industry/Plugging-in-What-electrification-can-do-for-industry-vF.pdf

148. Rong, S., Lu, W., Li, S., Chen, M., & Bu, Z. (2021). Study on Economy of Power Grid Side Energy Storage. *Energy and Conservation*, *3*, 35-38+72.

149. Saunders, P. J. (2020). *Land Use Requirements of Solar and Wind Power Generation:* https://www.innovationreform.org/wp-content/uploads/2020/10/1909-Energy-Reform-Land-Use-Requirements_digital.pdf

150. Scheelhaase, J., Maertens, S., & Grimme, W. (2019). Synthetic Fuels in Aviation – Current Barriers and Potential Political Measures. *Transportation Research Procedia*, *43*, 21–30. https://doi.org/10.1016/j.trpro.2019.12.015

151. Shen, B., Han, Y., Price, L., Lu, H., & Liu, M. (2017). Techno-economic Evaluation of Strategies for Addressing Energy and Environmental Challenges of Industrial Boilers in China. *Energy*, *118*, 526–533. https://doi.org/10.1016/j.energy.2016.10.083

152. Shukla, P. R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M., Khourdajie, A. A., Belkacemi, M., van Diemen, R., Hasija, A., Lisboa, G., Luz, S., Malley, J., McCollum, D., Some, S., & Vyas, P. (2022). *Climate Change 2022 Mitigation of Climate Change—Summary for Policymakers*. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf

153. *Sichuan Metallurgical Group*. (2021). Metallurgical Group. http://www.scykjt.cn/?Info189.htm

154. Sino-German Cooperation on Climate Change. (2021, December 13). *China 2021 Central Economic Work Conference (CEWC) Sets the Tone to Encourage Renewable Energy*. https://climatecooperation.cn/climate/china-2021-central-economic-work-conference-cewc-sets-the-tone-to-encourage-renewable-energy/

155. Song, X., Huang, Y., Zhao, C., Liu, Y., Lu, Y., Chang, Y., & Yang, J. (2018). An Approach for Estimating Solar Photovoltaic Potential Based on Rooftop Retrieval from Remote Sensing Images. *Energies*, *11*(11), Article 11. https://doi.org/10.3390/en11113172

156. Stamford, L., & Azapagic, A. (2018). Environmental Impacts of Photovoltaics: The Effects of Technological Improvements and Transfer of Manufacturing from Europe to China. *Energy Technology*, *6*(6), 1148–1160. https://www.semanticscholar.org/paper/Environmental-Impacts-of-Photovoltaics%3A-The-Effects-Stamford-Azapagic/82da494d620b5b7495ae04cffaa5365e3df676aa

157. State Council Information Office of the People's Republic of China. (2020). *The Potential of Electric Energy Substitution in the "14th Five-Year Plan" Period Is Expected to Exceed 600 billion kWh*. http://www.scio.gov.cn/ztk/dtzt/42313/44537/44544/Document/1695090/1695090.htm

158. Sun, J., Wan, Y., Zheng, P., & Lin, X. (2014). Coordinated Charging and Discharging Strategy for Electric Vehicles Based on Demand Side Management. *Transactions of China Electrotechnical Society*, *29*(8), 64–69. http://dgjsxb.ces-transaction.com/CN/abstract/abstract2584.shtml

159. Sun Y., Guo H., Hou Z., Deng X., & Sun J. (2022). Foreign Measures to Enhance the Flexibility of Power System and Its Enlightenment to China's Experience. *Modern Management*, *12*(01), 37–44. https://doi.org/10.12677/MM.2022.121006

160. Tan, L. (2022, February 17). The First Year of China's National Carbon Market, Reviewed. *China Dialogue*. https://chinadialogue.net/en/climate/the-first-year-of-chinas-national-carbon-market-reviewed/

161. Tao, Q. (2022, May 31). *Challenges Exist for Including Industries into the National Carbon Market*. http://www.cnenergynews.cn/huanbao/2022/05/31/detail_20220531124246.html

162. The China Council for International Cooperation on Environment and Development (CCICED). (2022). *China's Low Carbon Transition-Review of the 2022 Annual Meeting*. http://www.cciced.net/dxhd/nh/2018_8823/nhxw/202206/t20220621_131254.html

163. The Institute of Climate Change the Institute of Climate Change and Sustainable Development (ICCSD). (2020). *Comprehensive Report on "China's Long-Term Low-Carbon Development Strategy and Transformation Path Research." China Population, Resources and Environment*. *30*(11), 1–25. https://image.oversea.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFDTEMP&filename=ZGRZ202011001

164. The National People's Congress of the People's Republic of China (NPC). (2021). *Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China*. http://www.npc.gov.cn/npc/kgfb/202103/bf13037b5d2d4a398652ed253cea8eb1.shtml

165. The People's Bank of China (PBC). (2021, November 9). *The People's Bank of China Launches the Carbon Emission Reduction Facility*. http://www.pbc.gov.cn/en/3688110/3688172/4157443/4385345/index.html

166. PBC, NDRC, & China Securities Regulatory Commission. (2021, April 2). *Catalogue of Projects Supported by Green Bonds*. http://www.gov.cn/zhengce/zhengceku/2021-04/22/content_5601284.htm

167. The State Council. (2020). *Announcement of State Council Board Member Meeting in Sep. 02*. https://baijiahao.baidu.com/s?id=1676728457964485666&wfr=spider&for=pc

168. The State Council. (2021, October 27). *Full Text: Action Plan for Carbon Dioxide Peaking Before 2030*. http://english.www.gov.cn/policies/latestreleases/202110/27/content_WS6178a47ec6d0df57f98e3dfb.html

169. The State Council. (2022a). *China's GDP Expands 8.1% in 2021*. The State Council. http://english.www.gov.cn/archive/statistics/202201/17/content_WS61e4d14ec6d09c94e48a3b8c.html

170. The State Council. (2022b). *China's Total Renewable Energy Use Reached 750 million tons of Standard Coal in 2021*. http://www.gov.cn/xinwen/2022-06/24/content_5697606.htm

171. Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S. J. (2019). Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5 °C Climate Target. *Nature*, *572*(7769), Article 7769. https://doi.org/10.1038/s41586-019-1364-3

172. Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., & Luderer, G. (2021). Potential and Risks of Hydrogen-based E-fuels in Climate Change Mitigation. *Nature Climate Change*, *11*(5), Article 5. https://doi.org/10.1038/s41558-021-01032-7

173. United Nations Department of Economic and Social Affairs (UNIDO). (2021). *UNIDO Statistics Data Portal*. https://stat.unido.org/database/INDSTAT%202%202021,%20ISIC%20Revision%203

174. van de Ven, D.-J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021). The Potential Land Requirements and Related Land Use Change Emissions of Solar Energy. *Scientific Reports*, *11*(1), 2907. https://doi.org/10.1038/s41598-021-82042-5

175. Wang, K., Li, S., Lu, M., Wang, J., & Wei, Y. (2022). *China Carbon Market Review and Prospect (2022) (CEEP-BIT-2022-006)*. https://ceep.bit.edu.cn/docs//2022-01/eb3a1bf65b6e499281122c-9d55ef2f7d.pdf

176. Wang, K., Liu, F., Yin, M., & Liu, J. (2021). Research on China's Carbon Emissions Pathway Under the 1.5°C Target. *Climate Change Research*, *17*(7–17). https://doi.org/10.12006/j.issn.1673-1719.2020.228

177. Wang, X., Su, C., Lobonţ, O.-R., Li, H., & Nicoleta-Claudia, M. (2022). Is China's Carbon Trading Market Efficient? Evidence from Eissions Trading Scheme Pilots. *Energy*, *245*, 123240. https://doi.org/10.1016/j.energy.2022.123240

178. Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2021). *Empirically Grounded Technology Forecasts and the Energy Transition*. Institute for New Economic Thinking at the Oxford Martin School. https://www.inet.ox.ac.uk/files/energy_transition_paper-INET-working-paper.pdf

179. Wei, M., McMillan, C. A., & de la Rue du Can, S. (2019). Electrification of Industry: Potential, Challenges and Outlook. *Current Sustainable/Renewable Energy Reports*, *6*(4), 140–148. https://doi.org/10.1007/s40518-019-00136-1

180. Wind Machinery Branch of China Agricultural Machinery Industry Association. (2021). *China Wind Power Industry Development Report*.

181. World Steel Association (WSA). (2021a). *Steel Statistical Yearbook 2021*. https://worldsteel.org/publications/bookshop/ssy_subscription-2021/

182. WSA. (2021b). *Top Steelmakers in 2020*. https://worldsteel.org/steel-by-topic/statistics/top-producers/

183. Wu, L., & Zhu, Q. (2021). Impacts of the Carbon Emission Trading System on China's Carbon Emission Peak: A New Data-Driven Approach. *Natural Hazards*, *107*(3), 2487–2515. https://doi.org/10.1007/s11069-020-04469-9

184. Xinhuanet. (2020, September 5). *China Focus: Understanding "Dual Circulation" and What It Means for World*. http://www.xinhuanet.com/english/2020-09/05/c_139345700.htm

185. Xinhuanet. (2021a, May 27). *First Plenary of Leaders Group on the Works of Carbon Peaking and Carbon Neutrality*. http://www.gov.cn/guowuyuan/2021-05/27/content_5613268.htm

186. Xinhuanet. (2021b, October 24). *Full Text: Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy*. http://www.news.cn/english/2021-10/24/c_1310265726.htm

187. Xinhuanet. (2021c, October 26). *Full Text: Action Plan for Carbon Dioxide Peaking Before 2030*. http://www.news.cn/english/2021-10/27/c_1310270985.htm

188. Xinhuanet. (2022, January 12). *The Ministry of Public Security releases 2021 national motor vehicle data*. http://www.xinhuanet.com/auto/20220112/96eb38da7fbe4340aab55ad1ec182669/c.html

189. Xu, N. (2022, June 9). Rebooting China's Carbon Credits: What will 2022 bring? *China Dialogue*. https://chinadialogue.net/en/climate/rebooting-chinas-carbon-credits-what-will-2022-bring/

190. Yang, Y., Li, R., Zhu, Y., Sun, Z., & Zhang, Z. (2020). Experimental and Simulation Study of Air Source Heat Pump for Residential Applications in Northern China. *Energy and Buildings*, *224*, 110278. https://doi.org/10.1016/j.enbuild.2020.110278

191. You, X. (2021, June 3). Explainer: China Creates New 'Leaders Group' to Help Deliver Its Climate Goals. *Carbon Brief*. https://www.carbonbrief.org/explainer-china-creates-new-leaders-group-to-help-deliver-its-climate-goals

192. Yu, M., Li, S., Zhang, X., & Zhao, Y. (2021). Techno-economic Analysis of Air Source Heat Pump Combined with Latent Thermal Energy Storage Applied for Space Heating in China. *Applied Thermal Engineering*, *185*, 116434. https://doi.org/10.1016/j.applthermaleng.2020.116434

193. Yu, S., Horing, J., Liu, Q., Dahowski, R., Davidson, C., Edmonds, J., Liu, B., Mcjeon, H., McLeod, J., Patel, P., & Clarke, L. (2019). CCUS in China's Mitigation Strategy: Insights from Integrated Assessment Modeling. *International Journal of Greenhouse Gas Control*, *84*, 204–218. https://doi.org/10.1016/j.ijggc.2019.03.004

194. Yu, S., Lehne, J., Blahut, N., & Charles, M. (2021). *1.5°C Steel Decarbonizing the Steel Sector In Paris-compatible Pathways*. https://9tj4025ol53byww26jdkao0x-wpengine.netdna-ssl.com/wp-content/uploads/1.5C-Steel-Report_E3G-PNNL-1.pdf

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

196. Yuncheng City Government. (2021). A village's pursuit for carbon neutrality. https://www.yuncheng.gov.cn/doc/2021/08/25/137693.shtml

197. Zalk, J., & Behrens, P. (2018). The Spatial Extent of Renewable and Non-Renewable Power Generation: A Review and Meta-Analysis of Power Densities and Their Application in The U.S. *Energy Policy*, *123*, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023

198. Zeng, X., Li, W., & Xingyue, G. (2021). *The Guangdong Carbon Emissions Trading Scheme: Progress, Challenges and Trends (Harvard Project on Climate Agreement)*. https://www.belfercenter.org/sites/default/files/files/publication/zeng-et-al-guangdong-ets-english-v2.pdf

199. Zhang, L. (2022, June 15). *Special Envoy Xie Zhenhua: China Will Work on Pollution Abatement, Carbon Reduction, and Other Areas to Achieve Dual Carbon Goals.* https://www.bjnews.com.cn/detail/165528143614587.html

200. Zhang, Q., Tong, D., Davis, S. J., Guan, D., Xu, R., Tan, X., Yan, L., & Chen, C. (2021). *Carbon Emissions and Lock-In Effect of Global Energy Infrastructure 2021* [Folder]. https://www.efchina.org/Attachments/Report/report-lceg-20220303

201. Zhang, Q., Zhang, L., Nie, J., & Li, Y. (2017). Techno-economic Analysis of Air Source Heat Pump Applied for Space Heating in Northern China. *Applied Energy*, *207*, 533–542. https://doi.org/10.1016/j.apenergy.2017.06.083

202. Zhang, S., & Chen, W. (2022). Assessing the Energy Transition in China towards Carbon Neutrality with a Probabilistic Framework. *Nature Communications*, *13*(1), Article 1. https://doi.org/10.1038/s41467-021-27671-0

203. Zhang, Y., Ma, Q., Li, B., Fan, X., & Fu, Z. (2017). Application of an Air Source Heat Pump (ASHP) for Heating in Harbin, the Coldest Provincial Capital of China. *Energy and Buildings*, *138*, 96–103. https://doi.org/10.1016/j.enbuild.2016.12.044

204. Zheng, J., Zhou, Y., Yu, R., Zhao, D., Lu, Z., & Zhang, P. (2019). Survival Rate of China Passenger Vehicles: A Data-Driven Approach. *Energy Policy*, *129*, 587–597. https://doi.org/10.1016/j.enpol.2019.02.037

205. Zheng, X., Wei, C., & Qin, P. (2015). *Chinese Household Energy Consumption Report 2014*. China Science Publishing & Media.

206. Zheng, X., Wei, C., Song, F., & Xie, L. (2016). *Chinese Household Energy Consumption Report 2015*. China Science Publishing & Media, Beijing.

207. Zhou, D. D., Xu, K., Zhou, P., & Jiang, X. (2020). The Production of Large Blast Furnaces of China In 2018 and Thoughts of Intelligent Manufacturing in the Ironmaking Process. *Ironmaking & Steelmaking*, *47*(6), 650–654. https://doi.org/10.1080/03019233.2020.1807289

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