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China Energy Transformation Outlook

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The views and opinions expressed in this report are those of the *China Energy Transformation Outlook* (CETO) project team and are solely for research purposes but do not necessarily reflect the views and positions of any individual partner institute. Unless otherwise indicated, all data contained in this report is derived from the CETO modelling database and relevant analysis results.

"China will strive to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. This requires tremendous hard work, and we will make every effort to meet these goals."

President Xi Jinping

Statement at the General Debate of the 76th Session of the United Nations General Assembly, September 21, 2021

Preface

On September 22, 2020, during his address at the General Debate of the 75th United Nations General Assembly, President Xi Jinping asserted that the Paris Agreement on climate change charts the course for the world to transition to green and low-carbon development. It outlines the minimum steps to be taken to protect the Earth, our shared homeland, and all countries must take decisive steps to honour this Agreement. President Xi further declared that China would scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. We aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060. Following this declaration, China unveiled a suite of sector-specific carbon peaking action plans, supplemented by many measures to establish a "1+N" policy framework for carbon peaking and carbon neutrality. Today, the carbon peaking and carbon neutrality targets are the firm basis for China's future development, not only in the fields of energy and environmental protection but also for a more profound economic and social change.

Global developments in the past two years have unequivocally demonstrated that climate change is not a mere future threat but a pressing reality that endangers the entirety of humanity in the present. The ramifications of climate change are growing in severity, with extreme weather events becoming more and more commonplace. This trend jeopardises both economic and social progress, as well as the well-being of populations across various nations, including China. Moreover, the effects of climate change pervade every facet of daily life, encompassing the reliability of energy supply. It is also evident that the repercussions of climate change on energy security are poised to magnify in the upcoming years. Hence, it is of paramount importance that we undertake decisive and effective measures to respond to the global climate crisis, ensuring the world complies with the temperature control targets established by the *Paris Agreement*.

Besides the climate crisis, concerns about energy security have again become a main topic globally. Securing a reliable energy supply is imperative for sustaining economic and social development and promoting public welfare. Therefore, energy security should be a top priority for policymakers as they formulate strategic decisions. The green, low-carbon transformation of the energy system does not conflict with safeguarding energy security. Still, it requires a clear focus on each step in the transformation process to maintain energy security, affordability, and an environmentally sound energy system.

The 2023 version of the *China Energy Transformation Outlook (CETO 2023)* analysis shows how China can reach the carbon peak and carbon neutrality targets and comply with the *Paris Agreement* targets with a high degree of energy security throughout the energy transformation process and a focus on optimal strategies and choices to attain a cost-efficient transformation.

This report examines potential trajectories for China's future energy transformation by establishing a baseline scenario and analysing two carbon-neutral scenarios. The purpose of the scenarios is to showcase different pathways to reach the targets and the different technology options for the future energy system.

In addition to the scenario analyses, the CETO 2023 report includes several thematic analyses on energy security, carbon pricing, methane emission and experiences from concrete project implementation. The report also summarises the experiences of the Danish energy transformation as part of the international cooperation and partnership between the Energy Research Institute (ERI) and the Danish Energy Agency.

The China Energy Transformation Outlook is a think-tank research report that explores the study of pathways to achieve carbon neutrality. It is updated and released annually based on the actual development of the previous year and the latest assessment of future technologies. I hope the report will be useful as part of the research background for the short-term policy-making process in China and internationally to ensure a more sustainable, prosperous, and secure future for all.

Many thanks to the ERI team and colleagues from other participating institutions in China for their consistent efforts and contribution of expertise during the research and preparation stages, especially to the relevant departments (divisions) of the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA). Meanwhile, thanks to the Danish Energy Agency, the Center for Global Energy Policy (CGEP) of Columbia University, Ea Energy Analyses (Ea), and the Norwegian NORAD for their strong support and great input to the analyses, and, not least, our long-term cooperation partner, Children's Investment Fund Foundation (the United Kingdom) (CIFF), for their generous financial assistance and unwavering support throughout the years, which made it possible for the ERI to organise and prepare this outlook report.

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Table of Contents

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Abbreviation list

ACER	European Union Agency for the Cooperation of Energy Regulators
AI	Artificial intelligence
AR5	The Fifth Assessment Report
AR6	The Sixth Assessment Report
BECCS	Bioenergy with carbon capture and storage
BLS	Baseline Scenario
CAGR	Compound Annual Growth Rate
CBAM	Carbon Border Adjustment Mechanism
CBEEX	China Beijing Environmental Exchange
CBM	Coal bed methane
CCDR	Central Commission for Comprehensively Deepening Reform
CCERs	Chinese Certified Emission Reductions
CCIA	China Coal Industry Association
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CDM	Clean Development Mechanism
CGE	Computable General Equilibrium
CH_4	Methane
CHP	Combined Heat and Power
CM	Capacity Mechanism
CMM	Coal mine methane
CNEIA	China Nuclear Energy Industry Association
CNS1	Carbon Neutral Scenario 1
CNS2	Carbon Neutral Scenario 2
CO_2	Carbon dioxide
COP26	Climate Change Conference
CPC	Communist Party of China
CPI	Consumer Price Index
CPIA	China Photovoltaic Industry Association
CSDD	Corporate Sustainability Due Diligence
CSO22	Climate Status and Outlook 2022
CUFE	Central University of Finance and Economics
CWEA	China Wind Energy Association
DAC	Direct Air Capture
DACCS	Direct Air Capture and Carbon Storage

DEA	Danish Energy Agency
DEA	Greenhouse Gas
DR	Demand-side response
DRI	Direct reduction of iron
DSO	Distribution System Operator
EAF	Electric arc furnace
EDO	Electricity and District Heat Deployment Optimisation
EHB	European Hydrogen Backbone
ENTSO-E	European Network of Transmission System Operators
EPA	Environmental Protection Agency
ERAA	European Resource Adequacy Assessment
ESG	Environmental, Social, and Governance
ETS	Emissions Trading System
EVs	Electric vehicles
FYP	Five-Year Plan
GDP	Gross Domestic Product
GGFDI	Global Green Finance Development Index
GIP	Green Investment Principles
GMP	Global Methane Pledge
GWP	Global Warming Potential
ICPF	International Carbon Price Floor
ICVs	Intelligent connected vehicles
IEA	International Energy Agency
IIGF	International Institute of Green Finance
IIJA	Infrastructure Investment and Jobs Act
IMEO	International Methane Emissions Observatory
IMF	International Monetary Fund
IoT	Internet of Things
IT	Information technology
IPCC	Intergovernmental Panel on Climate Change
IPP	Implicit pricing
IPSF	International Platform on Sustainable Finance
IRA	The Inflation Reduction Act
LCOE	Levelised cost of electricity
LNG	Liquefied natural gas
LULUCF	Land use, land-use change and forestry

MIIT	Ministry of Industry and Information Technology
MOE	Ministry of Ecology and Environment
MOT	Ministry of Finance (MOF), Ministry of Transport
MRV	Monitoring, accounting, reporting and verification
$MtCO_2$	Million tonnes of carbon dioxide
MWR	Ministry of Water Resources
MWR	Ministry of Agriculture and Rural Affairs
NAFTA	North American Free Trade Agreement
NBS	National Bureau of Statistics
NDAM	National day-ahead market
NDAM	Market operator
NDCs	Nationally Determined Contributions
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NGFS	Supervisors Network for Greening the Financial System
NO_x	Nitrogen oxides
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Cooperation and Development
OGMP	Oil and Gas Methane Partnership
PBoC	People's Bank of China
PHEVs	Plug-in hybrid electric vehicles
PHEVs	Danish Council on Climate Change
PipeChina	National Petroleum and Natural Gas Pipeline Network Group Company
ppbv	Parts per billion by volume
PRI	Principles for Responsible Investment
PtX	Power-to-X
PV	Photovoltaic
SBN	Sustainable Banking Network
SDM	Sustainable Development Mechanism
SFDR	Sustainable Finance Disclosure Regulation
SFWG	Sustainable Finance Working Group
tce	Tons standard coal equivalent
Towngas	Hong Kong and China Gas Company
UHVDC	Ultra-high voltage direct current
UNFCCC	United Nation Framework Convention on Climate Change

UNFCCC	United Nation Framework Convention on Climate Change
V2G	Vehicle-to-Grid
VAM	Ventilation air methane
VRE	Variable renewable energy
WEET	West-to-East Electricity Transmission
WGIII	Working Group III
WMO	World Meteorological Organization
WTO	World Trade Organization

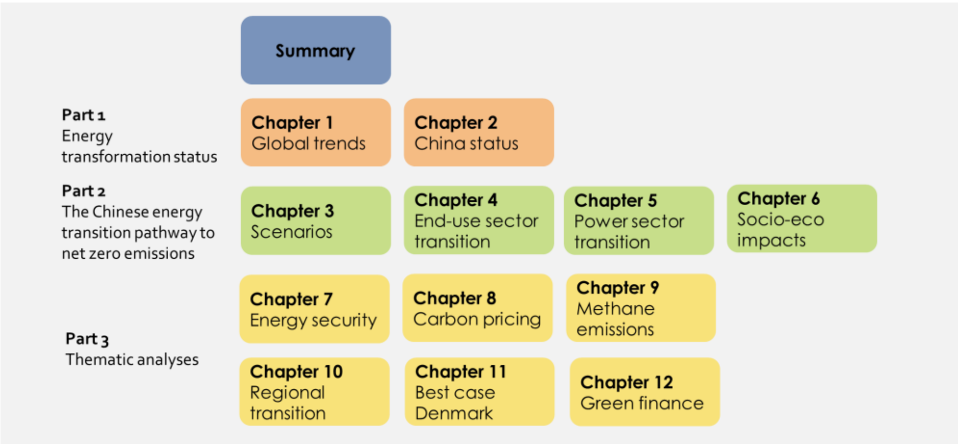
How to read the China Energy Transformation Outlook 2023

This report is a short summary of the full *China Energy Transformation Outlook 2023* (CETO 2023) report. The full report consists of three parts.

Part I gives a brief overview of the global climate crisis and the global energy development situation in Chapter 1, focusing on recent years' development. It also provides a status for the development of the Chinese energy system and for the energy policy in China in Chapter 2.

Part II is the modelling-based scenario analysis [a] of the Chinese energy system transformation towards 2060. It consists of four chapters: Chapter 3 summarises the overall transition situation of the energy system, including the framework design and assumptions of the three scenarios included in the Outlook. Chapter 4 dives into the energy consumption pathways in the end-use sectors, including the industry sectors, the building sector, the transport sector, and other sectors. Chapter 5 details the analysis of the power sector based on results from the power sector model. Chapter 6 analyses the socio-economic impact of the energy transformation.

Part III includes six thematic chapters unrelated to the modelling-based scenario analysis in Part II. Chapter 7 describes the energy security policies and current situation in China. Chapter 8 analyses an overview of the latest developing progress in carbon pricing in China. Chapter 9 describes the progress related to methane emissions control globally and in China. Chapter 10 analyses trends and case studies of local and regional energy transformation. Chapter 11 summarises the energy and climate policy developments in Denmark. Chapter 12 discusses the significance of green financing to the energy transition.



[a] Unless there is a specific note, the data for the four chapters in Part II (including the base year data) of the report are based on the CETO database and calculation of the CETO model.

The summary gives the highlights of the analyses in the Outlook report, including the key findings from the scenario analyses in Part II. The summary can be read as a separate document from the full report. The four chapters in Part II describe the overall conclusions and specific findings of the CETO scenario analyses in detail. Here, it is possible to dive into the details to understand the outlook scenario design and the detailed conclusions by sector. Each of the chapters in Part III can be read independently of the rest of the Outlook to gain insight into each topic.

Enjoy the reading!

Feedback to the Outlook is most welcome. Please send your feedback to ceto2023@cet.energy.

Summary

Three energy system scenarios

The starting point for *China Energy Transformation Outlook 2023 (CETO 2023)* is China's commitment to achieving carbon neutrality before 2060. Compared with previous low-carbon development targets, achieving peak carbon and carbon neutrality represents a more extensive and profound systemic transformation of the economic and social systems. Fulfilling this commitment requires significantly improved energy efficiency, a rapid expansion in non-fossil fuel energy, and carbon sinks or negative emission technologies to realise comprehensive carbon neutrality.

Within the framework of the "1+N" policy system for peaking carbon emissions and reaching carbon neutrality, CETO 2023 examines energy system transformation scenarios across various end-use sectors and the processing and conversion sector, with a focus on the feasibility and pathways to achieve the carbon neutrality milestone. Utilising the LEAP, EDO, and CETPA models, the research team has analysed end-use energy consumption, power and heat supply, and the subsequent environmental and societal impacts. The team then conducted a coordinated analysis of multiple goals, including economic development, carbon reduction, and energy security. The overarching perspective acknowledges that China's energy transformation should not only champion carbon goals, but also foster economic development and uphold living standards under the initiative for Building Beautiful China, culminating in the Chinese-style modernisation of harmonious coexistence between humanity and nature. Building a new-type energy system, with new power systems at its core, that is clean, low-carbon, secure and resilient, flexible and smart, highly efficient, inclusive, and shared, is crucial for achieving peak carbon and carbon neutrality.

CETO 2023 defines three scenarios for China's energy path leading up to 2060:

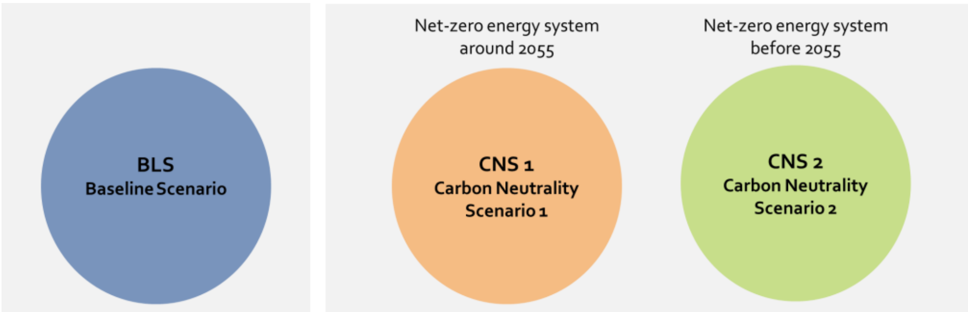
The Baseline Scenario (BLS) is developed by projecting current trends in energy system development and is calibrated to align with the objective of the *Paris Agreement* to limit the global average temperature increase to within 2°C this century. The analysis incorporates considerations of prevailing political and economic tensions across the globe, alongside newly proposed policies from key regions and countries. It assesses the likely impacts on the evolution of new and renewable energy sectors, as well as on the energy transition both globally and within China. A Baseline Scenario for China's energy transformation, characterised by relatively lower intensity, is presented. This serves as a standard for quantitative comparisons with two scenarios that envisage full carbon neutrality.

Two Carbon Neutrality Scenarios (CNS) operate under the supposition that the countries of the world unite and make concerted efforts to achieve the goal determined by the *Paris Agreement*, that is, to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to

1.5°C above pre-industrial levels". The two carbon neutrality scenarios set the forcing targets for China of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060, but there are differences in the choices of pathways and timing for the energy system to achieve net zero emissions.

The Carbon Neutrality Scenario 1 (CNS1): Advocates for renewable energy development, and by 2055, biomass power and remaining coal and gas power units are fully installed Carbon Capture, Utilisation and Storage (CCUS) facilities, targeting net zero emissions in the energy system around 2055.

Carbon Neutrality Scenario 2 (CNS2): Based on advocating renewable energy development, it is required to expand wind and solar PV power generation capacity further. The full load hours and power generation of coal power units both drop faster till naturally retired as a consequence. Prior to 2055, the biomass power and remaining gas power units are gradually installed as CCUS facilities, aiming for net zero emissions in the energy system before 2055.



Key findings of the scenario analyses

The scenario analyses can be summarised in the following key findings:

The global energy and climate situation calls for an accelerated global energy transformation. Both carbon neutrality scenarios (CNS1 and CNS2) show that **China's green and low-carbon transformation of the energy system can enable carbon neutrality by 2060.** CNS1 foresees net-zero emissions in the energy system around 2055, while CNS2 anticipates this before 2055. Concurrently, by 2060, China's economy quadruples its 2021 size, yet primary energy consumption is just about 60% of its 2021 level.

The BLS presents a reference scenario where energy transformation challenges and uncertainties escalate due to the unpredictability and deepening alterations in global political and economic spheres. Herein, fossil fuel use dips post-2030 but doesn't plummet significantly by 2060, underscoring the imperative for robust global policy cohesion to hasten energy system transformation.

Significantly improved energy efficiency is the premise and basis for achieving carbon neutrality, and it is essential to achieve a substantial level of electrification in end-use sectors to facilitate a green and low-carbon transformation of the energy sector. Comprehensive improvement of energy efficiency in end-use sectors and the energy supply sector can reduce total energy consumption and decouple economic growth from growth in energy demand. Hence, China's energy efficiency needs to improve continuously. A substantial level of electrification and the expansive development of hydrogen production within the end-use sectors are key drivers for accelerating the growth in electricity consumption. Electrification in the industrial, transportation, and building sectors helps reduce fossil fuel consumption in end-use sectors. The shift from thermal power generation to wind and solar power generation in the power sector can reduce energy processing and conversion losses in the supply sector. In CNS2, by 2060, while China's economic scale grows about fourfold, final energy consumption and primary energy consumption drops to 64% and 56% of the 2021 level, respectively ; the electrification rate of end-use sectors reaches 66%, and the total electricity consumption reaches 20,200 TWh.

Leapfrog development of renewable energy plays a pivotal role in shaping new power systems, marked by extensive growth in wind and photovoltaic power generation. In both the CNS scenarios aiming for net-zero emissions in the energy system, renewable energy's share in the primary energy supply surpasses 74% by 2060. The power system undergoes a comprehensive clean transformation, with renewable energies like wind and photovoltaic power emerging as the predominant sources. This shift leads to a significant increase in installed capacity, transforming renewable energy into an inexpensive and plentiful low-carbon resource. By 2060, renewable energy contributes over 94% of the total electricity production, with the remaining coming from nuclear energy. This shows that under the premise of coal power transformation, the deep decarbonisation of the energy mix and comprehensive transition towards non-fossil energy sources are imperative prerequisites for achieving net-zero emissions in the energy system.

The role of coal power is evolving from a baseload source to a more flexible power source. With the right technical backing, both CNS1 and CNS2 suggest that the yearly operating hours of these coal-fired units diminish over their operational life, leading to a more cost-effective energy system transformation. This strategic approach not only considers growth and safety but also moves towards achieving net-zero emissions in China's energy landscape. In this transformation, coal-fired power's role evolves, and its full adaptability for flexibility is achieved by 2040. After 2040, as the active units near their end-of-life, these coal-fired units begin phasing out, with their operating times sharply dropping to under 1,000 hours. Post-2050, coal-fired power generation in both CNS scenarios reduces to an exceedingly low level. The broader power infrastructure moves away from coal as its primary energy source. However, select decommissioned units are preserved and maintained, standing by as emergency backups.

Nuclear power plays an active and stable role as a low-carbon baseload power source. In all scenarios, nuclear power capacity grows consistently, reaching an estimated 120 GW by around 2040. Positioned along the country's coastlines, these installations operate as baseload units with a high number of operation hours.

As the growth in natural gas demand decelerates, its role in energy consumption is gradually adjusted. Scenario analyses indicate that the swift advancement of renewable energy enables China to bypass a period of high growth and dependence on oil and gas. In the power sector, factors such as the rapidly declining costs of wind and solar power generation, the relatively high price of natural gas, and the transition of coal-fired power units to peak shaving in the short to medium term collectively impede the growth of natural gas demand for power generation. Instead, natural gas is primarily utilised in end-use sectors. Additionally, the development and implementation of biomass gas in sectors like power generation, industry, and transportation could supplant some of the natural gas demand. In all three scenarios, the share of natural gas in the total primary energy demand decreases to less than 7% by 2060.

To establish a novel type of power system, comprehensive coordination and balancing of the system is essential, alongside constructing a highly intelligent new grid. Developing new-type energy storage, demand response, and smart energy systems are pivotal for maintaining power system security. The robust development of renewable energy within this new energy system continues to refine the grid structure, leading to an innovative grid pattern characterised by "West-East Power Transmission, East-West Power Cooperation, North-South Power Transmission, and South-North Power Interconnection." Integrating large-scale, fluctuating renewable energy sources effectively is crucial to satisfy future power users' needs, particularly during peak demand times. Emerging energy storage solutions, such as electrochemical storage, vehicle-to-grid (V2G) integration, and compressed air energy storage, complement traditional pumped storage stations and peak regulation reservoirs, progressively supplanting the peak-regulating roles of coal-fired plants. From 2021 to 2035, in the CNS2 scenario, the new-type energy storage technologies growth at an average annual rate of 26%, showcasing exponential expansion. Between 2030 and 2060, V2G's widespread adoption is anticipated, growing at an annual average rate of about 14%. By 2060, pumped storage, new energy storage, and demand-side response emerge as the primary regulatory resources of the power system, with electric vehicle storage playing a crucial role in ensuring its stable operation. Moreover, green hydrogen, while rising as a source to facilitate industrial transformation, contributes to balancing the power system load, primarily through the flexible production of hydrogen.

Carbon capture and storage (CCS) emerges as an important, albeit "last resort", tool for realising carbon neutrality. The primary application of CCS technology is to mitigate carbon emissions from those sectors that are challenging to decarbonise, CCS also could additionally aid in curbing emissions from coal and gas power plants. Pairing biomass power generation with bioenergy carbon capture and storage (BECCS) introduces an innovative approach to achieving a net-zero emission power system.

However, leaning heavily on CCS technology for carbon neutrality presents substantial risks. Scenario analyses indicate inherent technical limitations with CCS, and the potential pitfalls of over-reliance on it warrant careful consideration. To start, the CCS processes of capturing, compressing, transporting, and storing carbon demand significant energy and heat. This consumption hampers the efficiency of coal and gas power facilities, inadvertently causing further carbon emissions and amplifying the demands on the CCS system. Moreover, achieving complete carbon capture is elusive, even for plants equipped with advanced CCS. Thus, to truly attain carbon neutrality, alternative carbon removal strategies, such as the pricier direct air capture (DAC) technology or forest carbon offsets, become necessary. This implies that achieving a net-zero carbon footprint in the energy system remains challenging. Furthermore, the geologic prerequisites for CCS are stringent. Questions remain about the potential long-term leakage of stored CO_2, necessitating more extended research and experimental validation. The repercussions on local subterranean and surface ecosystems also require comprehensive assessment.

Green hydrogen serves a dual-purpose role as both a zero-carbon feedstock and fuel. The development and deployment of green hydrogen hold immense promise for sectors that are notoriously difficult to decarbonise, like steel and petrochemicals. Hydrogen can serve as a reducing agent, substituting the requisite coke in the iron smelting process and as a raw material, replacing coal in the production process of synthesising ammonia. Beyond that, hydrogen offers a viable replacement for fossil fuels like petrol and diesel in transportation. Additionally, hydrogen paves the way to produce other electrofuels (PtX), offering alternative fuel options for aviation and shipping. Across various projections, the appetite for hydrogen keeps growing, accompanied by a surge in related electricity consumption.

The shift towards green and low-carbon energy is essential for ensuring sustainable social and economic advancement in China. Meeting the targets of carbon peak and carbon neutrality necessitates comprehensive and deep-rooted systemic changes, with energy transformation being a key component. The swift and groundbreaking progress in clean energy technologies is pivotal in not only stimulating the growth of green industries but also in creating a greater number of green employment opportunities, while substantially reducing the source emissions of air pollutants. This energy transformation is crucial in providing a secure and efficient energy supply while concurrently aiding in the modernisation of industries, propelling high-quality economic development, and supporting the achievement of varied sustainable development objectives.

China energy flow charts

Figure 1 2021 China energy flow chart

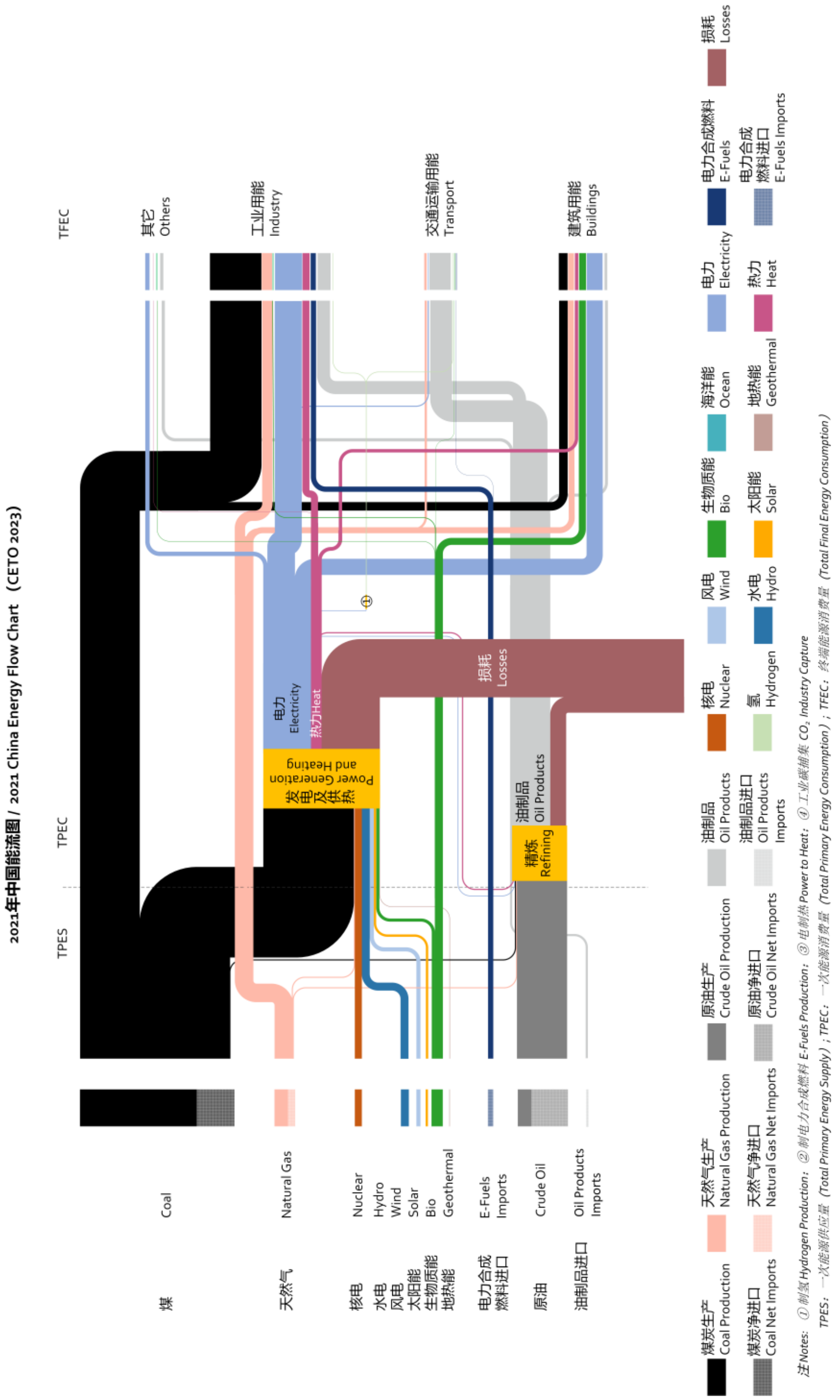
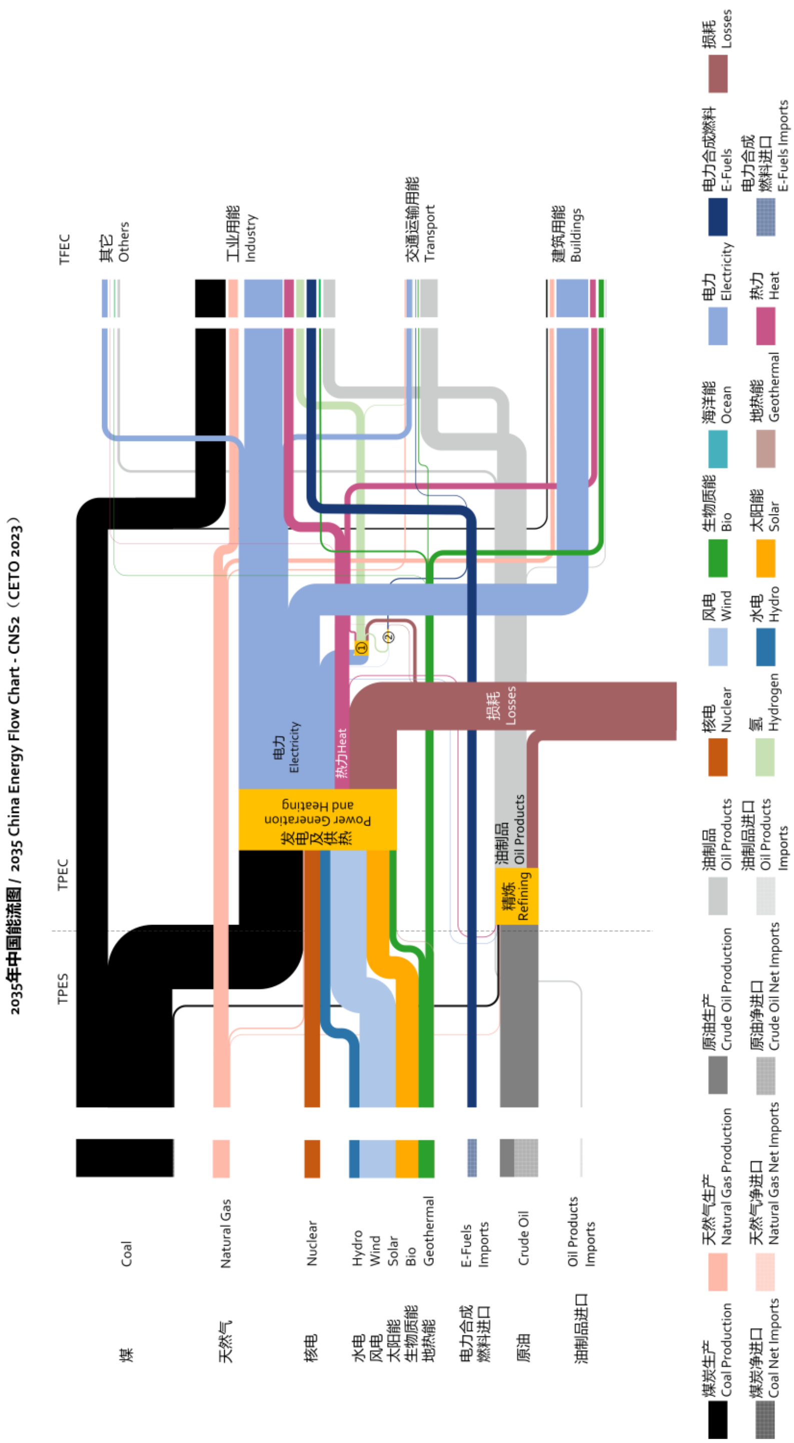


Figure 2 2035 China energy flow chart – CNS2



注Notes: ①制氢 Hydrogen Production; ②制电力合成燃料 E-Fuels Production; ③电制热 Power to Heat; ④工业碳捕集 CO_2 Industry Capture

TPES: 一次能源供应量（Total Primary Energy Supply）; TPEC: 一次能源消费量（Total Primary Energy Consumption）; TFEC: 终端能源消费量（Total Final Energy Consumption）

Figure 3 2050 China energy flow chart – CNS2

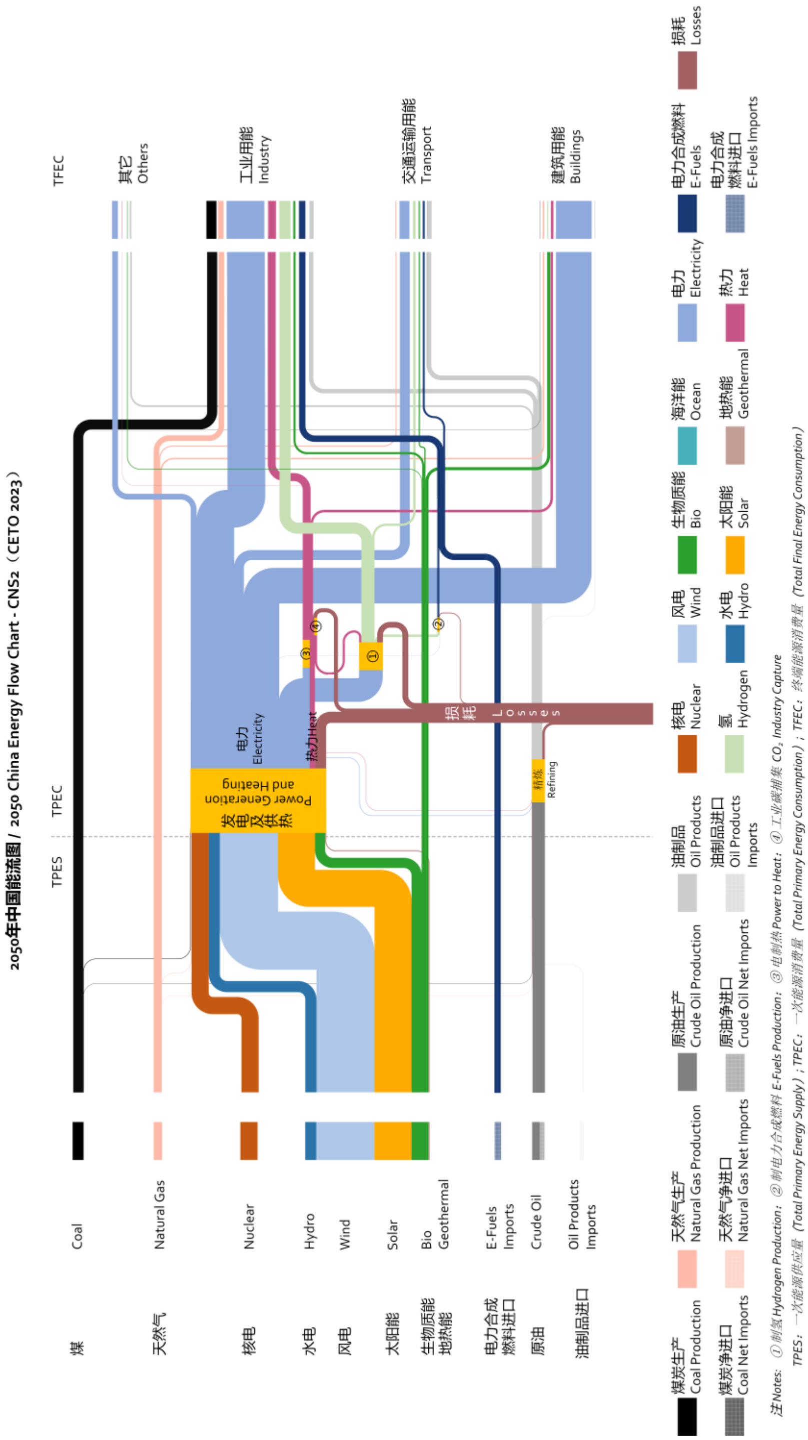
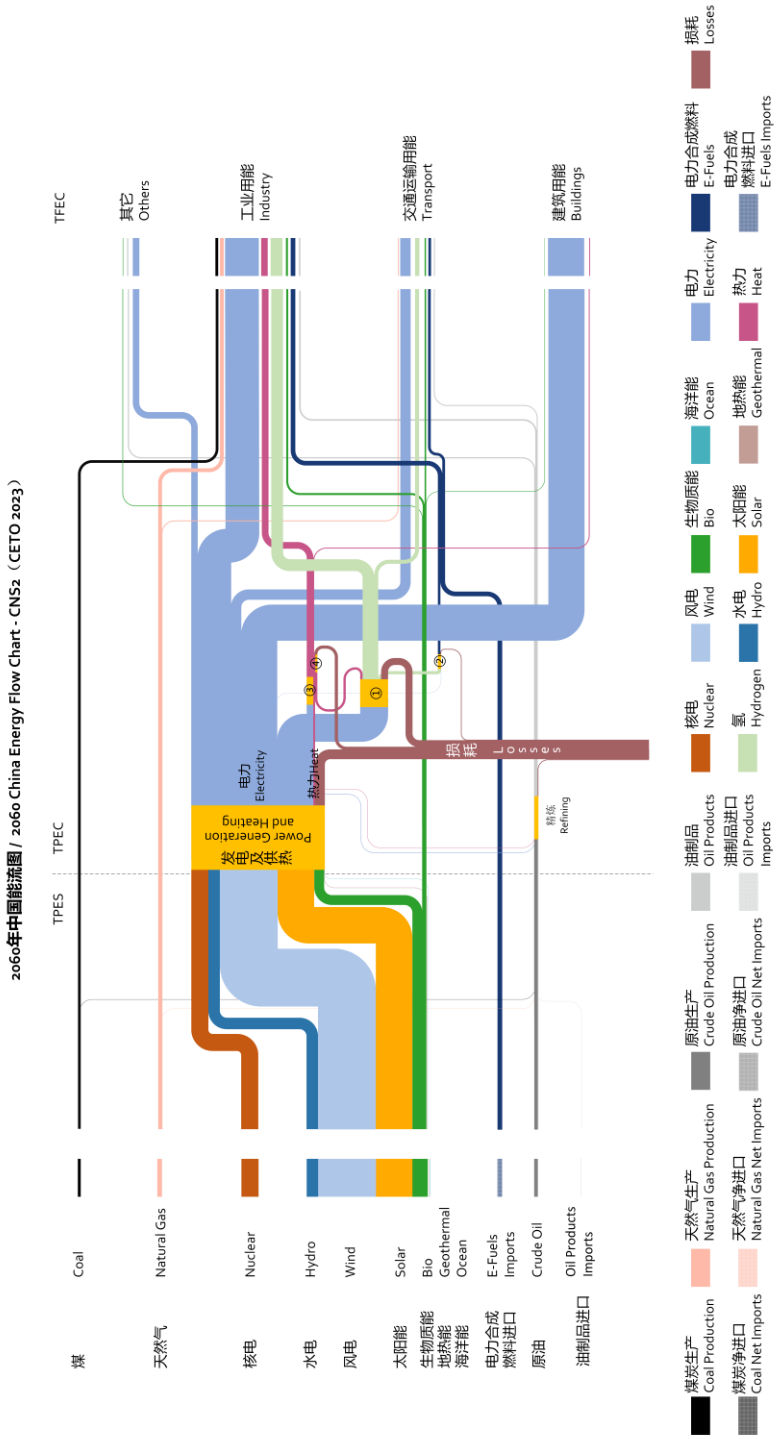


Figure 4 2060 China energy flow chart – CNS2



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Part 1: Energy transformation status

Chapter 1

New developments and challenges in global response to climate change and energy transition

1 New developments and challenges in global response to climate change and energy transition

In the current world, the repercussions of the COVID-19 pandemic continue to ripple through society. The interplay of geopolitical strife, unregulated competition, and international confrontations, amplified by the rapid pace of technological advancements, is propelling an unparalleled transformation. Currently, escalating climate change impacts are deeply influencing socio-economic progress across the globe. Extreme weather events, including heatwaves, droughts, water shortages, and harsh cold spells, have become frequent, causing extensive harm to habitats and ecosystems and jeopardizing food security. Concurrently, the persisting COVID-19 pandemic, the crisis in Ukraine, and other geopolitical shifts bring forth fresh uncertainties and challenges to the global energy transition. A novel rearrangement is unfolding in the energy supply-demand dynamic, typified by an increasingly fragmented and decentralised energy supply, politicized supply chains, and escalating costs of energy security and non-technical expenses. Numerous nations and regions are grappling with energy shortages and sky-rocketing prices, inflicting wide-reaching impacts on their economies and citizens' daily lives. Deep decarbonisation and comprehensive energy transition are gaining paramount importance as a foundational component to address climate change and global sustainable development. Nevertheless, the heightened urgency and importance of achieving these emissions reductions and transformations also bring to light additional formidable long-term challenges.

The global consensus on taking decisive action against climate change remains intact, and concerns over energy security and energy prices have not eroded confidence in the global energy transition. On the contrary, these challenges may spur global green and low-carbon energy transition on an international scale. This chapter introduces the new developments and challenges faced in global climate change and energy transition, setting the stage for subsequent detailed discussions on China's green energy transition.

1.1 Key messages

- Global climate change poses increasingly severe threats to human economic and social advancement, as underscored by the heightened frequency of extreme weather events and their associated risks to food security.
- Geopolitical tensions exacerbate the imbalance between energy supply and demand, putting many countries and regions under pressure from energy shortages and high prices. This intensifies the challenge of energy transformation.
- To address climate change and promote global sustainable development, substantial reductions in emissions and a significant energy transition have become essential, thereby fortifying the collective agreement on carbon neutrality.

1.2 Intensifying impact of global climate change

Over the past century, the burning of fossil fuels and inequitable, unsustainable energy and land use have resulted in a global temperature increase of 1.1°C above pre-industrial levels. This increase has led to not only more frequent and intense extreme weather events but also an escalating danger to nature and humanity worldwide.

In recent years, the effects of global climate change have become increasingly pronounced, as evidenced by frequent occurrences of extreme weather phenomena. According to the *State of the Global Climate 2022* released by World Meteorological Organization (WMO), the period from 2015 to 2022 was the warmest eight-year stretch on record. The global surface temperature in 2022 was approximately 1.15°C higher than the global average temperature between 1850 and 1900 (the "pre-industrial average temperature"). According to the report, the rise in global surface and ocean temperatures in 2022 amplified extreme weather and climate anomalies.

In September 2022, Hurricane Ian caused at least 149 deaths in the United States and resulted in over $50 billion in economic losses. According to PowerOutage.us, which tracks power outages nationwide in the United States, more than 491,000 customers in Florida were still without power five days after Hurricane Ian had passed. In East Africa, rainfall had been below average for four consecutive rainy seasons, marking the longest such period in nearly four decades. As a result of drought and other impacts, an estimated 18.4-19.3 million people in the region are at risk of food insecurity. In Pakistan, record-breaking rainfall in July and August led to widespread flooding, causing approximately 1,700 deaths, displacing 7.9 million people, and affecting 33 million people.

In 2022, most parts of the Northern Hemisphere experienced abnormal drought and heat. Temperatures reached over 40°C for the first time in the United Kingdom, with a temperature of 40.3°C recorded in Coningsby on July 19, surpassing the national record by 1.6°C. The heatwave in Europe extended as far north as northern Sweden, with a temperature of 37.2°C recorded in Målilla on July 21, the highest since 1947. Drought conditions in Europe intensified in August, with river flows in the Rhine, Loire, Danube, and other rivers reaching extreme lows.

During the summer of 2022, the middle and lower reaches of the Yangtze River in China experienced an unprecedented severe drought and prolonged high temperatures. This led to critical water shortages in this densely populated region, exerting immense pressure on ecological water use, domestic water supply, and power generation. Since that summer, parts of China and neighbouring countries have faced high temperatures and serious drought, leading to water shortages in some areas. The water scarcity induced by the drought, combined with water-related disasters and environmental issues, has strained national and regional water networks, exacerbating the conflict between water and energy. The rise in electricity demand caused by high temperatures and drought has led to a decrease in hydropower generation, necessitating various measures to ensure electricity supply or minimise power rationing and shortages, including boosting the generation of renewable energy, primarily through wind and solar power.

The impact of global climate change on human production and life is becoming increasingly significant. In response to this pressing issue, the WMO urges all nations to intensify their efforts in tackling climate change and safeguarding our shared home, the Earth.

Global CO_2 emissions still increasing

Global carbon dioxide emissions continue to grow, albeit at a slower pace. According to data from the International Energy Agency (IEA), global carbon dioxide emissions related to energy increased by 0.9% or 321 million tons in 2022, reaching a historical high of over 36.8 billion tons. After experiencing irregular fluctuations in energy consumption and emissions due to the COVID-19 pandemic and other factors, the rebound in 2022 exceeded 6% compared to 2021, but the average growth rate has slowed. Despite most countries setting carbon neutrality goals, there is a significant gap between current global carbon dioxide emissions and the efforts required to limit global warming to 2°C or even 1.5°C. According to the *Sixth Assessment Report* of the IPCC based on the Nationally Determined Contributions (NDCs) submitted by countries, global warming is projected to reach 2.8°C by the end of this century. To achieve the goal of limiting global warming to 1.5°C, global greenhouse gas emissions need to peak by 2025 and decrease by approximately 43% from the peak level by 2030, followed by achieving net-zero carbon dioxide emissions by 2050. Although it will be challenging for the world to achieve deep emissions reductions before 2030, countries still need to accelerate their energy transition and implement more robust measures, treating climate change as a common endeavour and taking concrete actions.

Figure 1-1 1990-2022 Global carbon dioxide emissions from energy combustion and industrial processes

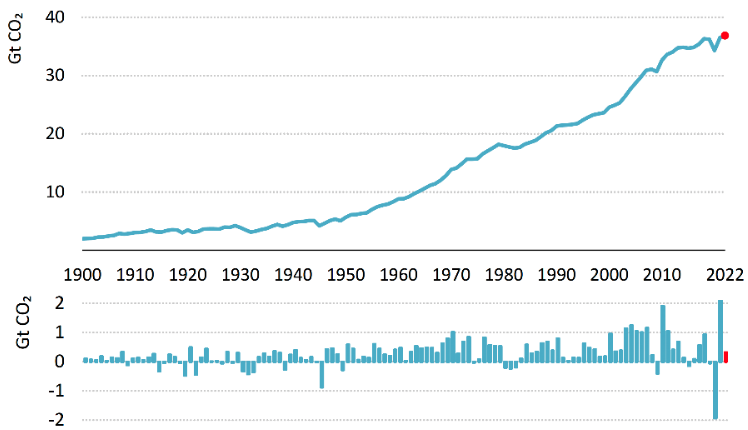


Image Source: International Energy Agency (IEA)

Box 1-1 The IPCC releases the Working Group III (WGIII) report to the *Sixth Assessment Report (AR6)*

On April 4, 2022, the Intergovernmental Panel on Climate Change (IPCC) released the Working Group III (WGIII) report to the *Sixth Assessment Report (AR6)*, *Climate Change 2022: Mitigation of Climate Change*. The report summarizes the progress made by the international scientific community in the field of climate change mitigation since the release of the *Fifth Assessment Report (AR5)*, describes the status of global greenhouse gas emissions, emission reduction pathways to limit global warming to different levels, and synergies between climate change mitigation and adaptation actions and sustainable development, and reveals the importance and urgency of implementing profound industry-wide GHG emission reduction, especially for energy systems, in order to achieve different levels of temperature rise control. Meanwhile, it also underscores the need for undertaking the climate change mitigation actions in the context of sustainable development, equity and poverty eradication, in order to make them more acceptable, sustainable and effective.

The report notes that limiting global warming will require major transitions in the energy sector. This will involve a substantial reduction in fossil fuel use, widespread electrification, improved energy efficiency, and use of alternative fuels (such as hydrogen).

“We see examples of zero energy or zero-carbon buildings in almost all climates,” said IPCC Working Group III Co-Chair Jim Skea. “Action in this decade is critical to capture the mitigation potential of buildings.”

Reducing emissions in industry will involve using materials more efficiently, reusing and recycling products and minimising waste. For basic materials, including steel, building materials and chemicals, low- to zero-greenhouse gas production processes are at their pilot to near-commercial stage.

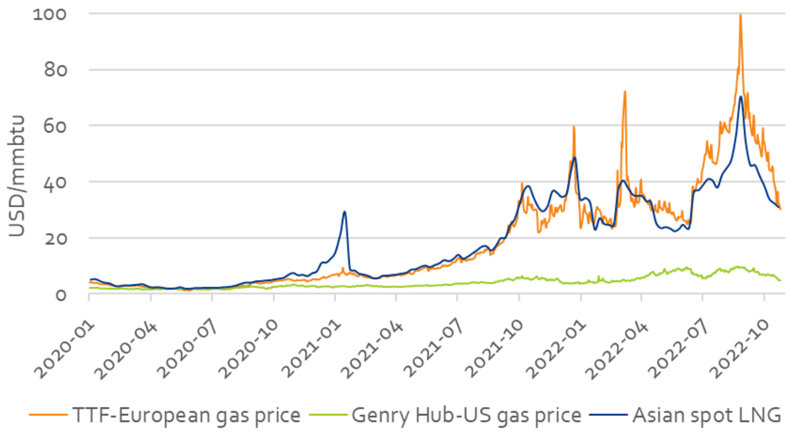
The energy sector accounts for about a quarter of global emissions. Achieving net zero will be challenging and will require new production processes, low- and zero-emissions electricity, hydrogen, and, where necessary, carbon capture and storage.

Agriculture, forestry, and other land use can provide large-scale emissions reductions and remove and store carbon dioxide at scale. However, land cannot compensate for delayed emissions reductions in other sectors. Response options can benefit biodiversity, help us adapt to climate change, and secure livelihoods, food and water, and wood supplies.

1.3 Geopolitical intensification exacerbates energy supply-demand imbalance, heightening difficulties and challenges in energy transition

Over the past two years, the COVID-19 pandemic has caused unparalleled impacts to global development. The Ukrainian crisis, super-loose monetary policies in developed nations, and other factors have stirred considerable turmoil in the global energy market. Furthermore, the uneven post-pandemic economic recovery, fragmented energy supply chain, and inadequate investment have disrupted the energy supply in the post-pandemic era. In the last two years, a severe oil and gas supply shortage has emerged in Europe, prompting many European nations to return to coal use and activate coal-fired power as emergency safeguards and strategic reserves. Beyond Europe, fluctuations in energy market supply and demand, coupled with a steep rise in energy prices, have affected the economies and livelihoods of numerous countries, resulting in adverse impacts on energy prices and stable energy supply in East Asia as well.

Figure 1-2 2020-2022 Natural gas price changes in the United States, Europe, and Asia



Source: Refinitiv Datastream

The volatility in the energy market has intensified due to multiple factors. Short-term factors include the ongoing impact of the COVID-19 pandemic and an uneven post-pandemic economic recovery across nations. The unresolved Ukraine crisis and the uncertain prospects of global economic growth inject significant uncertainty into the resurgence of energy demand. Medium-term factors include the influence of the low-carbon transition and rising investment and financing costs, leading to a 37% decline in global upstream oil and gas investment between 2016 and 2020, amounting to a mere $392 billion, compared to 2010-2015. The lack of investment interest in upstream sectors like oil and gas extraction underscores the issue of inadequate fossil fuel supply capacity in recent years. From a long-term perspective, the global shift away from fossil fuels and the evolution of carbon-neutral energy systems are crucial. If these complex factors and their frequent impacts are not effectively addressed, it will undeniably hamper the global energy transition.

Turbulence in the global energy market has compromised the energy security of various nations. Fossil fuel prices, including oil, natural gas, and coal, hit record highs in 2022, and surging fuel prices have inflated energy costs for residents, businesses, and other energy consumers. In particular, a considerable surge in natural gas prices has directly resulted in a rapid increase in energy costs for nations worldwide.

In Europe, the following trends have been observed: decreased demand for natural gas, a significant increase in liquefied natural gas (LNG) demand, expanded coal consumption, and an increased willingness to develop new oil and gas projects and infrastructure. In 2022, the overall natural gas demand in the European Union declined by 13%, with one-fifth of the decrease attributed to supply reduction rather than efficiency improvements or fuel switching. Europe's demand for LNG experienced a sharp increase during the first eight months of 2022, leading to a two-thirds growth in net LNG imports. To address electricity shortages, Europe has to expand its coal and renewable energy generation capacity.

In China, the primary trends are as follows: a historic decrease in natural gas consumption in 2022, significantly affecting industrial gas usage; a notable reduction in refined oil consumption, with domestic crude oil production returning to 200 million tons and a minor decline in crude oil imports; steady growth in overall electricity consumption, accelerating the low-carbon transformation of power supply, with non-fossil fuel power generation capacity nearing 50%; a deceleration in the growth rate of coal demand compared to the previous year, with prices in the second half of 2022 gradually declining from high levels. The mounting turmoil in the global energy market is detrimental to China's economic development. The increasing energy prices will incite fluctuations in upstream industries such as energy, transportation, and chemicals. Alongside a general surge in commodity prices, this trend will lead to a rise in production costs and consumer prices for manufactured goods and downstream industries in the supply chain.

1.4 The consensus on carbon neutrality has been strengthened, and the resilience of the energy system has become the new focus area

Although the turmoil in the energy market has intensified in the past two years, most developed countries regard accelerating the development of new energy and realising energy transition as the fundamental way to ensure energy security and effectively respond to global climate change. The consensus on striving to achieve carbon neutrality has further strengthened. Hence, the current crisis could accelerate the rollout of cleaner, sustainable renewable energy such as wind and solar, just as the 1970s oil shocks spurred major advances in energy efficiency and nuclear, solar and wind power. The crisis also underscores the importance of investing in robust energy network infrastructure to integrate regional markets better.

The security and resilience of the energy system have emerged as new focus areas in the global energy sector. The enhancement of energy systems' resilience is tied, on one hand, to the inherent characteristics of renewables, which are stochastic, intermittent, and volatile. The traditional centralised energy supply model, characterised by "large capacity, high parameters, and long-distance," allowed for significant control over energy flow and did not require supplemental resilience services from the energy system. However, with the continuous rise in the proportion of renewables worldwide, fortifying the energy system's resilience has become an unavoidable choice for steadily advancing energy transition. This is achieved through enhancing the energy storage capacity, peak shaving capability, and demand-side flexibility of power grids and heat networks. On the other hand, with the growing impact of various unforeseen events on the fossil fuel industry and supply chains, bolstering reserve capacity and improving energy systems' resilience has become essential to safeguard national energy security and ensure the regular operation of the economy and society. Given the continued impact on the global energy industry and supply chains, the topic of energy system resilience is gaining increasing attention from many countries.

REPowerEU boosts renewables in Europe

The European Commission's *REPowerEU Plan*, which builds on the goals of the *"Fit for 55" Plan*, aims to increases EU's climate and clean energy targets by including energy efficiency measures, such as a voluntary 15% reduction in natural gas demand and a mandatory reduction target of 5% of electricity use during peak hours. It also aims to diversify imports by adding 10 Mtons of green hydrogen and to accelerate Europe's clean energy transition while promoting smart investing. Electrification, energy efficiency, and uptake of renewables could allow the industry sector to save 35 bcm of natural gas beyond *"Fit for 55"* targets by 2030. The largest reductions in gas, almost 22 bcm, could be made from non-metallic minerals, cement, glass and ceramics, chemicals production and refineries. Around 30% of EU primary steel production is expected to be decarbonized based on green hydrogen by 2030.

Moreover, the EU Commission proposed increasing the EU's 2030 binding target for renewables from 40% to 45% as part of the *REPowerEU Plan*. This plan would bring total renewable energy generation capacities to 1,236 GW by 2030, compared to the 1,067 GW under the *"Fit for 55" Plan* for 2030. The *EU Solar Energy Strategy* within the *REPowerEU Plan* will help to expand the use of photovoltaic energy, with a goal of bringing online over 320 GW of solar photovoltaic installed capacity by 2025 and almost 600 GW by 2030. These additional capacities will displace the consumption of 9 bcm of natural gas annually by 2027.

Aside from *REPowerEU Plan*, other major policy initiatives and infrastructure projects have been approved in the EU, which include the introduction of minimum gas storage obligations, the *EU Action Plan* to digitalise the energy system, the expansion of existing regasification terminals for LNG, as well as approval of several interconnectors. Moreover, the European Commission presented in February 2023 the *Green Deal Industrial Plan*, which aims to guarantee the manufacturing capacity of key technologies that will be necessary for the green transition in the EU. Furthermore, the EU Commission proposed in March 2023 to reform the EU's electricity market design to accelerate a surge in renewables and the phase-out of gas.

On a country level, Germany, Belgium, Luxembourg and Denmark implemented regulations to accelerate replacement of natural gas boilers with heat pumps and France announced plans to build six new large reactors starting in 2028. In Denmark, the newly formed Danish Government intends to adjust the long-term climate target and make the country reach net-zero in 2045, instead of 2050.

***The Inflation Reduction Act* in the United States encourages green innovation and green transformation**

In August 2022, US President Joe Biden signed the *Inflation Reduction Act (IRA)* – the most significant climate and clean energy legislation in U.S. history. The IRA provides $370 billion of support for clean energy technologies, including solar panels, wind turbines, electric vehicles, heat pumps and low-carbon hydrogen. Most funding in the IRA is in the form of tax incentives, providing long-term certainty for investors in these technologies.

Provisions throughout the IRA focus on building a trained clean energy work force in the United States, as well as supporting low-income communities and communities transitioning from conventional energy to the clean energy economy. The principal barriers to implementation of the IRA include permitting delays and supply chain shortages.

The IRA builds on several other statutes enacted in the United States in the past several years, including the *Infrastructure Investment and Jobs Act* (IIJA -- sometimes called the Bipartisan Infrastructure Bill), which President Biden signed in November 2021. The IIJA includes more than $100 billion for mass transit, $15 billion for electric vehicles and $73 billion for power infrastructure, including connecting renewable energy sources to the electric grid.

Chapter 2

China continues to push forward energy transition to provide strong support for carbon peak and carbon neutrality

2 China continues to push forward energy transformation to provide strong support for carbon peak and carbon neutrality

Over the past two years, China has vigorously championed its economic development and energy transformation, placing significant emphasis on the delicate equilibrium between fostering this energy transformation and safeguarding energy security amid escalating demands for energy and electricity. Despite experiencing instances of supply constraints in certain areas, during specific periods, and within various energy sectors—consequences stemming from fluctuations in international geopolitics, disturbances in the global energy markets, and overhauls within local industrial and energy frameworks—overall energy security has been well safeguarded. Moreover, the progress of green and low-carbon energy transformation has been steadfast and continuous.

2.1 Key messages

- As China's economy develops, total primary energy consumption continues to rise. Meanwhile, the reliance of energy consumption on economic growth steadily wanes. Since the 18th CPC National Congress, China's energy intensity fell by 26.4%, equivalent to energy savings approximating 1,410 Mtce.
- Clean energy development is accelerating, highlighting the increasing importance of renewable energy. In 2022, China's installed capacity of renewable energy surpassed that of coal-fired power for the first time, hitting 1,210 GW. Concurrently, China's renewable energy generation reached 2700 TWh, paralleling the EU's electricity consumption in 2021.
- The level of clean utilisation and energy efficiency of coal and coal-fired power continue to improve, playing a pivotal role in ensuring energy supply stability. Technological improvements aimed at energy conservation and cogeneration transformation have propelled ongoing enhancements in the efficiency of China's coal-fired power plants. By 2022, the carbon dioxide emissions per unit of electricity generated by China's thermal power plants fell by 21.4% compared to its 2005 level. Despite safeguarding power supply, the share of coal-fired power in China's total electricity generation has been continuously declining, dropping below 60% in 2021.
- The rate at which electricity was consumed increased at a notably swift pace, and the robustness and reserve capabilities of the energy infrastructure were further reinforced. In the year 2022, China witnessed a 3.6% surge in power consumption, which exceeded the growth rate of its GPD by 20%, yielding an elasticity coefficient of 1.2. During the same period, the country's newly installed capacity for innovative energy storage solutions, such as electrochemical storage systems, hit 8.7 GW. Within this segment, lithium-ion batteries represented a substantial 94.5%. This

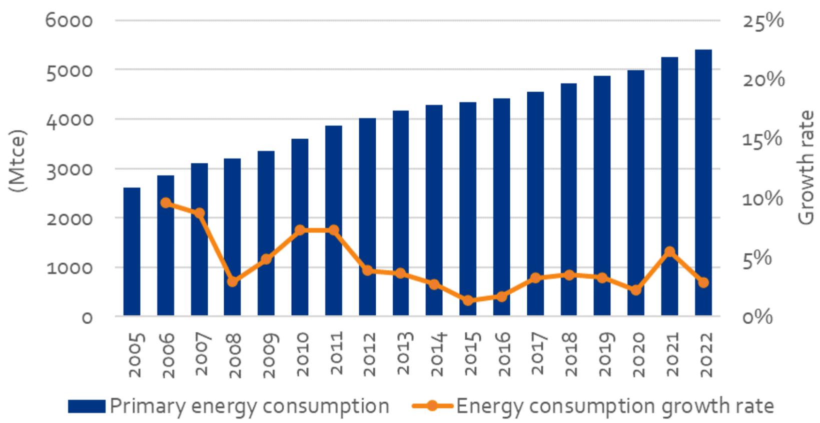
expansion, alongside the completion of pumped hydro storage power facilities totalling 45.8 GW, significantly bolstered the resilience of China's energy network.

- Advancements in low-carbon technology were notable, and the pace at which the modern energy system was being developed accelerated. By 2022, the fleet of new energy vehicles in China had expanded to 13.1 million, capturing 25.6% of the market share. Low-carbon innovations and products, exemplified by new energy vehicles and eco-friendly buildings, increasingly garnered preference among Chinese consumers. The National Energy Administration (NEA) unveiled the *14th Five-Year Plan for a Modern Energy System*, which set the development agenda for the period in question around three core objectives: fortifying the security of the energy industry's supply chain, advancing the shift towards greener and more sustainable energy practices, and enhancing the sophistication of the energy industry's infrastructure.

2.2 Energy consumption continues to grow, while energy intensity steadily declines

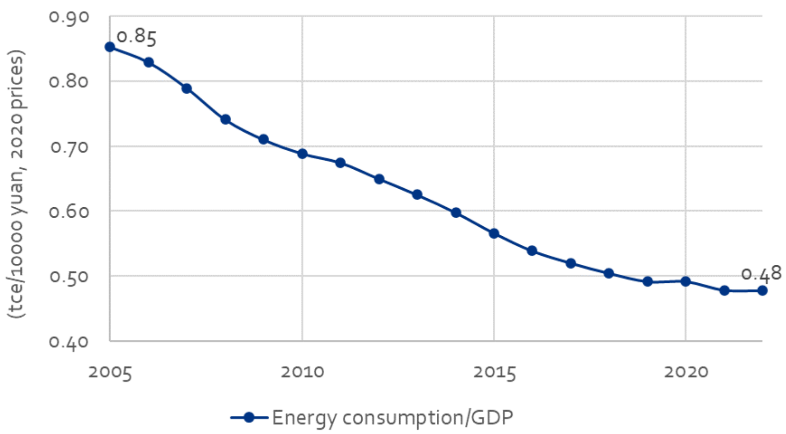
According to the data released by the National Bureau of Statistics (NBS) [1], China's primary energy consumption exhibited a generally upward trend from 2006 to 2022 (Figure 2-1), reflecting the fundamental characteristics of China as a developing nation. China's primary energy consumption has consistently been on an upward trajectory, registering an average annual growth rate of 3.8% during the *12th Five-Year Plan* period (2011-2015). This was followed by a slightly more modest average annual increase of 2.8% throughout the *13th Five-Year Plan* period (2016-2020), with the rate accelerating to an average of 4.2% in the initial two years of the *14th Five-Year Plan* period. In the year 2022, China's consumption of primary energy hit 5,410 Mtce, marking a 2.9% rise from the preceding year.

Figure 2-1 2005-2022 Primary Energy Consumption and Growth in China



Source: National Bureau of Statistics (NBS)

Figure 2-2 2005-2022 Energy Consumption per Unit of GDP in China

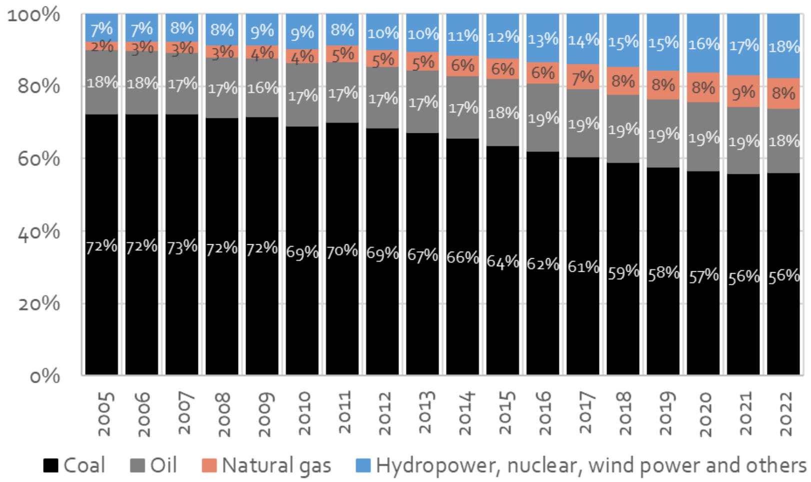


Source: National Bureau of Statistics

China's dependency on energy consumption for economic growth continues diminishing as energy consumption per unit of GDP consistently declines. From 2012 to 2022, China's energy consumption per unit of GDP gradually decreased, shifting from 0.65 tce per 10,000 RMB (2020 prices) to 0.48 tce per 10,000 RMB (2020 prices). The decrease represents a cumulative reduction of 25.9% (Figure 2-2), resulting in a total energy savings of 1,410 Mtce. Since the 18th CPC National Congress, China experienced an average annual energy consumption growth of 3%, which bolstered an average annual economic growth rate of 6.2%. Consequently, the nation's economic development is progressively transitioning towards a higher-quality, more efficient, equitable, sustainable, green, and low-carbon trajectory.

At the same time, China's energy consumption structure is evolving towards a cleaner and lower-carbon direction. The proportion of coal in China's primary energy consumption has been consistently decreasing, constituting 56.2% of energy consumption in 2022, down 12.3 percentage points from the 2012 level (Figure 2-3). The share of oil consumption has been gradually stabilising, with oil accounting for 17.9% of primary energy consumption in 2022, up 0.9 percentage points from the 2012 level. Meanwhile, the consumption of natural gas, hydropower, nuclear power, wind power, and other clean energy sources has notably increased, representing 26.3% of total consumption in 2022, representing an 11.4 percentage point growth compared to 2012. In 2022, non-fossil energy consumption accounted for 17.5% of primary energy consumption in China. This achievement signifies that China has met its 15% non-fossil energy consumption target by the end of the *13th Five-Year Plan* period and is progressing steadily towards its 20% target by the end of the *14th Five-Year Plan* period.

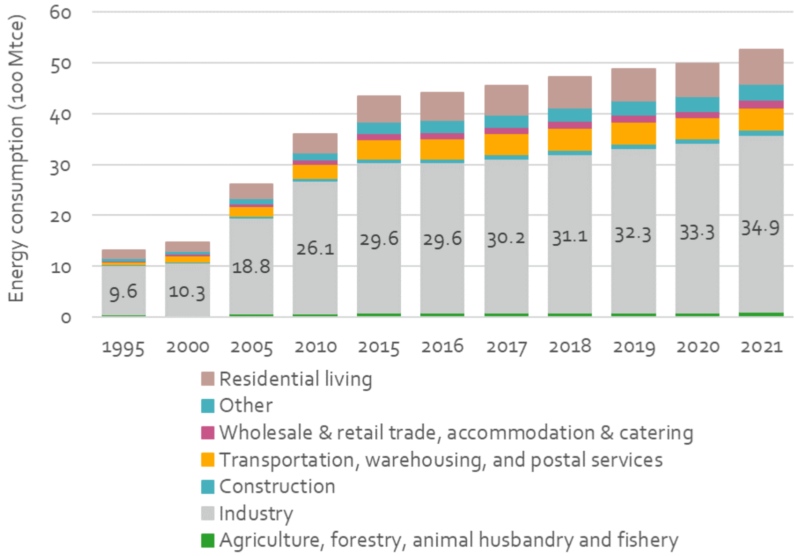
Figure 2-3 2010-2022 China's Primary Energy Consumption Structure (Based on Coal Consumption Method for Power Generation)



Source: National Bureau of Statistics

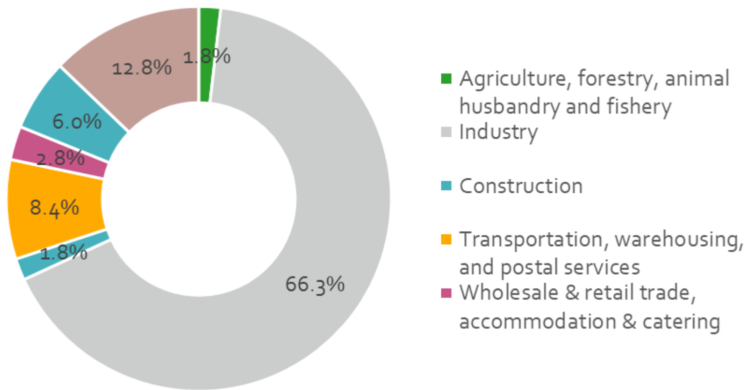
The industrial sector has long been the most significant contributor to China's energy consumption. As indicated in the *China Energy Statistics Yearbook 2022*[2], the sector ranks as the highest energy-consuming sector in China. In 2020, when viewed through the lens of total energy consumption across various industries (based on the coal consumption method for power generation used in China's energy statistical system), it is clear that the industrial sector emerges as the predominant consumer of energy within China. In 2021, the energy consumption of this sector amounted to a sizable 66.3% of the nation's primary energy consumption, as demonstrated in Figure 2-4 and Figure 2-5. The next highest energy-consuming sector is the residential sector, making up 12.8% of the total energy consumption. This is followed by a collective consumption of 8.9% by wholesale and retail, accommodation and catering, and other industries, and the transportation sector consuming 8.4%. Energy consumption within the agriculture, forestry, animal husbandry and fishery sector, and the construction sector are relatively small, each accounting for only 1.8% of the total.

Figure 2-4 1995-2021 Energy Consumption Structure by Sector in China from 1995 to 2021 (Based on Coal Consumption Method for Power Generation)



Source: National Bureau of Statistics

Figure 2-5 Final Energy Consumption by Sector in China in 2021



Source: National Bureau of Statistics

As the Chinese economy has transitioned into a new developmental phase, the proportion of industrial energy consumption in primary energy consumption has declined. At the same time, the ratios of residential and service industries have gradually increased. In 2021, the proportion of industrial energy consumption in primary energy consumption was 4.5 percentage points lower than in 2012. Meanwhile, the proportions of energy consumption in construction, transportation, wholesale and retail, other industries, and residential living have exhibited varying increases (Table 2-1). Among them, the collective energy consumption ratios attributed to residential living, wholesale and retail, accommodation and catering, and other industries have experienced the most notable increase, with their respective proportions in 2021 rising by 2.3 percentage points and 1.8 percentage points, respectively, compared to the 2012 level.

Table 2-1 2010-2020 Proportions of Comprehensive Energy Consumption by Sector in China (Based on Coal Consumption Method for Power Generation)

Year	Industry	Agriculture, forestry, animal husbandry, and fishery	Construction	Transportation, storage, and postal services	Wholesale & retail trade, accommodation & catering	Other	Residential living
1995	73.3%	4.2%	1.0%	4.5%	1.5%	3.4%	12.0%
2000	70.1%	2.9%	1.5%	7.8%	2.2%	4.2%	11.4%
2005	71.9%	2.6%	1.3%	7.3%	2.3%	4.0%	10.5%
2010	72.5%	2.0%	1.5%	7.5%	2.2%	4.2%	10.1%
2012	70.8%	1.9%	1.6%	8.1%	2.5%	4.6%	10.5%
2015	68.2%	1.9%	1.7%	8.9%	2.6%	5.1%	11.6%
2016	67.0%	1.9%	1.8%	9.0%	2.7%	5.3%	12.3%
2017	66.3%	2.0%	1.8%	9.2%	2.7%	5.3%	12.6%
2018	65.9%	1.9%	1.8%	9.2%	2.8%	5.6%	12.8%
2019	66.2%	1.8%	1.9%	9.0%	2.8%	5.7%	12.7%
2020	66.8%	1.9%	1.9%	8.3%	2.6%	5.7%	12.9%
2021	66.3%	1.8%	1.8%	8.4%	2.8%	6.0%	12.8%
2020 compared to the 2012 level	-4.5 pp	-0.1 pp	0.3 pp	0.3 pp	0.3 pp	1.5 pp	2.3 pp

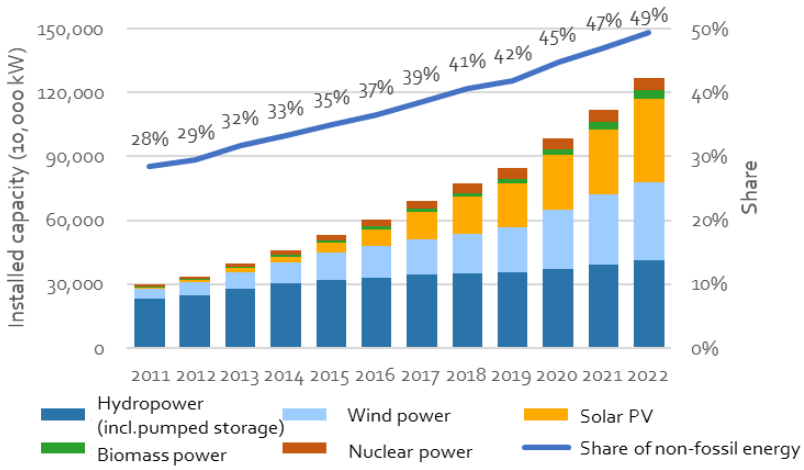
Source: National Bureau of Statistics

2.3 Intensified efforts in clean energy development help create a new pattern of energy development

China has been actively developing renewable energy sources by pursuing the new development concept of innovation, coordination, greenness, openness, and sharing and continuously leveraging its industrial advantages. The country has pursued both centralised development and distributed utilisation, and has expedited the construction of seven onshore new energy bases in strategic regions such as the upper Yellow River reaches, the Hexi Corridor, the "Ji-shaped" Yellow River bend, and Xinjiang. Additionally, it has coordinated the construction of two water and wind power bases in south-eastern Tibet and Sichuan-Yunnan-Guizhou-Guangxi, along with a cluster of offshore wind power bases. The State has taken a comprehensive approach to renewable energy development by focusing on decentralised wind power, rooftop photovoltaics, and renewable energy heating while promoting the safe use of nuclear power and nuclear heating. China's efforts in this direction have significantly increased non-fossil fuel energy consumption, accounting for 17.5% of the total energy consumption in 2022, marking a rise of 0.8 percentage points from the previous year.

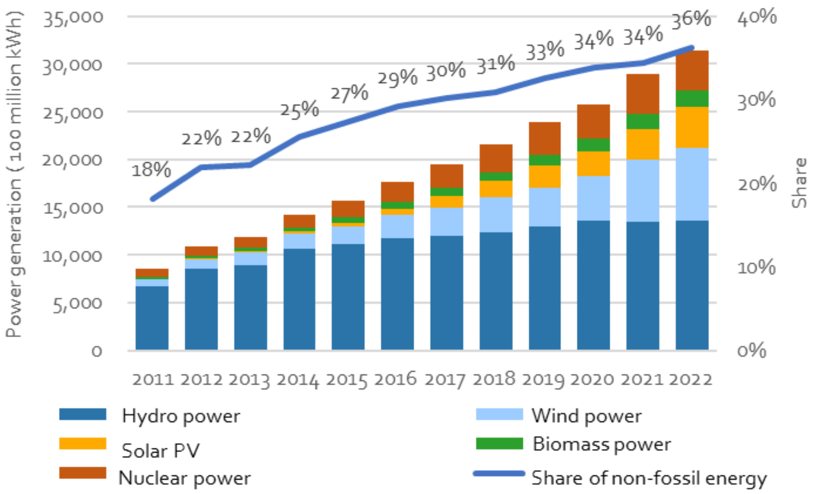
In a ground-breaking development, renewable energy installed capacity has, for the first time, surpassed national coal-fired power installed capacity. In 2022, China achieved a historic milestone as the annual newly added installed capacity of renewable energy sources, such as hydro power, wind power, and photovoltaic power generation reached unprecedented levels, solidifying their status as the primary component of China's new electric power installations. By the end of 2022, China's renewable energy installed capacity had reached 1,213 GW, outpacing the national coal-fired power installed capacity and representing 47.3% of the country's total installed electricity generating capacity (Figure 2-6). This resulted in an annual output of over 2,700 TWh, accounting for 31.6% of the total social electricity consumption (Figure 2-7), equivalent to the European Union's full-year electricity consumption in 2021. When nuclear power is considered, China's non-fossil fuel energy generation reaches a total installation volume of up to 1,270 GW, increasing its proportion to 49.6% as a share in the total power generation capacity (Figure 2-6).

Figure 2-6 2011-2022 Installed capacity and shares of various types of non-fossil energy sources



Source: National Energy Administration (NEA)

Figure 2-7 2011-2022 Changes in electricity generation and shares of various types of non-fossil energy sources



Source: National Energy Administration

The second significant milestone is that the combined production of wind and photovoltaic power has surpassed 1,000 TWh for the first time in history (Figure 2-7). In 2022, China accelerated the construction of wind and solar power facilities in the desert, Gobi, and barren regions. The initial phase of 100 GW of wind and photovoltaic bases has been fully launched, with newly installed capacities for wind and photovoltaic power exceeding 120 GW, constituting 66% of the country's total new installed capacity. The cumulative installed capacity has now surpassed 700 GW. By 2022, the average output of wind and solar power generation in most parts of China accounted for approximately 15% of the average electricity load, reaching peaks as high as 40% (Figure 2-7). With over 1,000 TWh produced by wind and solar energy sources, newly added wind and photovoltaic power generation contributed to around 69% of the country's total new power generation capacity.

Thirdly, the clean replacement of fuels in the end-use sectors has accelerated. In the northern region, the clean heating target has been met ahead of schedule, following the completion of a total of 15.6 billion m^2 in the clean heating area, at a clean heating rate of 73.6%. Cumulatively, the consumption of more than 150 million tons of loose coal was replaced, contributing to more than one-third of the reduction in $PM_{2.5}$ concentration and improved air quality. The promotion of nuclear heating is swiftly gaining momentum. Haiyang City in Shandong Province has successfully achieved full coverage of nuclear heating in urban areas. In addition, nuclear power plants such as Qinshan in Zhejiang and Hongyanhe in Liaoning have also launched pilot programs in nuclear heating, extending to longer distances and larger areas.

2.4 Green and low-carbon transformation of coal and coal power helps safeguard national security, uphold economic stability and benefits people's livelihoods

Over the past two years, the rapid growth in electricity demand has outpaced the newly added renewable energy generation capacity, resulting in an inability to meet power requirements across all regions and periods. Coal-fired and gas-fired power have served as crucial "ballast stones" for maintaining power security at critical moments. In 2022, China's installed generating capacity reached approximately 2,560 GW, reflecting a year-on-year increase of 7.8%.[3] Among the different sources, China's coal-fired installed capacity exhibitied a growth rate significantly lower than that of wind power (11.2%) and solar power (28.1%). The new coal power capacity primarily aimed to ensure the security of China's electricity supply. China's power generation facilities with a capacity exceeding 6 MW were utilised for 3,687 full-load hours, 125 hours less than last year. China emphasises energy-saving and low-carbon development within its coal-fired power generation sector. In 2021, the standard coal consumption for electricity supply in Chinese thermal power plants with an installed capacity exceeding 6,000 kW was 303 grams/kWh. Additionally, electricity self-consumption rate for thermal power plants with a capacity exceeding 6,000 kW was 4.36% in China, down 0.29 percentage points from the previous year, and the generation efficiency of coal power is consistently improving. In 2022, the national CO_2 emissions per unit of thermal power generation were about 824 g/kWh, 21.4% less than the 2005 level. In recent years, the share of coal-fired electricity in the total electricity generation mix has been on a steady decline, falling to 58.4% in 2022, thereby dipping below the 60% threshold. Notably, during the third quarter of 2022, China’s hydroelectric power stations experienced a significant reduction in water inflow. In response, coal-fired electricity generation stepped in effectively to offset the shortfall in hydroelectric power, thereby playing a pivotal role in upholding the stability of the electricity supply. Most of the thermal power plants across China are now integrated into the carbon market regulatory framework by four categories: conventional coal-fired units with a capacity exceeding 300 MW, conventional coal-fired units with a capacity of 300 MW or less, non-conventional coal-fired units and gas power units. Each category is allotted specific carbon emission allowance (refer to Box 2-1 for additional context).

Box 2-1 The foundational framework for China's carbon market operation gradually took shape in 2022

In January 2023, the Ministry of Ecology and Environment (MEE) published the inaugural compliance period report for China's national carbon emissions trading market. The report revealed that the aggregate transaction volume of carbon emission allowances during the first compliance period of the national carbon market reached 179 million tons, generating a total revenue of RMB 7.7 billion. The market functioned efficiently and systematically, exhibiting stable and ascending trading prices. Consequently, the foundational framework for China's carbon market operation has been established, with the price discovery mechanism demonstrating its initial effectiveness. Enterprises have exhibited enhanced awareness and capabilities in reducing emissions. The intended objectives have been successfully achieved.

The first compliance period of China's carbon market spanned from January 1, 2021, to December 31, encompassing 2,162 key emitting units within the power generation sector. The annual greenhouse gas emissions covered by this period amounted to approximately 4.5 billion tons of CO_2, representing around 40% of China's total emissions. This positions China's carbon market as the largest worldwide in terms of coverage.

Contrary to similar initiatives adopted by the EU and other nations, China's allocation of emission quotas is not predetermined by a fixed cap. Instead, it relies on an intensity benchmark (tCO_2/MWh), which factors in the escalating energy demand and its alignment with national-level intensity-based energy and carbon emission targets. Enterprises with coal-powered facilities that exceed the benchmark intensity are required to acquire quotas from more efficient power plants that emit below the benchmark intensity level. Moreover, enterprises may utilise Chinese Certified Emission Reductions (CCERs) to offset up to 5% of their compliance commitments; CCERs are credit values granted by government-approved domestic emission reduction initiatives. Examples of such activities encompass renewable energy production, forestry endeavours, waste-to-energy conversion schemes, and more.

During the inaugural compliance period of China's carbon market, spot trading of carbon emission quotas took place among key emitting entities within the power generation sector. There were 847 such entities, with a collective quota shortfall of 188 million tons. Roughly 32.7 million tons of CCERs were employed for quota offsetting and settlement. Overall, the market trading volume is relatively close to the quota gap of the key emitting units, indicating that compliance completion is the primary objective for transacting parties. The transaction volume essentially satisfies the compliance requirements of these key emitting units. As of December 31, 2021, the overall compliance rate for national carbon market quotas stood at 99.5%, with all 1,833 key emitting units finalising their quota settlements punctually and in full.

The inaugural quota allocation plan for the performance period has while maintaining a reliable power supply, assigned carbon emission reduction obligations to enterprises across the nation through market mechanisms for the first time. This approach has initially fostered positive incentives for high-efficiency, low-emission operations such as gas-fired, ultra-supercritical, and cogeneration units. By employing offsetting mechanisms, the plan has yielded approximately RMB 980 million in benefits for project owners or pertinent market entities associated with 189 CCER projects, including wind power, photovoltaics, and forestry carbon sequestration projects. Consequently, the plan has played a constructive role in advancing China's energy structure transformation and enhancing ecological compensation mechanisms.[4]

Meanwhile, the national carbon market encourages funds to be directed towards enterprises with lower emission reduction expenses via quota allocation and market trading. This facilitates the gradual phasing out of power generation units with high emission reduction costs and obsolete technology, thus promoting the control of CO_2 emissions across the entire industry. Quota allocation is conducted entirely free of charge, and by leveraging market trading and offset mechanisms, it helps decrease emission reduction costs for key emitting units that encounter greater challenges in reducing emissions.

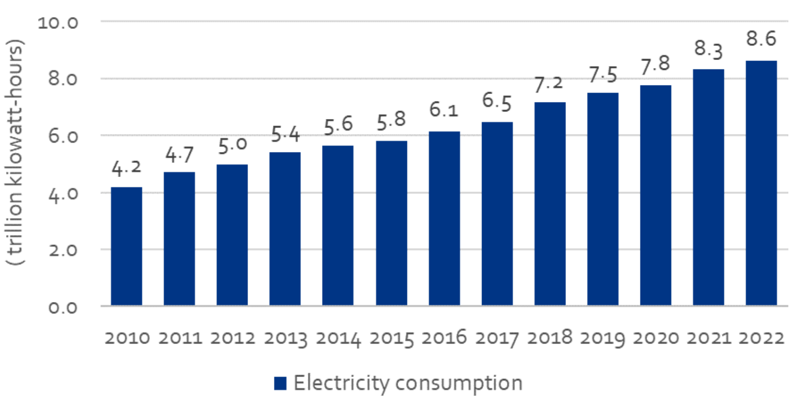
Moving forward, the Chinese government will persist in advancing various facets of the national carbon market development. Building upon the successful implementation of quota spot markets in the power generation sector, it plans to progressively extend market coverage to additional high-emission industries, diversify trading products and approaches, and effectively harness market mechanisms to control greenhouse gas emissions and promote innovation in green low-carbon technologies.

In terms of coal consumption structure, whilst the coal consumption of non-power sectors declines, that of the power sector is rising, thus contributing to pollution reduction and carbon reduction and cleaner and more efficient use of coal overall. According to the statistics of the China Coal Industry Association (CCIA), China's coal consumption in 2021 was around 4.3 billion tons, of which four industries, i.e., electricity, iron, and steel, chemical and building materials, consumed 93%[5] of the country's total coal consumption combined. Meanwhile, the decentralised use of "scattered coal" by small boilers and kilns is shrinking as a share of total coal consumption. Of the country's newly added coal consumption over the past two years, coal for power generation accounted for more than 90%, suggesting an increasing coal share in the power generation industry and a cleaner and more efficient coal consumption pattern. China is committed to promoting the gradual transformation of coal into clean fuels, superior raw materials, and high-quality materials. According to preliminary estimates, the coal used as raw materials and materials in the industry sector exceeds 100 Mtce per year. Most of carbon atoms in the coal are sequestered in the products and are not emitted into the atmosphere.

2.5 The rate of electricity consumption is surging swiftly, alongside a strengthened capacity for regulatory control and reserve provision

Over the past five years, electricity consumption in China has exhibited a consistent upward trend, as illustrated in Figure 2-8. In 2022, the total societal electricity consumption soared to 8,637 TWh, marking a year-on-year increase of 3.6%, albeit lower than the 10.3% spike witnessed in 2021. Notably, the electricity consumption within the primary industry reached 115 TWh, registering a year-on-year rise of 10.4%, primarily attributed to marked improvements in rural electrification and the sustained elevation of electrification levels across China in recent years. The secondary industry consumed 5,700 TWh, reflecting a modest year-on-year growth of 1.2%. Within this sector, the high-tech and equipment manufacturing industry saw an increase of 2.8% in its electricity demand, whereas the combined growth for the four major energy-intensive industries – specifically metallurgy, building materials, non-ferrous metals, and chemicals – was a mere 0.3%. Electricity consumption within the tertiary industry amounted to 1,486 TWh, with a year-on-year growth of 4.4%. Remarkably, the electric vehicle-related charging and swapping service sector surged by 38.1% in its electricity usage. Residential electricity consumption – encompassing both urban and rural settings – climbed to 1,337 TWh, with a significant year-on-year increase of 13.8%. This was largely impacted by extreme weather conditions, including the sustained high temperatures in August and the quartet of national temperature declines in December. The latter was due to the incursion of four cold air masses, resulting in the lowest national average December temperature for nearly a decade.

Figure 2-8 2010-2022 Total societal electricity consumption in China



Source: China Energy Statistical Yearbook 2021, 2022 China Power Industry Economic Operation Report by the China Electricity Council, and data released by the National Energy Administration

China's new-type energy storage has gradually evolved from R&D demonstration to early-stage commercialised development, with its market application scale steadily expanding. In 2022, the installed capacity of China's new-type energy storage exceeded 8.7 GW. Significant progress has been made on new-type energy storage technology, as evidenced by improved efficiency, reduced cost, extended life span and enhanced safety. Energy storage has begun to demonstrate its supporting role in the energy transformation. New-type energy storage application scenarios and business models continue to expand, and diversified application scenarios, such as new energy plus energy storage, base power supply equipped with energy storage, "internet + energy storage", and "distributed smart grid and energy storage", are emerging one after another. The policy system and market mechanisms for new-type energy storage is initially taking shape. A batch of new favourable mechanisms and policies for innovation planning, application project management, and power market and dispatching operation participation are being developed and implemented.

2.6 The swift progress in low-carbon technological innovation is hastening the development of a modern energy infrastructure

In the end-use energy consumption sector, significant advancements have been made in promoting energy-efficient and low-carbon technologies across the transportation, construction, and industrial fields.

In the transportation sector, electric vehicles have emerged as a new focal point. In 2022, China's production and sales of new energy vehicles reached 7.1 million and 6.9 million, respectively, reflecting year-on-year increases of 96.9% and 93.4%. This achievement secured China's position as the global leader for the eighth consecutive year. New energy vehicles constituted 25.6% of the nation's total automobile sales.[6] The number of new energy vehicles in China has reached 13.1 million, with a growth rate of 67.1% compared to 2021, showing a rapid growth trend.[7] Among them, there are 10.5 million pure electric vehicles, accounting for 79.8% of the total number of new energy vehicles. By the end of 2022, over 5.2 million charging stations and 1,973 battery-swapping facilities were established across the country, with 259,300 new charging stations and 675 swapping facilities added during that year alone. The pace of charging infrastructure construction has accelerated significantly. Moreover, by the end of 2022, China's power battery recycling service network had expanded to over 10,000 locations, effectively providing local recycling options for power batteries. As of the end of 2020, the number of new energy public transport vehicles reached 466,100 units, accounting for 66.2% of the total public transport fleet. This transition has led to the widespread replacement of gasoline and diesel vehicles in urban public transit systems.

In recent years, the development of green and low-carbon buildings has been the primary focus in the construction sector. In 2021, China completed a total of over 8.5 billion m^2 of green building area; the proportion of new green buildings in urban areas nationwide was 84% of the new building area of the same year, with a total of nearly 10 million m^2 of ultra-low energy and near-zero energy building space completed.[8] As of the first half of 2022, the proportion of green buildings in newly constructed urban buildings in China has exceeded 90%.[9]

In the industrial sector, both economic and technological efficiencies have witnessed consistent advancements. In 2022, the overarching energy consumption per unit of key energy-intensive industries within China saw a reduction of 1.6% for calcium carbide and 0.8% for synthetic ammonia, while there was a minor increase of 1.7% for steel. Energy consumption for electrolytic aluminium saw a slight decrease of 0.4%. Moreover, the standard coal consumption for every kilowatt-hour of thermal power generation showed a downward trend, reducing by 0.2%. This data reflects a stable improvement in energy technological efficiency.[10]

On 22 March 2022, the Chinese government promulgated the *14th Five-Year Plan for the Modern Energy System*, with the objective of steering the evolution of a modern energy system through a tripartite approach. **Firstly, the focus is to reinforce the robustness and reliability of the energy supply chain**. Commencing with the *14th Five-Year Plan*, China is set to bolster its all-encompassing energy security – spanning strategic, operational, and emergency aspects. By the year 2025, it is envisaged that China's comprehensive energy production capability will surpass 4,600 Mtce, satisfying the demands of both economic and societal progress and securing the well-being of its populace. **Secondly, the Plan prioritises the shift towards greener and more sustainable modes of energy production and consumption**. This period of the Five-Year Plan is deemed pivotal for China as it strides towards its peak carbon goals. Efforts will concentrate on augmenting the provision of clean energy ("addition") while concurrently curtailing carbon emissions within the energy sector ("subtraction"), thus cultivating a green and low-carbon paradigm of energy usage. By the target year of 2025, the share of non-fossil fuel energy consumption rises to around 20%. **Lastly, the Plan endeavours to raise the modernisation bar of the energy industry's value chain**. Throughout the duration of the *14th Five-Year Plan* period, technological innovation is earmarked as the cornerstone propellant for energy sector evolution. The *Plan* envisages amplifying the capabilities for innovation in energy technology, accelerating the transition to digital and intelligent energy industry processes, significantly enhancing the efficiency of energy systems, and globally advancing the sophistication of the industry's foundational base and its value chain modernisation.

In March 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the *Implementation Plan for the Development of New-type energy storage during the 14th Five-Year Plan Period*. This document posits new-type energy storage as a pivotal technology and essential component for crafting a new power system, critical for realising the ambitions of carbon peaking and carbon neutrality. Additionally, the NDRC released the *Medium- to Long-Term Development Plan for the Hydrogen Energy Industry (2021-2035)*, underscoring hydrogen energy's fundamental role within the prospective national energy mix and as a key conduit for attaining a green and low-carbon conversion in the end-use sectors of energy. The Plan underscores the necessity to fully harness hydrogen energy's potential as a medium for large-scale and efficient renewable energy utilisation, exploiting its strengths in long-duration energy storage. This approach is set to smooth the way for a recalibration of energy resource allocation across different regions and seasons, nurturing the amalgamation of hydrogen, electrical, and thermal energy systems, and contributing to the establishment of a versatile, synergistic, and integrated contemporary energy supply system.

Box 2-2 Developments in China's Carbon Peaking and Carbon Neutrality Policy

Under the coordinated efforts of the CPC Central Committee and the State Council, as well as the organisation of the Leading Group on Carbon Peaking and Carbon Neutrality, China is diligently and systematically advancing various tasks related to its carbon peak and carbon neutrality goals in a structured and effective manner.

1) Establishing a "1+N" Policy Framework: The CPC Central Committee and the State Council have jointly issued the *Opinions on Fully Implementing the New Development Concept to Achieve Carbon Peaking and Carbon Neutrality in a Thorough, Precise, and Comprehensive Manner*.[11] Additionally, the State Council has promulgated the *Action Plan for Peaking Carbon Emissions by 2030*.[12] Relevant departments have formulated and issued implementation plans and supporting policies tailored to various sectors and industries. These encompass key areas such as the transition towards green, low-carbon energy development; energy conservation for reduced carbon emissions and enhanced efficiency; industrial sector carbon peaking action plans; green, low-carbon transportation action plans; carbon reduction through circular economy action plans; and green, low-carbon technological innovation action plans. A series of supplementary measures have also been introduced, including technology development, carbon sequestration, fiscal taxation policies, and financial incentives. Each province (autonomous region or municipality) has developed its own local implementation plan for achieving carbon peak and carbon neutrality, thereby forming a "1+N" policy framework to accomplish these objectives. These measures will encourage China's economic and social development to decouple from greenhouse gas emissions, ensuring that economic growth is no longer achieved at the expense of increased emissions. They will also expedite China's clean energy development initiatives while facilitating the transition of traditional energy sources towards greener, low-carbon alternatives. Moreover, they will create opportunities for scaling up emerging technologies, such as electric vehicles, hydrogen fuel cells, storage systems, and distributed renewable energies.

2) Encouraging green and low-carbon energy transformation in a safe and orderly manner. Considering the fundamental national reliance on coal, it is essential to vigorously promote the clean and efficient use of coal, advance pollution reduction and carbon mitigation efforts, implement the "three improvement linkage" for coal-fired power units and strategically plan for the construction of large-scale wind power and photovoltaic bases with a total capacity of 450 GW in the desert, Gobi, and barren regions. At present, China's installed capacity of renewable energy has surpassed 1,100 GW, claiming the top position globally.

3) Diligently advocating for industrial structure optimisation and upgrading. It is essential to concentrate on the active development of strategic emerging industries, prioritise the promotion of energy-saving and carbon reduction transformations in key industries, and firmly curb the reckless expansion of high energy-consuming, polluting, and low-output projects. Compared to 2012, China's energy intensity has experienced a substantial decrease of 26.4% by 2022.

4) Advocating for low-carbon transformation in construction, transportation, and other sectors. It is essential to proactively foster the development of green buildings and advance the green and low-carbon transformation of existing buildings. By 2022, the total newly added green building area in urban regions across the nation surpassed 2 billion m^2. It is also critical that we intensify efforts to promote energy-efficient and low-carbon vehicles. China has been a global leader in the production and sales volume of new energy vehicles for eight consecutive years, with the number of vehicles owned constituting more than half of the world's total.

5) Consolidating and enhancing the carbon sequestration capacity of ecosystems. We must continue to carry out integrated protection and restoration of mountains, waters, forests, lakes, grassland, and deserts and to advance large-scale national greening action in a scientific way; having maintained growth in both forest coverage rate and forest growing stock, China has become a global leader with the largest increase in forest resources.

6) Establishing and improving relevant policy mechanisms. It is important that we optimise and improve the dual control policy on energy consumption and energy intensity, create a unified and standardised carbon emission statistics and accounting system, roll out support tools for carbon emission reduction and special refinancing loans for clean and efficient use of coal, and launch a national carbon market. It is also important to improve the green technology innovation system, provide more training to professionals, further promote the green living creation action, advocate green lifestyles, and encourage green consumption.

7) Actively participating in global climate governance. It is important that we play an active and constructive role in multi-bilateral mechanisms; step up efforts to create a fair and reasonable global environmental governance system featuring win-win cooperation; deepen South-South cooperation in addressing climate change; solidly advance the construction of the green One Belt and Road; and support the green and low-carbon energy development of developing countries.

Part 2: The Chinese energy transition pathway to net zero emissions

Chapter 3

China's energy transition pathway to 2060

3 China's energy transition pathway to 2060

3.1 Key messages

- CETO2023 delineates three distinct scenarios: the Baseline Scenario (BLS), Carbon Neutrality Scenario 1 (CNS1), and Carbon Neutrality Scenario 2 (CNS2). The distinctions in scenario boundaries and assumptions stem primarily from varying emission constraints, the pace of retiring and adding fossil energy, the progression of end-use technology and activity levels, and the evolving cost curve of new energy technologies. CNS2, the primary scenario recommended by CETO2023, focuses on accelerating the development of new and renewable energy through more comprehensive market mechanisms, increased technological innovation, and a more rapid and effective approach to achieving net zero emissions in the energy system.
- Under the carbon neutrality scenario, China embarks on a transformative path towards green, low-carbon growth. This shift leads to a revolutionary change in the primary energy demand structure, bolstering low-carbon industrial competitiveness. This period sees a doubling in per capita electricity consumption and a halving of carbon emissions. The enhancement of energy efficiency and the growth of green electricity occur concurrently, creating opportunities for high value-added new types of electricity and energy consumption. By 2060, in the CNS2 scenario, the proportion of non-fossil energy rises to 96%, and the total societal electricity consumption reaches 20.2 trillion kilowatt-hours.
- Energy consumption in end-use sectors transitions from "electrification" to "electrification-hydrogenation" for deeper decarbonization. Up to 2035, electricity demand in end-use sectors grows rapidly. After the peak of carbon emissions, green hydrogen becomes an important supplement to electrification, serving as a zero-carbon raw material and fuel. This drives deep decarbonization in industries with challenging emission reductions in end-use sectors. By 2060, in the CNS2 scenario, electricity's share in end-use energy consumption is 66%, with electricity for hydrogen production accounting for 22.1% of the total societal electricity consumption.
- The development, emission reduction, and safety of the new power system are optimized in a coordinated manner. The power system shifts comprehensively towards renewable energy, making wind and photovoltaic power affordable and abundant mainstay sources. Coal power undergoes fundamental changes, transitioning from a base load power source to a flexible regulation power source. The scale development of diversified electricity flexibility resources occurs. Nuclear power plays an active and stable role as a low-carbon base load power source.
- Key clean energy technologies experience rapid and leapfrog development. Renewable energy technologies continue to develop at a high speed, electricity

flexibility technologies undergo exponential evolution, and new end-use energy technologies replace existing ones, driving energy transformation and creating green employment and new areas of green growth.

- Promoting market-oriented reforms in the energy sector remains unwavering. Creating a technologically neutral and well-structured energy market, ensuring sustainable energy transition investment, continuously injecting impetus into technological innovation, and vigorously promoting international cooperation in the global energy transition are crucial for achieving the carbon neutrality pathway.

3.2 Scenario framework of the Chinese energy transformation

The CETO scenario framework captures China's energy system's unique characteristics, focusing on both its immediate carbon peak and eventual carbon neutrality ambitions. It extensively explores technological trajectories for the long-term energy shift while dynamically assessing the patterns and potential pitfalls during the near to medium-term transformation. Accordingly, CETO2023 presents three refined scenario blueprints: the **Baseline Scenario (BLS)**, **Carbon Neutrality Scenario 1 (CNS1)**, and **Carbon Neutrality Scenario 2 (CNS2)**. Both the Carbon Neutrality scenarios are predicated upon a set of shared fundamental conditions: a world where nations are in close concert, working collaboratively to honour the commitments of the *Paris Agreement* with heightened vigour, striving to achieve the ambition to "keep the rise in global average temperature well below 2°C above pre-industrial levels, while continuing efforts to limit the temperature increment to 1.5°C above those levels"; they also necessitate China to attain its carbon peak before the year 2030 and realise carbon neutrality prior to 2060, aligning with China's strategic pledges. Both scenarios are designed to present two divergent yet transformative strategies for realising the aspirations of carbon peak and carbon neutrality, underpinned by comprehensive deliberations on the uncertainties characterising the technological avenues to carbon neutrality. Distinct differences emerge in the chosen trajectories and the timelines for the energy system to achieve net-zero emissions.

Baseline Scenario (BLS)

The Baseline Scenario (BLS) portrays the extrapolated development trends of the energy system, absent any constraints for achieving net zero emissions within the forecast period. Anchored in existing technological advancements, policy interventions, and industry movements, this scenario envisions no marked increase in policy intensity, factoring in the challenges posed by the dynamic nature of energy transformation, both from internal and external environmental shifts, thereby enabling a comprehensive analysis of the long-term development trend of the energy system. The BLS is committed to realising the aspiration enshrined in the *Paris Agreement*: to contain the global average temperature increase below 2 degrees Celsius by the century's close. Nonetheless, attaining net-zero emissions within the energy system may remain an elusive target within the outlook period.

This year's iteration of the BLS accentuates the perils associated with the ongoing energy shift both within China and around the globe, as the global energy market currently grapples with disruptions like oscillations in supply chains, geopolitical conflicts, surging energy and resource costs, and technological bans. These hurdles stall the energy transformation tempo, precipitating energy shortages in certain countries. The BLS delves deep into the repercussions of the relevant risk elements on the energy transformation, tallying costs associated with extended transformations, elevated emission peaks, and augmented expenditures. It is juxtaposed as a reference against the carbon neutrality scenarios to discern the most prudent trajectory.

Carbon Neutrality Scenario 1 (CNS1)

The CNS1 delineates a pathway for reaching the objectives of carbon peak and carbon neutrality, with the energy system on track to realise net-zero emissions around the year 2055. The fundamental aim of the CNS1 construct is to proffer a viable strategy for accomplishing these carbon milestones. It acknowledges China's prevailing dependence on coal as a primary energy source and underscores coal's significance in bolstering energy security. The scenario accounts the myriad challenges associated with transitioning from coal, as well as the implications of the clean energy shift, the expansion of renewable energy, and the hurdles presented by existing institutional and systemic frameworks. It advocates a measured progression and methodology for the energy transition to fulfil the carbon peak and carbon neutrality targets. Technologically, CNS1 envisages a robust expansion of renewable energy sources, alongside the gradual elimination of coal from the energy mix, either through natural retirement or delayed decommissioning. This scenario necessitates a relatively heightened reliance on carbon compensation and negative emissions technologies, such as CCS, particularly in coal, natural gas, and biomass power generation. Concurrently, it imposes less stringent requirements for the adoption of clean energy technologies.

Carbon Neutrality Scenario 2 (CNS2)

The CNS2 envisions an accelerated transformation towards achieving the goals of carbon peak and carbon neutrality, aiming for a net-zero emissions energy system before 2055. The linchpin of this scenario is to unlock the full potential of green energy, promoting a substantial inclusion of renewable energy sources from both supply and consumption sides. This is facilitated by intensified policy initiatives, an expedited pace, and an elevated deployment of sustainable energy innovations. CNS2's energy transformation trajectory seamlessly melds governmental oversight with market dynamics, capitalising on market-driven mechanisms to bolster green energy competitiveness and spur bottom-up innovation. Technologically speaking, the cost trajectory of sustainable energy solutions witnesses a steeper decline, electrification rates soar, fossil energy diminishes more briskly, kindling a heightened appetite for renewables, power flexibility, energy efficiency, green hydrogen, and other avant-garde solutions. The capacity of renewable energy installations, including wind and solar photovoltaic systems, is persistently on the rise. Concurrently, the operational duration and output of coal-fired power stations are diminishing more rapidly, culminating in the natural retirement of such coal-powered units.

In summary, CNS2 emerges as the more promising path, where market mechanisms and technological innovations are pivotal, galvanising all stakeholders to partake proactively in the energy transformation, with more robust deployment of renewable energy, steering the Chinese energy system more promptly and effectively towards net-zero emissions. As a result, CNS2 is lauded as the premier choice in CETO2023.

3.3 Main scenario assumptions and boundary conditions

Scenario distinctions

The triad of CETO2023 scenarios are built on a consistent set of macroeconomic and existing policy parameters, along with constraints concerning energy reliability and ecological conservation. These parameters include: 1) Macroeconomic indicators such as population dynamics, GDP growth, urbanisation trends, inclusive of provincial nuances; 2) Current policy frameworks like the *14th Five-Year Plans*, and the most recent energy and climate-centric industrial policies (with the BLS solely taking into account the policies supporting the existing pathways); 3) Safeguards related to energy system robustness and ecological conservation serve as the bedrock across all scenarios. Specifically, ecological guidelines are drawn from the "Three Lines and One List"[b] unveiled by the Ministry of Ecology and Environment, branching into ecological environment constraints for various energy varieties and sectors, including electricity, industry, building, and transportation, encompassing both pollution and non-pollution constraints such as biomass energy and farmland redlines, and more; 4) a consistent baseline carbon pricing is embedded across scenarios to mirror the innate benefits of diminishing expenses in avant-garde energy techniques; and 5) all scenarios span the timeline from 2020 to 2060. Given the ramifications of the COVID-19 pandemic, 2020 showcased pronounced variations, thus 2021 emerges as the reference year.

The scenarios diverge in boundary conditions, encompassing carbon emission constraints, fossil energy retirement and integration rhythms, and restrictions on clean energy supply capacities. From a modelling perspective, each scenario projects distinct activity levels of end-use energy sectors and cost structures for new energy innovations, displaying energy demand-supply cost gradients for varying scales of deployment. For instance, the CCS demand in CNS1 is pronounced, translating to more pronounced cost reductions than CNS2, where the scaled growth in new energy manufacturing prompts a swifter descent in clean energy technology costs.

[b] The "Three Lines and One List" refers to formulating an ecological environment admission checklist based on ecological protection redlines, environmental quality baselines, and resource utilisation upper limits.

Table 3-1 Core parameters and assumptions for each scenario

	BLS	CNS1	CNS2
Key boundary conditions			
Sustainable development constraints			
Carbon emission constraints	No net-zero emissions constraint within the forecast period is specified; instead, a coal consumption upper limit is set in accordance with the *Paris Agreement*	Peak carbon emissions before 2030; Carbon neutrality before 2060; Net-zero emissions in the energy system around 2055	Peak carbon emissions before 2030; Carbon neutrality before 2060; Net-zero emissions in the energy system before 2055
Energy and power system security constraints	Consistent across three scenarios		
Ecological and environmental protection constraints	Consistent across three scenarios		
Fossil fuel energy development constraints			
Fossil fuel power generation and end-use coal consumption	Natural or delayed retirement		Natural retirement
Key assumptions			
Macroeconomic development parameters	Consistent across three scenarios, with specific parameters set for each province		
Energy and climate policies	Consistent across three scenarios, with existing policies and provincial policies included		
Energy and power supply side			
Renewable energy and flexibility technology costs	High		Low
Power system flexibility technology cost	High		Low
Carbon capture, utilisation, and storage (CCUS) technology costs	High	Low	Medium

<table>
<tr><td>Nuclear power capacity growth</td><td colspan="3">Consistent across three scenarios</td></tr>
<tr><td>Carbon prices and fossil fuel prices</td><td colspan="3">Consistent across three scenarios, with specific prices set for each province</td></tr>
<tr><td colspan="4">Energy demand side</td></tr>
<tr><td>Electrification level</td><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td>Energy intensity</td><td>High</td><td>Medium</td><td>Low</td></tr>
<tr><td>Output of high-energy-consuming products</td><td colspan="3">Consistent across three scenarios</td></tr>
<tr><td>Industrial added value</td><td colspan="3">Consistent across three scenarios</td></tr>
<tr><td>Proportion of value added in high-energy-consuming industries</td><td>High</td><td colspan="2">Low</td></tr>
<tr><td>Proportion of value added in traditional light industries and high value-added industries</td><td>Low</td><td colspan="2">High</td></tr>
<tr><td>Rate of end-use new technological substitution</td><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td>Number of registered vehicles</td><td colspan="3">Consistent across three scenarios</td></tr>
<tr><td>Penetration rate of electric vehicles</td><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td>Level of power-to-X (PtX) fuel demand</td><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td>Total building area</td><td colspan="3">Consistent across three scenarios</td></tr>
<tr><td>Level of urbanisation</td><td colspan="3">Consistent across three scenarios</td></tr>
<tr><td>Proportion of energy-saving buildings, ultra-low/near-zero energy consumption buildings</td><td>Low</td><td>Medium</td><td>High</td></tr>
</table>

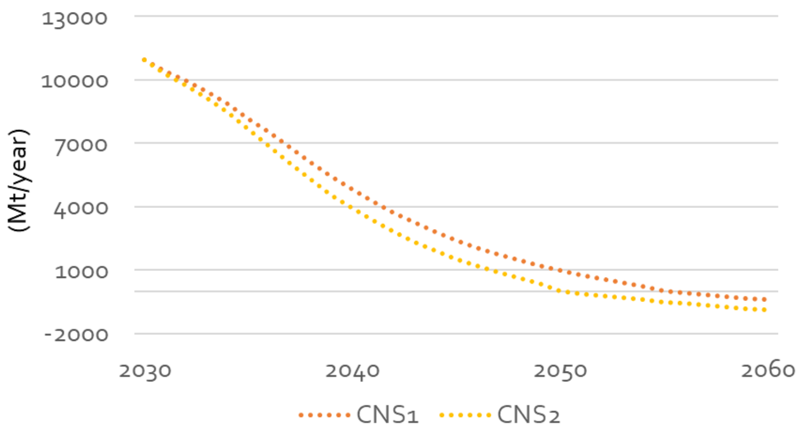
Overarching goals of the energy transformation

The Chinese energy transformation demands a harmonious alignment of multifaceted objectives, spanning development, emissions reduction, and security. This articulates that the Chinese energy transformation ought to serve the purpose of leading the attainment of carbon peak and carbon neutrality goals, fostering sustainable economic growth, satisfying the prerequisites for improving the quality of life under the vision of a Beautiful China, and coordinating a harmonious coexistence between humankind and nature through a distinctly Chinese modernisation. In pursuit of these milestones, an urgency beckons to expedite the pivot towards green, low-carbon development, construct a new-type energy system that is clean, low-carbon, secure, and efficient, while actively and prudently navigating towards carbon peak and carbon neutrality.

At the heart of the Chinese energy transformation lies the imperative to honour China's commitment to the *Paris Agreement*. This commitment underscores China's pursuit of a low-carbon developmental trajectory, aimed at reducing the energy sector's climatic repercussions. It aligns with the aspirations articulated in Article 2 of the *Paris Agreement*: to maintain the global temperature rise below 2°C while earnestly working to confine it to 1.5°C. In 2020, China undertook the ambitious pledge to reach its carbon dioxide emissions peak by 2030, with a vision for carbon neutrality by 2060. For a holistic achievement of carbon neutrality by 2060, the *China Energy Transformation Outlook (CETO)* posits that the energy system should be a vanguard in accomplishing carbon neutrality, and ahead of schedule, if possible, thus forging leeway for emissions reduction in other sectors. In alignment with this perspective, both CNS1 and CNS2 in CETO2023 aim for net-zero emissions in the energy system around 2055 and before 2055, respectively.

CETO2023 draws from the *Cadre's Handbook on Carbon Peak and Carbon Neutrality*, offering an exhaustive definition of the ambit of "carbon neutrality", encompassing carbon dioxide neutrality. The sectors scrutinised for carbon dioxide emissions are exclusively related to energy activities. Drawing upon both the *National Communication of the People's Republic of China on Climate Change* and the *Biennial Update Report on Climate Change of the People's Republic of China*, it is found that energy-related activities in 2014 constitute 79.8% of China's overarching greenhouse gas emissions (inclusive of LULUCF). It is crucial to recognise that non-CO_2 greenhouse gases, like methane (CH_4), possess notable climatic detriments. Despite methane's transitory atmospheric tenure, its influence on the greenhouse effect is pronounced. While methane's inclusion in the present scenario model remains absent, CETO2023 presents a dedicated analysis on methane emission reductions, buttressing endeavours to mitigate methane release.

Figure 3-1 2020-2060 Boundary conditions for carbon dioxide emissions from the energy system in different scenarios



Macroeconomic assumptions

Economic growth

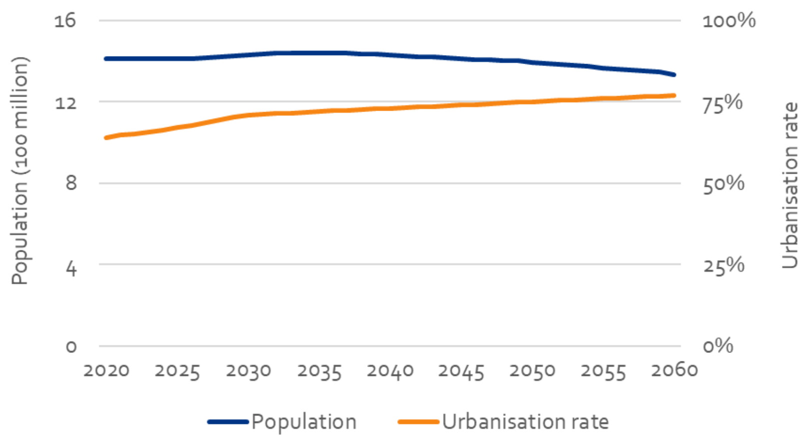
Economic growth stands as the bedrock for the sustained economic growth in China. The low-carbon transformation of the Chinese energy system necessitates fostering perpetual economic growth, thereby infusing vitality into ecological expansion. While Gross Domestic Product (GDP) is traditionally seen as the key economic indicator gauging a nation's economic advancement, China's shift from rapid growth to a more nuanced, mature economy necessitates broader metrics. The *14th Five-Year Plan* retains GDP growth as an indicative goal without setting specific parameters. It proposes that GDP "maintains an average growth rate within a reasonable range, with specific targets set on a yearly basis." It also reiterates the goal of achieving a per capita GDP at the level of moderately developed countries by 2035. Indicators such as per capita GDP, employment, income and consumption of residents, energy intensity, and carbon intensity necessitate maintaining China's economic growth at a certain scale. Considering these goals and the "Duo-Centennial Milestones," CETO2023 predicts China's GDP to quadruple from 2020 levels by 2060.

Demography and urbanisation

Both population size and structure significantly influence energy consumption. **In terms of quantity**, China's demographic development exhibits new traits, entering a phase of slowed growth. In 2020, China's population reached 1.412 billion, expanding by 72.05 million compared to 2010. The average annual population growth rate during 2010-2020 was 0.53%, slightly lower than the rate during 2000-2010. In 2022, China experienced its first population decline in 60 years, decreasing from 1.413 billion in 2021 to 1.412 billion. Despite declining fertility rates, inertial growth persists due to reduced mortality and lingering effects of past high birth rates. Predictions estimate that China's population peaks between 2025 and 2030, ushering in an era of demographic regression thereafter. **In terms of structure**, the data from the seventh national census reveals a gradual acceleration of the trend towards aging. Between 2021 and 2030, both the size and proportion of the working-age population continue to decline rapidly, with the proportion of elderly population reaching approximately 25% by 2030. Urbanisation rate remains a pivotal indicator for end-use energy sectors, particularly the building sector. In 2022, China's urban population constituted 65.2% of the total population (also known as urbanisation rate). With new urbanisation and urban-rural integration, urbanisation continues rising but gradually decelerate after reaching 75%.

CETO's demographic projections are sourced from estimates of prestigious national and global institutions for China's population, including the Academy of Macroeconomic Research, Chinese Academy of Social Sciences, and the World Bank. Predictions take into account possible impacts of demographic and fertility policies in the near to medium term. The urbanisation rate assumption is mainly based on research by the Institute of Social Research at the Academy of Macroeconomic Research. CETO2023 predicts a population of 1.43 billion in 2030, 1.39 billion in 2050, and 1.33 billion in 2060, with urbanisation rates of 71%, 75%, and 77% respectively.

Figure 3-2 CETO2023 Population and urbanisation rate assumptions



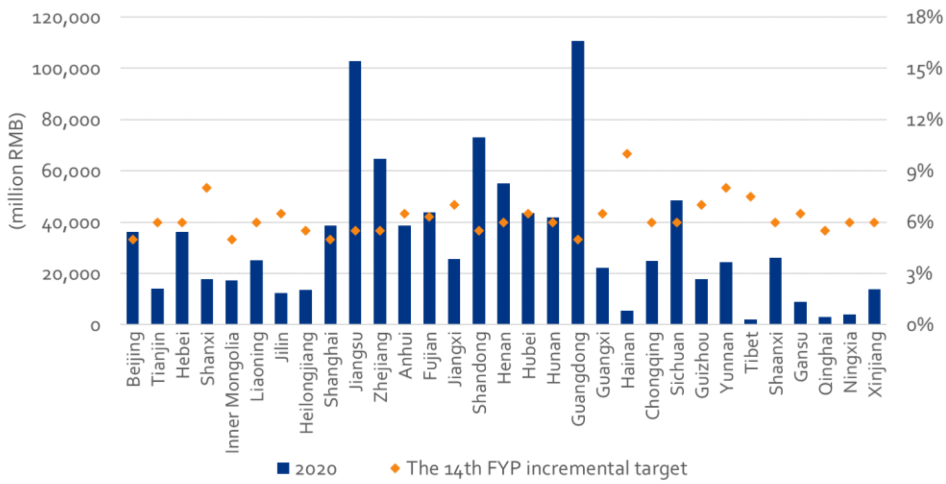
Regional development and provincial parameters

The CETO scenario relies on the premise of provincial proportions of electricity and electricity-derived fuels in the national total. It undertakes a comprehensive analysis of power supply, heating, and technical layout models. Variations in provincial macroeconomic parameters and industrial structure exert influence on the demand for electricity and electricity-derived fuels.

The model for provincial electricity consumption proportions is informed by computations of secondary industry and urban-rural residential electricity usage. **With respect to the secondary industry**, provincial GDP growth pace constitutes a pivotal driver of industrial electricity demand. Near-term GDP expansion percentages employ the objectives from each province's *14th Five-Year Plan*. Long-range GDP increases account for the nationwide augmentation percentage, the maturity of each province's economy, and China's regional development strategy. **With respect to urban-rural residential electricity consumption**, the model weighs the per capita residential electricity usage in the baseline year for each province, coupled with the discrete economic and societal maturation levels and latent electricity consumption growth in each province, to forecast the per capita residential electricity usage for 2060. Western provinces exhibit greater potential for electricity consumption expansion. By integrating provincial population projections, CETO obtains the absolute electricity utilisation for urban and rural residents in each province. The provincial population forecasts refer principally to research by the Institute of Social Research at the Academy of Macroeconomic Research. Provincial electricity usage undergoes calibration with the national electricity outlook and serves primarily for proportional computation.

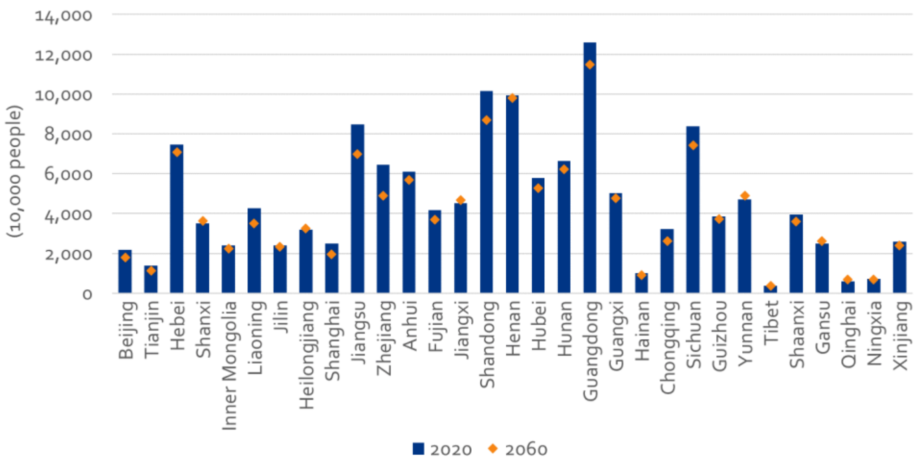
The provincial proportion of electricity-derived fuel demand depends chiefly on baseline data and anticipations for fossil fuel substitution. The LEAP model investigates the national requirement for fuels like ammonia, methanol, and hydrogen and distributes it to each province based on baseline provincial fuel demand data and assumptions about fossil fuel replacement. Given the lack of provincial data on baseline demand for ammonia and methanol, CETO employs 2020 regional goods turnover statistics and per capita GDP growth predictions to allocate national demand. Moreover, fuels like hydrogen in the steel industry, undergo policy-driven determination, so, CETO establishes the allocation of their provincial demand via expert consultations and factors such as provincial supply and cost of green hydrogen production.

Figure 3-3 GDP and 14th Five-Year GDP growth rate assumptions for provinces in 2020



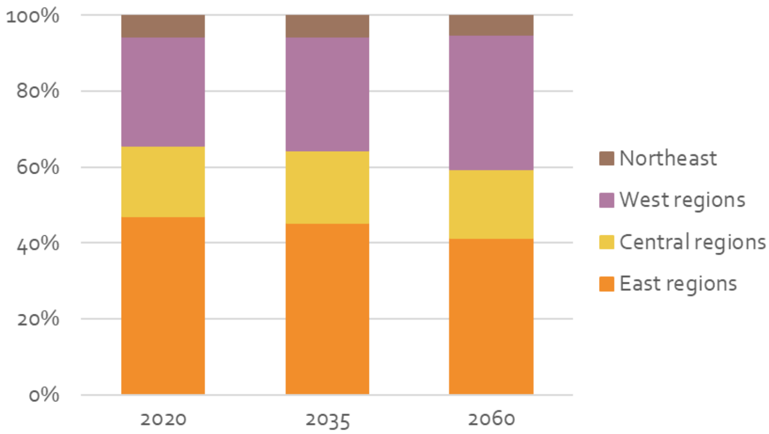
Data source: National Bureau of Statistics, Provincial 14th Five-Year Plans

Figure 3-4 Provincial population in 2020 and assumptions for 2060



Data source: 2020 data from the National Bureau of Statistics, 2060 assumptions from the CETO model.

Figure 3-5 2020-2060 Assumptions for distribution of regional electricity demand shares



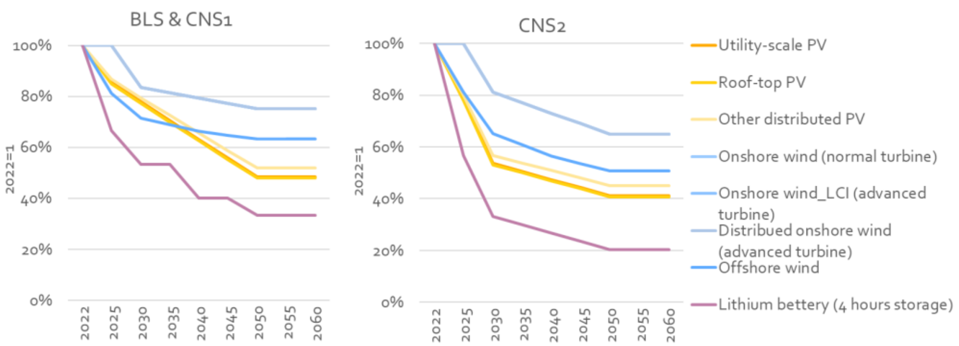
Key technical cost assumptions

The study of China's energy supply transformation primarily hinges on the EDO (Electricity and District heating Optimisation) model, an innovation by our research team. This model factors in an array of boundary conditions and policy constraints. It aims to optimise electricity generation capacity expansion, unit design, and operational scheduling, and to evaluate the choice of electricity generation and heating technologies based on the principle of minimum costs. Two crucial factors for determining the technology mix are the power generation technology's cost reduction curve and the fossil fuel cost assumptions for thermal power plants.

Regarding power generation technology costs, CETO projects a decline in clean energy technology costs throughout the forecast period. This decrease is attributed to technological innovations, economies of scale, and supportive policy measures. In contrast, opportunities for cost reductions in conventional energy technologies, such as thermal power investment costs, appear more constrained. CETO's baseline figures for power generation technology costs draw from the most recent empirical data from China's power sector. The cost reduction trajectory for renewable energy technologies integrates both domestic and international research findings, encompassing insights from wind and photovoltaic industry associations as well as the U.S. National Renewable Energy Laboratory (NREL).

Regarding fuel pricing, renewable technologies like wind and solar inherently possess zero marginal fuel costs. In contrast, traditional energy sources, including fossil fuels and nuclear power, are subject to market volatility and the implications of resource scarcity. As a result, renewables have a sustained cost advantage. CETO2023 evaluates the repercussions of the global energy crisis on fossil fuel pricing. Commencing in 2021, a constricted global energy market precipitated a significant rise in China's medium-to-long term coal prices, thereby escalating thermal coal costs. During 2021 and 2022, the average price of thermal coal surged by 16% and 10% year-on-year, respectively. CETO2023 anticipates an annual decrement of 1% to 3% in thermal coal prices until 2030, with prices stabilising between 570-770 RMB/ton from 2031 to 2060. Predictions for natural gas prices are set at $7.7/mbtu for 2030, $6.8/mbtu for 2050, and $6.5/mbtu for 2060.

Figure 3-6 2020-2060 Assumptions for declining cost curves of major technological investments in different scenarios



3.4 Main sectorial energy transformation policies

CETO2023 consolidates main policies introduced post the 2020 carbon neutrality pledge, concentrating on 2022 updates. The year 2022 proved pivotal in policy formulation, signifying key junctures en route to carbon peak and carbon neutrality objectives. The "1+N" policy framework matured, several strategies from the *14th Five-Year Plans* were rolled out, and the 20th National Congress Reports detailed fresh mandates for energy security and premier development in the subsequent phase. The scenarios analysis considers the following main policies:

The "1+N" policy framework

Achieving carbon peak and carbon neutrality demands a holistic systemic approach, intersecting diverse facets of economic and societal growth. In the wake of the carbon neutrality commitment, two salient documents, namely the *Opinions of the Central Committee of the Communist Party of China and the State Council on Thoroughly Adopting the New Development Philosophy and Excelling in Carbon Peak and Carbon Neutrality* and the *Action Plan for Carbon Peak Before 2030*, were sequentially unveiled. These top-level design texts constitute the "1" in the "1+N" strategy, sketching the schedule and strategy for related endeavours. The "N" represents specific strategies for sectoral carbon peak achievements spanning areas in energy, industry, transport, urban and rural construction, complemented by supportive schemes in technological innovation, energy security, carbon sinks, fiscal and monetary policies, pricing, standard measurement systems, as well as inspection and evaluation systems. As of 2022, implementation plans for key sectors like energy, industry, urban and rural construction, transport, agriculture, and rural areas, as well as plans for key industries like coal, petroleum and natural gas, steel, nonferrous metals, petrochemicals, and building materials, and supporting plans for technology, finance, statistics, and talent development were all finalised. Additionally, plans for carbon peak implementation in 31 provinces, regions, and municipalities have been in place. A suite of documents has carefully built the policy scaffolding for carbon peak and carbon neutrality, delineating 10 principal carbon peak initiatives.

Table 3-2 "1+N" policy framework for carbon peak and carbon neutrality

Commitment for Carbon Peak and Carbon Neutrality	
"1": Top-level design documents	
Opinions of the Central Committee of the Communist Party of China and the State Council on Thoroughly Adopting the New Development Philosophy and Excelling in Carbon Peak and Carbon Neutrality	*Action Plan for Carbon Peak Before 2030*
"N": Underpinning 10 key initiatives	
• Green and low-carbon energy transformation action • Energy conservation, carbon mitigation, and efficiency augmentation action • Industrial sector carbon peak action • Urban and rural construction carbon peak action • Green and low-carbon transit action	• Circular economy-driven carbon mitigation action • Green and low-carbon technological innovation action • Carbon sequestration capacity fortification and enhancement action • Green and low-carbon engagement action for all people • Phased carbon peak initiative across various regions

The *14th Five-Year Plan*

The *14th Five-Year Plan* framework is pivotal to CETO2023's policy foundation. National blueprints incorporate the *14th Five-Year Plan for a Modern Energy System* and the *14th Five-Year Plan for Renewable Energy Development*. In 2022, provinces, municipalities, and autonomous regions across the country proffered their energy development visions for this period, with some additionally presenting renewable energy strategies and an overarching vision through 2035. The *14th Five-Year Plan* carries legal weight, with its targets providing a robust directive for energy development.

Ad-hoc energy policies

In 2022, China's energy landscape embraced a myriad of targeted policies bolstering developing a new-type energy system. This exerted a notable influence on the CETO model's specific technical trajectories. Directives such as the *Opinions on Refining System Mechanisms and Policy Measures for Green and Low-Carbon Energy Transformation* and *the Implementation Plan for Promoting the High-Quality Development of New Energy in the New Era* outlined the overall development direction. Certain explicit developmental aspirations were mirrored in annual policies. For instance, *Guiding Opinions on Energy Work for 2022* championed the rapid establishment of expansive wind and solar infrastructures in desert, Gobi, and barren terrains.

On the energy supply front, **there emerged a pronounced emphasis on innovative energy storage and hydrogen energy**. In 2022, official communiqués like the *Medium and Long-Term Development Plan for the Development of the Hydrogen Energy Industry (2021-2035)*, *Guiding Opinions on Accelerating the Development of New-type Energy Storage*, and the *Notice on Further Promoting the Participation of New-type Energy Storage in the Electricity Market and Dispatching Us*e, reinforced the *Implementation Plan for New-type Energy Storage Development during the 14th Five-Year Plan Period* propounded in 2021. **The Flexibility transformation of thermal power plants gathered momentum.** Directives, namely the *Implementation Plan for the Transformation and Upgrading of Coal-Fired Generating Units Nationwide*, and *the Benchmarking and Reference Levels in Key Fields of Clean and Efficient Coal Utilisation (2022 Edition)* amplified the policy delineation for the transformation and upgrading of coal-fired facilities. **Support for decentralised renewable energy sources magnified**, with enactments like the *Notice on Publishing the List of Rooftop Distributed Photovoltaic Development Pilots in Whole Counties (Cities, Districts)* amplifying the thrust towards distributed energy development.

Green transformation benchmarks and endeavours are accentuated within end-use energy sectors. **In the industrial sector**, *Guiding Opinions on Catalysing High-Quality Development of the Steel Industry* earmarked the ambition for reaching peak emissions by 2030. *Guidelines for Energy-Saving and Carbon Reduction Transformation and Upgrading of the Cement Industry* instituted pertinent energy efficiency standards. Guidance for the high-quality development of industries such as petrochemicals, synthetic fibres, and textiles enumerated phased carbon peak milestones and proffered protective protocols.

In the building sector, a succession of policies, including the *Opinions on Augmenting Green Growth in Urban and Rural Development*, the *14th Five-Year Plan for Technological Advancement in Housing and Urban-Rural Construction*, the *14th Five-Year Plan for Building Energy Efficiency and Green Building Development*, and the *Implementation Plan for Carbon Peaking in Urban and Rural Construction*, were consecutively launched.

Policies pertaining to energy market reforms

The mechanisms for incentivising and constraining carbon peak and carbon neutrality were continuously improved, while energy sector price reforms deepened. Post-2020, to further the development of renewable energy at a larger scale, China pursued market-driven reforms concerning on-grid power tariffs for thermal power, adopted policies for parity-based grid access of new energy sources, innovated the pricing mechanism for pumped storage energy, fine-tuned peak-to-valley time-of-use (TOU) electricity pricing structures, enforced more rigorous tiered electricity pricing policies for industries with high energy consumption, and expedited the crafting of an energy price policy system congruent with high-quality development and carbon peak and carbon neutrality mandates. Monetary tools were meticulously enhanced. By mid-2022, policy funds surpassing RMB 180 billion were allocated through carbon reduction support tools, with an additional RMB 35 billion through special re-lending for the clean and efficient coal utilisation, stimulating private sector investments in carbon reduction.

Carbon market construction gained momentum. On July 16th, 2021, China launched the national carbon emissions trading market, initially encompassing 2,162 power companies and accounting for an annual carbon dioxide emission volume approximating 4,500 $MtCO_2$ — positioning it as the world's premier carbon market by covered emissions. The national carbon market system's development was in steady progression. Effective from February 1, 2021, the *Administrative Measures for Carbon Emission Rights Trading (for trial implementation)* were initiated, forging a foundation for carbon emission rights registration, trading, settlement, enterprise GHG emission accounting and reporting, and expedited updates to the *Interim Measures for Voluntary Greenhouse Gas Emission Reduction Trading* and pertinent technical standards. Collectively, these mechanisms facilitate the regulation of different aspects and responsibilities related to the national carbon market mechanism, while strengthening the establishment, operation, and supervision of the market.

3.5 Main conclusions from scenario analysis

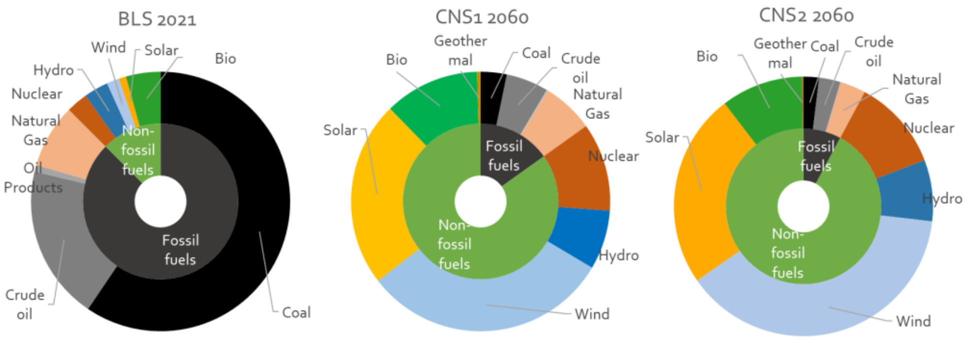
A radical shift in primary energy demand structure

Attaining carbon neutrality necessitates a radical overhaul of the energy structure. On the carbon neutrality trajectory, fossil fuels are phased out entirely. CNS2 shows the total primary energy demand to escalate to 7.0 Btce by 2035, subsequently reducing to 5.8 Btce by 2060 (based on the coal substitution method). In both CNS scenarios, the contribution of non-fossil fuels to primary energy demand surpasses 50% prior to 2035. By 2060, these contributions could elevate to 92% and 96% for CNS1 and CNS2, respectively — around 20 percentage points higher than the BLS scenario. Concurrently, the renewable energy shares in primary energy demand might surpass 86% and 90%, respectively, by 2060 in both CNS scenarios (based on the coal substitution method). Thus, even under the CNS1 scenario, which allows a gradual coal phase-out, deep decarbonisation, and a comprehensive shift to non-fossil energy in the energy structure are inevitable requirements for achieving carbon neutrality.

In all scenarios, there is a consistent trend of declining coal demand. From a policy standpoint, in line with the "1+N" policy framework, China aspires to moderate coal consumption expansion during the *14th Five-Year Plan* period and incrementally diminish coal consumption throughout the *15th Five-Year Plan* period. From a market standpoint, the viability of thermal power plants faces significant challenges due to the drastic fluctuations in fossil energy prices. Owing to policy and market forces, the share of coal in the energy demand structure is on a downtrend, a pattern consistent across three scenarios. Even in the BLS and CNS1, the decline of coal consumption begins to take effect in the short-term future. In both CNS scenarios, coal's share in primary energy demand falls below 2% by 2060.

The expansion of renewable energy alleviates the growth in natural gas demand. The CETO2023 scenarios demonstrate that the rapid progress of electrification and renewable energy replaces the incremental demand for oil and gas, leading to a gradual slowdown in the growth of oil and gas demand. In all three scenarios, the total demand for fossil energy peaks before 2030, supporting the attainment of carbon peaking targets. By 2060, the proportion of natural gas in the total energy demand drops to less than 7%. The high price volatility of natural gas and the rapid increase in renewable energy collectively mitigate the growth in natural gas demand. In the power sector, the decreasing costs of wind and solar power generation, combined with relatively expensive natural gas prices, and the transition of coal-fired power units towards peak shaving in the near to medium term, comprehensively constrain the growth in natural gas power generation demand. Natural gas is mainly used in end-use sectors. Furthermore, the development and application of biomass gas in sectors such as power generation, industry, and transportation replace some of the potential demand for natural gas.

Figure 3-7 Primary energy demand structure in different scenarios (2021 vs 2060)



Charting a carbon-neutral pathway towards sustainable and low-carbon growth

China, as the world's largest developing nation, plays a pivotal role in the global fight against pressing climate challenges. The CETO scenario delineates how China's approach to carbon neutrality markedly deviates from the historic energy-economic trajectories of developed countries. China is set to embrace a transformative low-carbon shift, characterised by reduced per capita energy consumption and carbon emissions. This establishes a new path of green growth in China, characterized by lower per capita energy consumption and carbon emissions, along with an accelerated pace of low-carbon transformation.

Firstly, this transformation emphasises consistent energy consumption to bolster economic growth. Under CNS2, by 2035, China's economy expands to roughly 1.8 times its 2021 size, leading to a 52% reduction in energy consumption per unit of GDP (based on electric heating equivalents). **From the perspective of per capita economic growth and energy consumption**, China's per capita GDP quadruples by 2060. Yet, CNS2 predicts that per capita energy consumption (in terms of primary energy consumption) sees a modest rise from 4 tce annually in 2021 to 4.9 tce in 2035, eventually decreasing to 4.4 tce by 2060. This rate of growth is substantially lower than the corresponding rise in per capita income. Stabilising per capita energy consumption entails boosting energy efficiency through technological advancements and efficient resource management, thus mitigating excessive usage.

Figure 3-8 2021-2060 Total amount and structure of primary energy demand (energy basis method)

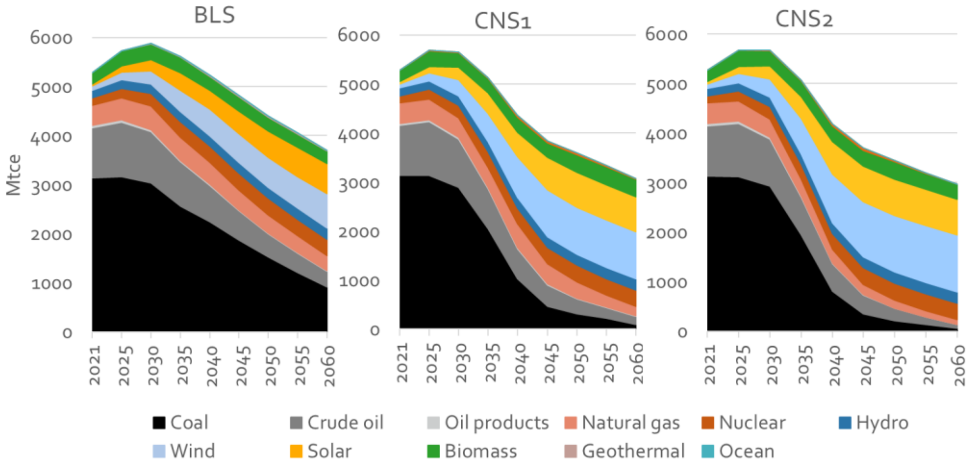
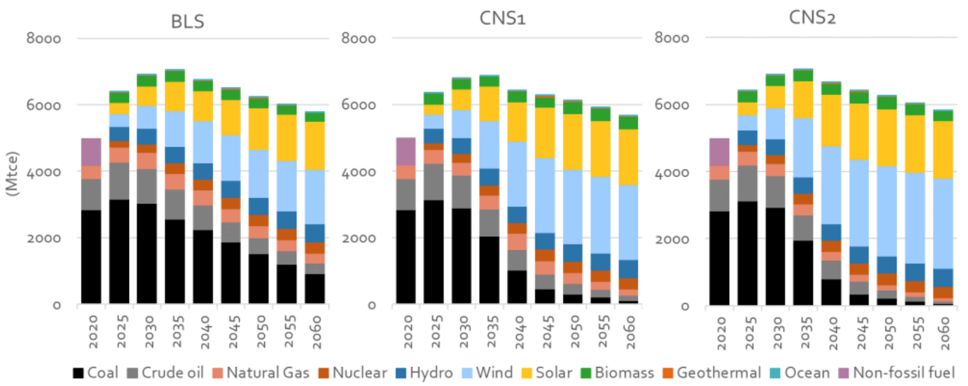


Figure 3-9 2021-2060 Total amount and structure of primary energy demand (coal substitution method)

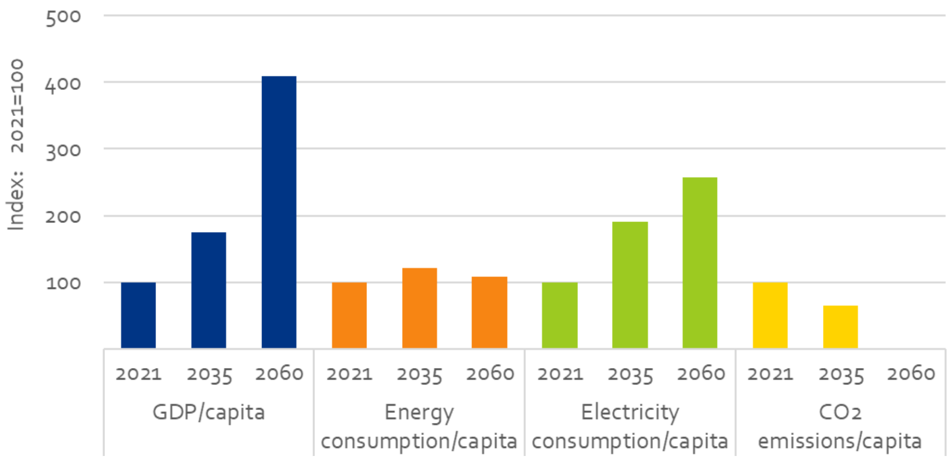


Note: 2020 is historical data, the data of other years are modelling results.

Secondly, the transformation encompasses a concurrent doubling of per capita electricity consumption and a 50% reduction in carbon emissions. Per capita electricity usage is an indicator of household electrification, a key metric of enhanced living standards. As of mid-2023, China's societal per capita electricity consumption stands at 16.7 kWh/day, with around 2.4 kWh/day dedicated to urban and rural household needs. The CETO scenario underscores energy efficiency improvements needn't compromise living standards. By 2035, under CNS2, societal per capita electricity consumption rises to 31 kWh/day and by 2060, it touches 42 kWh/day – approximately 2.6 times the present figures. In tandem, per capita carbon emissions decline from 8.2 tons of CO_2 annually in 2021 to 5.3 tons in 2035, a reduction of 35%.

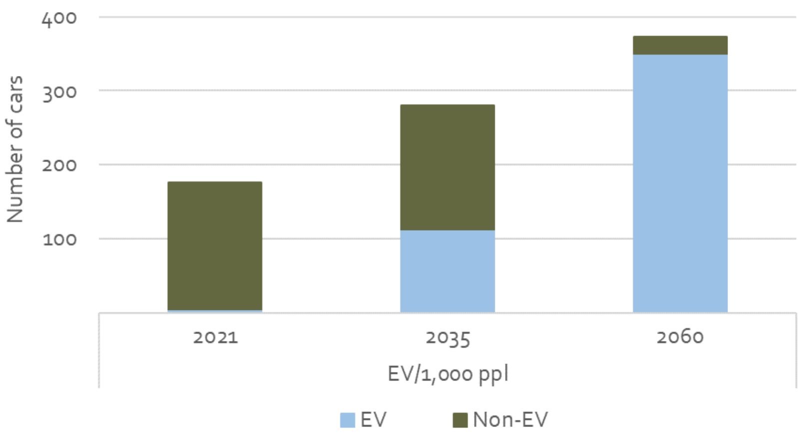
Attaining this reduction in per capita carbon emissions is contingent upon the widespread substitution of clean energy for conventional high-carbon energy sources in both production and consumption, coupled with a commitment to low-carbon lifestyles. Consider the transportation sector where the shift towards electrification and carbon-conscious practices is evident. In 2021, out of 176 passenger cars per thousand people in China, a mere 5 were fully electric. By 2035, 280 cars per thousand with 40% being electric, and by 2060, these numbers escalate to 373 cars with a staggering 94% being electric. For comparison, globally, the U.S. boasts about 868 cars per thousand, Denmark around 540, and the typical count for developed countries hovers around 600 cars. In both CNS1 and CNS2, China embraces an innovative and environmentally sound strategy for the evolution of its transport sector, marked by low carbon intensity. The rate of car ownership per individual is regulated to remain at an appropriately moderate level. Adhering to a trajectory of low carbon, efficiency and sustainability is essential to usher in a new age of zero-carbon production and living, enabling China to harmoniously blend economic prosperity with environmental preservation, meeting societal aspirations for an improved quality of life.

Figure 3-10 2021-2060 Trends for per capita energy dynamics in CNS2 (2021=100)



Note: Per capita energy consumption is determined by primary energy use, quantified using coal consumption for power generation. Per capita electricity usage employs the total consumption metric.

Figure 3-11 2021-2060 Changes in passenger car ownership and structure in CNS2

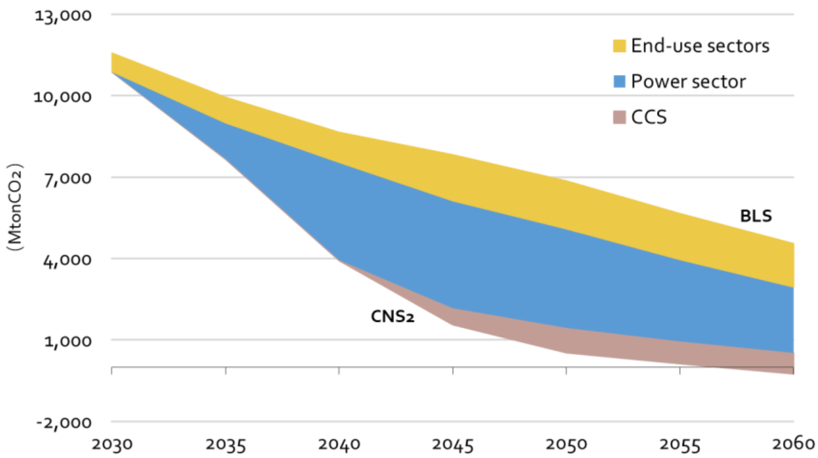


Sustained improvement in industrial low-carbon and zero-carbon competitiveness

The CETO scenario analysis suggests that carbon neutrality mandates unprecedented emissions cuts. Between 2030 and 2060, in both CNS1 and CNS2, China reduces its carbon emissions annually by approximately 360 and 370 $MtCO_2$, respectively. OECD data from 2021 reveals that the 28 EU member states emitted around 2,900 $MtCO_2$. Consequently, post its carbon peak, China's eight-year emissions reduction equals the EU's current annual emissions. Such data emphasises China's imperative to harness advanced clean energy technologies, bolstering innovation and policy initiatives. These rigorous efforts precipitate substantial declines in economic and sectoral carbon intensity, fortifying the growth and competitiveness of low and zero-carbon industries.

Comparative analysis of the scenarios highlights the necessity to amplify carbon reduction endeavours of both the power and end-use sectors. While all three projections attain a carbon peak prior to 2030, the paths of carbon emissions thereafter begin to increasingly diverge. The contrast between BLS and CNS2 underscores the trajectory and intensification of emission reduction initiatives required to transition from the peak to the realisation of carbon neutrality. The deviation between the BLS and CNS2 scenarios outlines the pathway from carbon peak to neutrality. Meeting the CNS2 recommended trajectory necessitates further cuts of 560 $MtCO_2$ by 2045 and 400 $MtCO_2$ by 2060 when juxtaposed against the BLS scenario. The power and industrial sectors emerge as pivotal for emissions reduction. For indirect emissions, power generation stands as the primary contributor, forming 60% of the gap between BLS and CNS2 by 2060. For direct emissions, achieving zero emissions of carbon dioxide in the building sector is relatively easier during the process of decarbonising end-use sectors, while achieving zero emissions of carbon dioxide in the industrial and transportation sectors is more challenging. In CNS2, by 2060, direct emissions from end-use energy sectors are approximately 640 $MtCO_2$, a sharp 92% decrease from 2020 levels. The bulk of carbon emissions originate from the chemical industry, contributing an estimated 540 $MtCO_2$. In comparison, direct carbon emissions from steel and cement production stand at roughly 70 $MtCO_2$. To neutralise these emissions, further investment in carbon-negative technologies is indispensable.

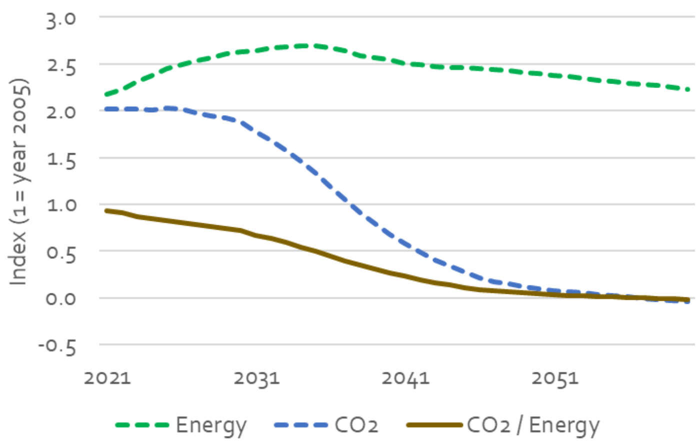
Figure 3-12 Decomposition of emission reductions by sector in CNS2 relative to BLS



Significant decline in industrial carbon intensity. Industry plays a pivotal role in energy consumption and carbon emissions. In 2020, it contributed roughly one-third of the total energy-related emissions, equivalent to 3,900 $MtCO_2$. China's industrial sector is on the brink of notable carbon reduction milestones. By 2060, under CNS2, the industrial carbon intensity descends from 1.25 metric tons of CO_2 per 10,000 RMB (2010 constant prices) to a mere 0.062, signifying a 95% reduction. This substantial decrease is attributed to a series of policies and measures, including industrial restructuring, improved energy efficiency, and low-carbon technological breakthroughs.

Steel and cement production is a significant contributor to energy consumption and carbon emissions within the industrial sector. In 2020, steel production stood at an estimated 1.07 billion tons, consuming energy equivalent to roughly 734 Mtce and emitting around 169 $MtCO_2$. Cement production totalled approximately 1.9 billion tons, consuming energy of about 174 Mtce and emitting nearly 287 $MtCO_2$, excluding emissions from industrial processes. The carbon intensity for steel production averaged 1.58 tons of carbon dioxide for each ton of steel, whereas cement production exhibited an intensity of roughly 0.15 tons of carbon dioxide per ton. Under the projections of all CETO scenarios, by 2060, both steel and cement production witnesses a marked reduction. Steel output declines to around 600 million tons, while cement output might reduce to close to 800 million tons. This anticipated decrease can be attributed to an extensive adoption of technologies like the electric arc furnace (EAF) and hydrogen-based direct reduced iron (DRI), leading to a considerable reduction in the carbon intensity associated with steel production. As per the BLS, CNS1, and CNS2 scenarios, by 2060, the carbon intensity of steel production falls to 0.47, 0.24, and 0.09 tons of carbon dioxide per ton of steel, respectively. The carbon intensity of cement production is also likely to see a decline in these scenarios, estimated at 0.06, 0.02, and 0.02 tons of carbon dioxide per ton of cement, primarily due to the integration of alternative clinker technologies, and enhanced utilisation of substitute materials and fuels. Under CNS2, the initial 30 years witness a gradual reduction in the carbon intensity of steel and cement sectors. However, a pronounced acceleration is envisioned in the decade leading up to carbon neutrality. In CNS2, between 2020 and 2050, the average annual reduction rate in these industries hovers around 4-5%, escalating to 11-12% from 2050 to 2060.

Figure 3-13 2021-2060 Changes in energy consumption, CO_2 emissions and energy carbon intensity under CNS2 (2005=1)



Guaranteeing new opportunities for energy consumption with green electricity and improved energy efficiency

The leapfrog development of green electricity paves the way for high value-added energy consumption. An uptick in energy consumption within emerging industries epitomises economic growth. The electricity usage for CETO2023 surpasses previous benchmarks. By 2060, the total societal power consumption of BLS, CNS1, and CNS2 reaches 16,400 TWh, 18,300 TWh, and 20,200 TWh, respectively. These figures represent increases of 1.9, 2.2, and 2.4 times their 2021 levels. This conclusion arises from multifarious drivers of energy consumption augmentation. Firstly, with China's continuous economic growth and enhanced living standards, the demand for commodities, transport, and electronics escalates, leading to enhanced energy comfort levels in areas such as building cooling and heating. Secondly, the development of digital economy has accentuated electricity usage, with technologies like big data, artificial intelligence, cloud computing, the Internet of Things, mobile devices, and blockchain being pivotal contributors. Notably, data centres have emerged as predominant energy consumers. Lastly, advancements in end-use sector electrification and the burgeoning appetite for green hydrogen amplify electricity demands. These consumption patterns, coupled with affordable and plentiful renewables, herald a new round of end-use energy consumption growth, particularly in supporting the electricity consumption.

The improvement of energy efficiency needs to be in tandem with the growth of green electricity. While the profusion of green electricity augments the capacity for diversified energy consumption, the bedrock for carbon neutrality remains energy efficiency. Amplifying end-use efficiency can counterbalance novel energy consumption hikes, playing an instrumental role in bolstering energy utilisation efficiency, effectiveness, and catalysing a carbon-conscious transformation. Industrial restructuring, deep electrification (transitioning from fossil-based energy to electricity), and relentless tech-driven innovations hold promise for marked efficiency improvements in especially the medium and short term. Joint endeavours targeting these domains suggest that, by 2060, under the CETO scenarios, industrial energy intensity plummets by 85% relative to 2020 levels, fostering a more resilient energy paradigm.

In summary, the future energy system is sculpted by high efficient end-use devices, and abundant but affordable clean energy. Solely fixating on energy consumption ceilings is difficult to assess the energy system decarbonisation progress. Green electricity's leapfrog development provides foundation for a marked increase in the level of electricity consumption, a factor that is pivotal for sustaining economic expansion. To expedite the journey towards carbon peak and carbon neutrality, it is imperative to transition from the "dual control" system of energy consumption, focusing on both total quantity and intensity, to a "dual control" framework cantered on carbon emissions. This necessitates the ongoing refinement of incentive and restraint mechanisms directed at pollution and carbon mitigation, alongside the development of comprehensive policies. By capitalising on the cost-effectiveness and plentiful supply of renewable energies, and by maximising the potential of energy efficiency initiatives, we can formulate a comprehensive strategy.

Figure 3-14 2021-2060 Total electricity generation

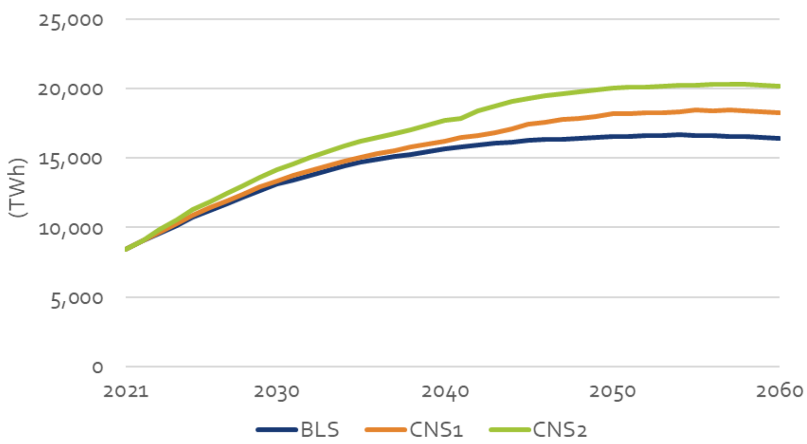
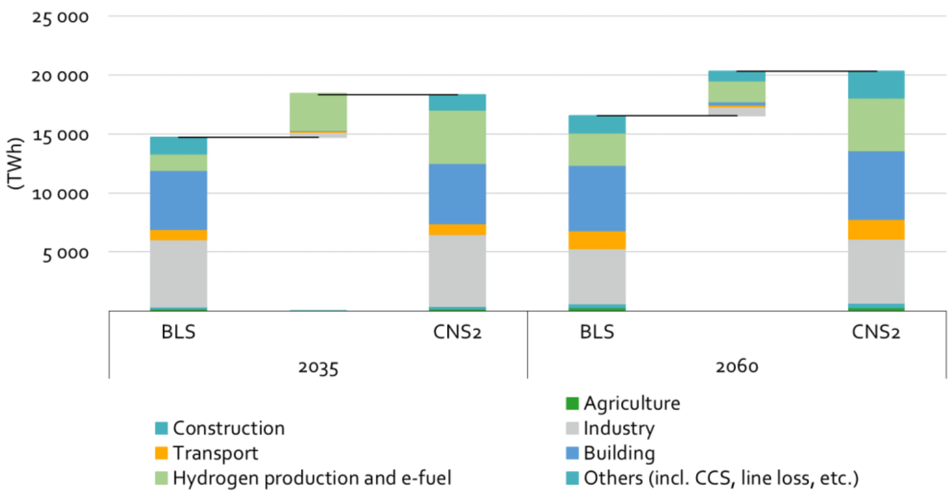


Figure 3-15 Variations in electricity consumption in 2035 and 2060



Shifting from "electrification" to "electro-hydrogenation" in end-use energy consumption

The transformation of end-use energy consumption in the near- and medium-term hinges on industrial restructuring and efficiency improvement, while medium- and long-term transformation are anchored in deep electrification and innovative low/zero-carbon fuel substitutes.

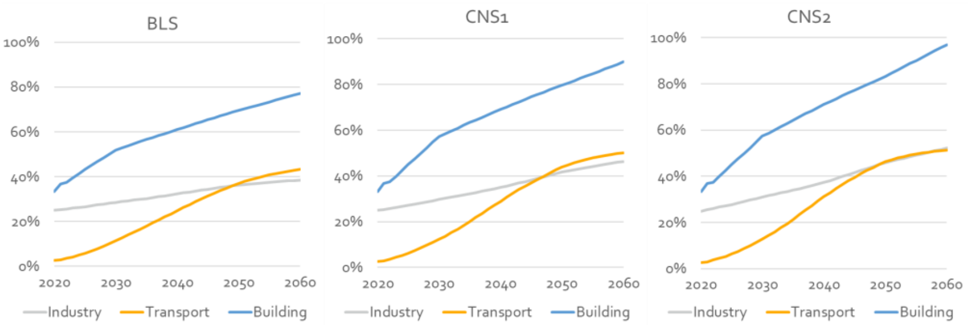
The push toward energy system electrification propels the transformation of end-use sectors. The three CETO2023 scenarios envision significant electrification in every end-use energy consumption sector within China. In the BLS scenario, the share of electricity consumption to total end-use energy consumption rise from 25% in 2021 to 36% by 2035, and then to 51% by 2060. For CNS1, this figure is 39% in 2035 and 60% in 2060. The CNS2 scenario forecasts even greater growth, with a share of 40% in 2035 and 66% in 2060. Due to increased electrification coupled with industrial restructuring, the electricity consumption of end-use sectors first surges, then wanes. In all three scenarios, a peak in end-use electricity consumption emerges around 2050, with a moderate decline following. By 2060, direct electricity consumption of end-user sectors in the BLS, CNS1, and CNS2 scenarios reaches 12,800 TWh, 13,300 TWh, and 14,000 TWh, respectively.

Industrial electricity demand experiences consistent growth until 2035. From 2020 to 2035, the rapid development of high value-added industries, particularly in the fields of machinery manufacturing and transportation equipment manufacturing, results in a doubling of added value compared to 2020, thereby driving a swift surge in electricity demand. In the BLS scenario, industrial electricity consumption rises from 4,750 TWh in 2020 to 6,350 TWh by 2035. The CNS2 scenario shows an even higher trajectory, achieving 6,710 TWh. Post-2035, there is a reduction in demand due to significant declines in heavy industry outputs. By 2060, the CNS2 scenario projects industrial electricity demand to diminish to 5,840 TWh. Traditional heavy industries, such as steel, witness decreasing electricity demand. Even with the ascendancy of electric arc furnace steelmaking to 65% by 2060, crude steel output drops below 60%. Concurrently, improvements in energy efficiency contribute to this reduced demand.

The proliferation of electric vehicles spurs a continual surge in electricity demand in the transportation sector. By 2060, the BLS, CNS1, and CNS2 scenarios project transportation electricity demands of 1,530 TWh, 1,630 TWh, and 1,670 TWh, compared to 100 TWh in 2020. The transportation sector's electricity demand maintains an average annual growth rate of about 7% from 2020 to 2060.

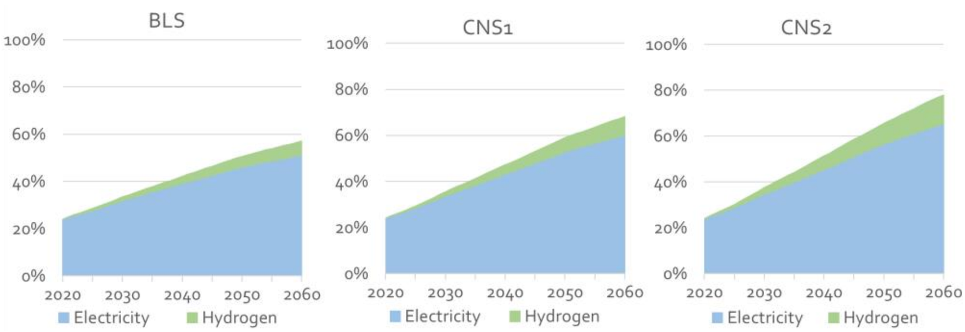
In the building sector, electricity demand sharply rises until 2035, increasing from 2220 TWh in 2020 to 5,120 TWh, at an average annual growth rate of 5.7%. However, post-2035, this growth decelerates, culminating in a 2060 electricity consumption of 5,810 TWh at an average annual growth rate of 0.5%. The CNS2 scenario projects the building sector's electrification rate to exceed 90% by 2060. The primary drivers for this upsurge in the building sector are data centres, public building electronic devices, and residential cooking.

Figure 3-16 2020-2060 Electrification rates by sector in different scenarios



Upon achieving peak carbon emissions, green hydrogen's integration into end-use sectors emerges as a pivotal adjunct to electrification, ushering in a shift towards "electro-hydrogenation" for end-use energy. Hydrogen assumes a crucial dual role: as a zero-carbon raw material and as a zero-carbon fuel, offering invaluable benefits for hard-to-decarbonise industries like the petrochemical sector. Beyond direct electricity consumption in end-use sectors, some electricity facilitates the generation of green hydrogen and clean heating. Post-2030, electricity-derived hydrogen sees accelerated adoption in end-use sectors. Hydrogen offers promise as a substitute for coking coal in crude steel manufacturing and can supplant current coal-driven ammonia synthesis processes. Additionally, hydrogen holds potential to replace petroleum products in transportation. Moreover, a segment of the electricity goes towards other power-to-X (PtX) fuels. In each of the three scenarios, rising hydrogen demand presumes a proportional uptick in electricity consumption. In the BLS scenario, electricity usage for hydrogen generation in 2035, 2050, and 2060 stands at 1,400 TWh, 2,300 TWh, and 2,700 TWh, respectively, constituting 9.5%, 14.1%, and 16.2%, respectively, of total electricity consumption, respectively. For the CNS1 scenario, these figures for 2035, 2050, and 2060 are 1,600 TWh, 2,800 TWh, and 3,300 TWh, respectively, representing 10.9%, 15.4%, and 17.7% of total electricity consumption, respectively. In comparison, the CNS2 scenario reaches 2,500 TWh of electricity for hydrogen generation in 2035, forming 15.2% of the total, a figure surpassing the BLS's 2050. By 2050, this figure reaches 3,800 TWh, exceeding CNS1's 2060. By 2060, it rises to 4,500 TWh, making up 22.1% of end-use sectors' total electricity consumption, underscoring hydrogen's integral role in end-use energy.

Figure 3-17 2020-2060 Proportions of electricity and hydrogen in end-use energy demands



Development, emissions reduction, and security are the three indispensable elements in the new power system.

China's emerging power framework emphasises cleanliness, low-carbon output, safety, economic efficiency, and the synchronisation of supply and demand, enhanced by flexible and intelligent capabilities. Both CNS1 and CNS2 achieve net-zero emissions in the power sector by around 2045, aspiring for negative carbon emissions thereafter to bolster broader energy and societal carbon neutrality. This transition sees a notable surge in low and zero-carbon power generation technologies, augmented system regulatory capacity, ongoing enhancement of the power market structure, an ample supply of cost-effective green electricity, and the harmonisation of aspects like emissions reduction, power supply security, and ecological safety.

The power system is undergoing a profound shift towards renewables, with wind and photovoltaic energy emerging as affordable and predominant sources. Under the CNS2 scenario, the nation's power generation capacity reaches 9,807 GW by 2060. By 2035 and 2060, renewables comprise 77% and 98% of the installed capacity, and 71% and 95% of power generation, respectively. By 2060, wind and photovoltaic sources represent 92% and 83% of the total installed capacity and power generation, marking an increase 17-fold from 2021, solidifying their position as primary energy sources. By the same year, the LCOE for onshore wind, offshore wind, and photovoltaic power fall to 0.20 RMB/kWh, 0.21 RMB/kWh, and 0.14 RMB/kWh respectively, reflecting a decrease of 40%, 67%, and 58% from 2021 levels, thereby ensuring a copious and cost-effective green electricity supply to achieve carbon neutrality.

The role of coal-fired power undergoes fundamental changes, with select units being retired yet retained, transitioning from base-load electricity sources to flexible regulation power providers. The CETO2023 scenarios indicate that a staged decommissioning of coal-fired power is not only vital for achieving net-zero emissions but also an inevitable market choice driven by the emergence of new energy technologies and continuous cost reductions. Under the CNS1 and CNS2, even when accounting for a smooth transition of coal power, its gradual phase-out remains an indispensable technological pathway to achieve carbon neutrality. The peak of coal-fired power capacity touches 1,250 GW between the *14th Five-Year Plan* and the *15th Five-Year Plan* periods, and it is entirely retired by 2060. Both the CNS scenarios emphasise that given the relatively nascent stage and advanced technological framework of China's coal-fired units, their transition is marked by a shift in their grid roles. Prior to 2040, operational coal-fired units incrementally cease operation, undergoing profound retrofits – known as the "*triple renovations*" [c] - into flexible power sources, thereby serving an essential regulatory function. Post-2040, as active units near their operation life, coal-fired units progressively retire, and operational durations decrease to sub-1,000 hours. Post-2050, coal-fired power generation in both CNS scenarios undergoes a significant decline, eventually reaching exceedingly low levels, eliminating reliance on coal for power regulation. Nevertheless, certain decommissioned units are retained, albeit in a non-operational state, receiving essential upkeep and positioned as long-term emergency reserves. It is noteworthy that the BLS reflects a downward trajectory in coal power capacity as renewable energy costs decrease. Yet, based on prevailing policies and the present rate of renewable energy cost reduction, the descent in coal-powered capacity decelerates post-peak, failing to achieve complete retirement by 2060. Such insights underline the need for more aggressive coal reduction strategies and holistic investments in renewable technologies to enable the coal power units retirement required for carbon neutrality.

[c] The phrase "*triple renovations*" denotes three technological renovations directed at coal-fired power plants, specifically energy efficiency and carbon emissions mitigation retrofits, heating system upgrades, and flexibility augmentations.

Figure 3-18 Power generation capacity structure and operational hours in 2021

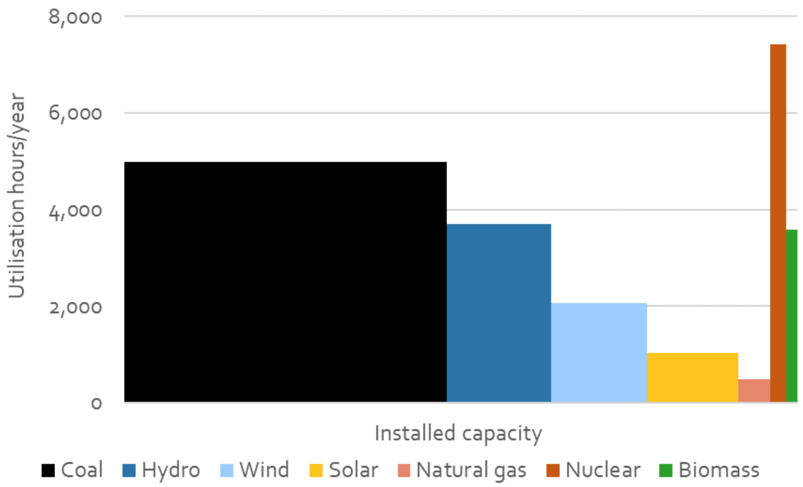
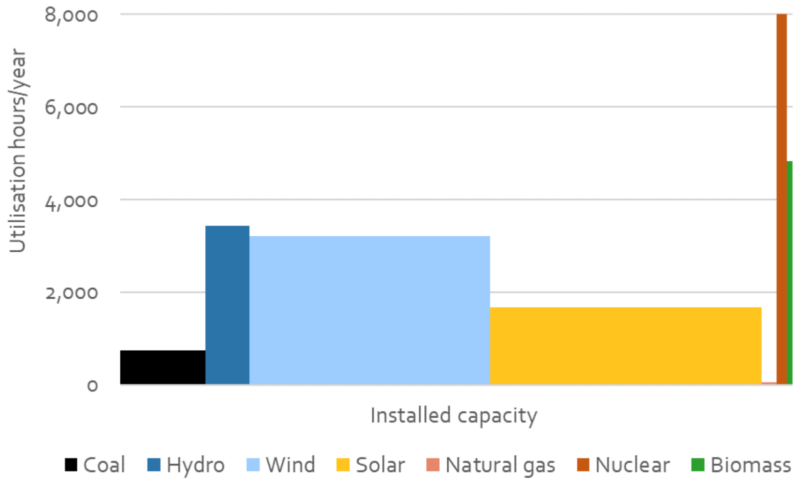


Figure 3-19 Power generation structure and operating hours for CNS2 scenario in 2040



Flexible resources in the power system underpin scalable and multifaceted advancements. As the emergent power grid, primarily driven by new energies, takes shape, the flexible resources in the power system exhibit a rich diversity and scalability. By 2035, the capacity of flexible resources in both CNS1 and CNS2 aligns with BLS predictions. Flexible coal-fired electricity and pumped storage hydropower predominantly serve as key regulation power sources. By 2060, the cumulative capacity of CNS2's flexible resources not taking into account the flexible coal power units surpasses 2,800 GW—6% greater than CNS1 and 5% more than BLS projections. During this period, multi-temporal energy storage and demand-side response solutions ascend to prominence. This trend emerges from CNS2's more aggressive shift from coal-based to renewable energies, necessitating enhanced flexible resources to maintain grid stability. Notably, pumped storage hydropower and novel energy storage technologies demonstrate a marked capacity growth compared to other scenarios, underscoring the economic benefits of expansive flexible solutions. By 2060, an estimated 470 million electric vehicles contribute over 560 GW of vehicle-to-grid (V2G) regulation capacity. Post carbon emission peak, China's heightened commitment to renewable energy heralds a holistic developmental phase for diverse novel flexible resources. Varied technological solutions are imperative to facilitate flexibility across diverse temporal scales. Conventional regulation resources, such as coal power, gradually cede ground to emerging solutions like V2G and electrolytic hydrogen. The profusion of wind and solar energy further facilitates the proliferation of innovative technologies, including electricity-driven hydrogen production.

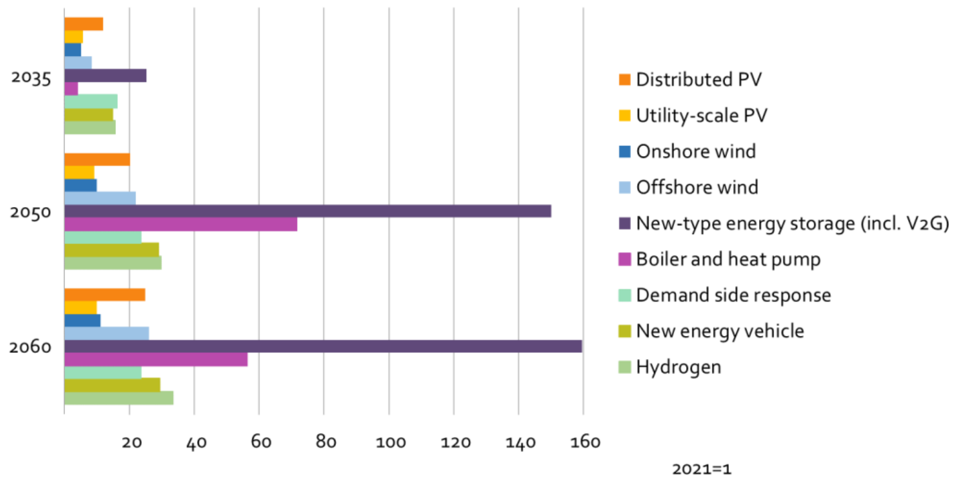
Nuclear power stands as a steadfast, low-carbon base-load energy source. With its potent energy density, exceptional unit availability, and dependable output, nuclear power is presently the sole base-load power alternative to large-scale coal-fired energy. It not only offers load trackability but also avails strategic placement near demand hubs and seamless integration with renewable energy. It remains a pivotal choice for ensuring energy security, accommodating escalating electricity needs, and furthering carbon neutrality ambitions. As of April 2023, China boasts 54 operational nuclear power units, aggregating a capacity of 56.8 GW, placing it third globally. An additional 24 units are under development, projecting a combined capacity close to 26.8 GW, solidifying China's global lead in under-construction nuclear power capacity. The country's nuclear energy policy exhibits an increasingly favourable tilt. The 20th CPC National Congress underscored the need to "advance the proactive, secure, and orderly growth of nuclear energy, improve the development of the energy generation, distribution, storage, and marketing framework, and safeguard energy security." As projected by China Nuclear Energy Association (CNEA), by 2030, China's operational nuclear power capacity achieves a leading position globally, marking a pronounced stance in the worldwide nuclear landscape. Given nuclear power's policy-driven trajectory, and factors like approval processes, fabrication capabilities, developmental timelines, and public acceptance, CETO2023 delineates a uniform growth trajectory for nuclear capacities across all scenarios. By 2035, China's nuclear capacity hits 110 GW, comprising roughly 6% of the total power output— a marked ascent from 2021's figures by 2.2 times. Post-2035, this capacity sees a steady annual rise of 1 GW, culminating at 120 GW by 2045. Such growth is instrumental in underpinning the power sector's carbon neutrality aspirations.

Rapid and leapfrog development in key clean energy technologies

In the past decade, China has experienced a burgeoning advancement of clean energy technologies, positioning it as one of the global leaders in the green energy market. Under the CETO scenarios, impressive growth of new energy in recent times marks merely the outset of an extensive journey, given the pressing need to achieve carbon peak and carbon neutrality. It is imperative for key clean energy technologies to sustain consistent, if not exponential, development trajectories. Numerous emergent energy technologies have transitioned from concept to reality, fuelling fresh avenues for green economic expansion. Both CNS1 and CNS2 show that every clean energy technology, on both the supply and demand fronts, witnesses substantial growth within the forecast period. Renewable energy technologies, in particular, maintain their momentum during this period. Before 2035, advancements in new-type energy storage, offshore wind power, and demand-side response technologies are likely to outpace other sectors. However, from 2035 to 2060, with renewable energy occupying a predominant share in the power system, there is an accelerated focus on power flexibility technologies (including V2G and smart charging), heat pump and electric boiler technologies, and hydrogen-based solutions.

Renewable energy technologies maintain their momentum for leapfrog development. Under the CNS2 scenario, from 2021 to 2035, owing to continual efficiency improvements and persistent reductions in costs of photovoltaic and wind power technologies, the annual average growth rates for installed capacities of photovoltaic power, onshore wind power, and offshore wind power are approx. 18%, 12%, and 16%, respectively. By 2035, the accumulative installed capacity for these technologies grows around 8-, 5- and 8-fold, respectively, from their 2021 levels. Post 2035 until 2060, with renewable energy gaining predominance and a diminishing energy demand, the annual growth rates for wind and photovoltaic capacities taper to about 3%. By 2060, the total renewable energy capacity stands at 9,630 GW, marking an 9.3-fold increase from 2021 and surpassing the forecasts of the CNS1 and BLS scenarios by 20% and 57%, respectively.

Figure 3-20 Multipliers of the growth of selected clean energy technologies under the CNS2 scenario (2021=1)



Note: Power generation technology is calculated based on cumulative installed capacity, while end-use energy technology is calculated based on the number of devices held.

Power flexibility technologies are on track for exponential growth, with new-type energy storage taking into shape from non-existence to maturity, and from small capacity to scaled-up development. New-type energy storage technologies, along with demand-side response technologies and intelligent energy systems, bolster the resilience and security of the power grid, a crucial requirement for assimilating significant shares of fluctuating renewable energies and managing peak demands. The CETO scenarios encompass diverse facets of new-type energy storage, i.e., electrochemical storage, vehicle-to-grid integration for electric vehicles, compressed air storage, and more. The CNS2 projects the compound annual growth rate (CAGR) for these emerging energy storage solutions to stand at approximately 26% between 2021 to 2035, marking a transition from non-existence to a phase of rapid development. As electric vehicles gain momentum and intelligent energy management refines, V2G emerges as a pivotal storage solution, offering the grid a cost-effective, scalable, and high-grade flexibility. Between 2030 and 2060, V2G grows at a CAGR of 14%. By 2060, the cumulative capacity of new-type energy storage systems, inclusive of V2G, is estimated to be 638 GW—a figure surpassing the projections in the CNS1 and BLS scenarios by 13%. Concurrently, under the CNS2 scenario, demand response (DR) technologies, such as smart electric vehicle charging and industrial responses, present considerable promise. From 2021 to 2035, DR experiences a CAGR of roughly 22%, with its operational scale in 2035 being a substantial 16-fold or more of its 2021 level. However, from 2035 to 2060, this growth rate tapers off to 1.5%.

Emerging end-use energy-saving technologies are being deployed and increasingly superseding traditional ones. Electric vehicles, intelligent home systems, and industrial electrification are pivotal means for diminishing carbon footprints. The broader embrace of electric mobility and clean energy-integrated industrial processes substantially curtails conventional energy usage and pollutant emissions. Additionally, the scope of hydrogen energy technology widens. The ascendancy of hydrogen energy, a potent and environmentally benign energy conduit, exerts a significant influence in sectors such as industry and transportation. As per the CNS2 projections, from 2021 to 2035, the annual growth rates of heat pumps and electric boilers, new energy vehicles, and hydrogen energy deployment are estimated at 10.5%, 21.2%, and 21.7% respectively. From 2035 to 2060, these rates stand at 11%, 2.8%, and 3.1% respectively. By 2060, the deployment scale of these three technologies amplifies to 56-fold, 29-fold, and 33-fold their 2021 levels.

Pronounced and sustained investment in energy transformation and technical innovation is key to driving the rapid and leapfrog development of clean energy. Notwithstanding considerable advancements in clean energy in China during the past decade, a more proactive and innovative strategy is imperative to expedite the development of renewable energy technologies, power system flexibility solutions, electrification of end-use sectors, hydrogen energy systems, and intelligent energy technologies, to chart a path to future carbon neutrality. Pronounced and sustained increases in investment support are indispensable to fuel research and innovation, hasten technological fruition, realise commercial viability, and register significant headway towards carbon neutrality objectives. Concurrently, such capital infusions also invigorate economic prosperity, generate employment opportunities, and bolster China's vanguard position in the global clean energy arena.

Box 3-1 "The Future Technologies Remain Uncharted - Navigating Uncertainty in Scenario Analysis

Given the intricate nature of the energy system and the multitude of influencing factors, CETO employs scenario analyses using models like ERI-LEAP, ERI-EDO, and CETPA to project the potential impacts of diverse energy policies, technological progress, and market dynamics. This approach provides a comprehensive evaluation of mid- to long-term energy development. It's essential to distinguish between assumption-driven 'prospects' and 'predictions'. Scenario analysis inherently involves various uncertainties.

Regarding technological innovation and advancement, disruptive technologies, such as advanced renewable energy, next-generation grids, new modalities of large-capacity and long-duration energy storage, hydrogen and fuel cells, advanced nuclear energy, and novel materials, have the potential to radically transform the energy landscape in the upcoming years. Policies such as the *14th Five-Year Plan for Technological Innovation in the Energy Sector* highlight recent pivotal tasks in energy technology innovation. Over the long term, the advent of disruptive innovative energy technologies could spark a new era in the energy industrial revolution. Moreover, the projected strategic emerging technologies, like hydrogen energy, are still grappling with issues around cost-effectiveness, technological maturity, and the development of their industrial chain. As delineated in the mid- to long-term plan for hydrogen energy, ongoing enhancements in key core technology capabilities, fuel cell reliability, stability, and durability, along with breakthroughs in vital core technologies in the hydrogen energy infrastructure sector, are imperative for its industrial advancement.

Regarding model optimisation principles, the EDO model is based on cost optimisation with boundary conditions reflecting industry and market realities. However, actual industrial development often entails more intricate choices than what the models can encapsulate. For instance, this year's outlook suggests, solely from a cost optimisation's perspective, current electricity pricing conditions suggest that electrochemical energy storage has limited economic benefits before 2030. Existing flexibility technologies, such as hydropower, coal power flexibility transformation, pumped storage, and demand-side response, are adequate for meeting the short-term needs of intermittent renewable energy grid connections. Moreover, regional and phased disparities in energy supply and demand, alongside shifts in peak load demand, may give rise to new security challenges and requirements for energy and power systems, thus injecting substantial uncertainty into energy system investments.

Regarding energy supply-demand patterns, the dynamics within end-use sectors, and the trajectory of economic, social, and population development, the evolving nature of production and living patterns, modes of travel and office work, as well as the expansion of the digital economy and breakthroughs in information technology, all hold considerable sway over the development trajectory of the energy system.

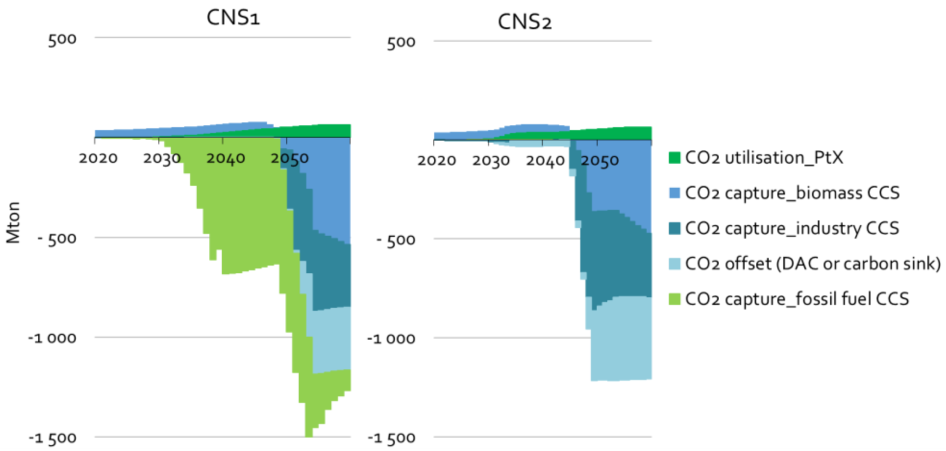
CETO scenario analyses duly acknowledge the ramifications of these uncertainties. Hence, the proposed pathway of robust growth in clean energy technology is grounded on the prevailing technological, economic, policy, and market conditions, arriving at relatively optimal choices through model-based optimisation. Energy transformation necessitates the unwavering creation of an equitable and high-performing level playing field. This transformation should uphold technological impartiality, ensure ample financing, and introduce mechanisms tolerant of innovation-related missteps, all aiming to proffer effective strategies for hastening the journey to carbon neutrality.

The constraints of CCS technology merit careful consideration

While CCS serves as a critical and "last resort" for meeting carbon neutrality objectives, the CETO2023 scenario analysis underscores the potential risks associated with large-scale CCS implementation, especially given its current technological limitations.

CCS represents an important and "last resort" solution for carbon neutrality. Biomass power generation, when coupled with CCS, paves the way for a power system with net-negative emissions. As we navigate the path to carbon neutrality, CCS functions to counteract the inescapable carbon emissions from various industrial and end-user sectors. During transitional phases, sectors with substantial carbon footprints, such as the power industry, require a grace period for adjustment and transformation. CCS offers a vital intermediary step, enabling these sectors to curtail emissions and progressively attain net-zero emissions. Under the **CNS1**, the extensive deployment of coal-fired power CCS results in carbon capture volumes of 560 $MtCO_2$, 620 $MtCO_2$, and 100 $MtCO_2$ in 2040, 2050, and 2060 respectively. **Under the CNS2**, the dependency on coal-fired power for CCS is less pronounced compared to CNS1, owing to the diminishing trajectory of coal-fired power generation. Concurrently, biomass power generation, when integrated with CCS, assumes a significant role in achieving carbon neutrality. From 2045 onwards, biomass power combined with CCS leads to net-negative emissions within the power sector. By 2060, the combined capacity for biomass power generation employing CCS reaches 67 GW. This corresponds to carbon capture figures of 360 $MtCO_2$ and 470 $MtCO_2$ respectively, thereby making monumental strides towards either net-zero emissions or net-negative emissions in the energy system. **In both CNS1 and CNS2,** industrial CCS stands out as an essential tool for sectors facing challenging emission reduction targets, forecasting a carbon capture volume exceeding 300 $MtCO_2$ or beyond by 2060.

Figure 3-21 Scale of carbon capture and utilisation under the carbon neutrality scenarios from 2020 to 2060 (in terms of carbon dioxide equivalent)



Excessive reliance on CCS as a pathway to carbon neutrality presents inherent risks. Current scenario analyses delineate pronounced challenges in scaling up CCS deployment. **To begin with, the energy overheads associated with CCS and CCUS warrant attention.** The carbon capture and storage process in the CCS system necessitates a substantial amount of energy support. The multifaceted stages of CCS, encompassing carbon dioxide capture, compression, transport, and storage, demand substantial electricity and thermal energy. This energy commitment erodes the operational efficiency of CCS-integrated power plants, leading to additional carbon discharges and diluting the net carbon-reduction efficacy of CCS. By 2060, the aggregate electricity consumption for CCS technology in both CNS1 and CNS2 scenarios stands at 9 TWh. **Secondly, CCS does not guarantee absolute carbon capture.** Our model suggests that the option for carbon capture installation is endogenously determined, applicable to both the inception of new energy facilities—including cogeneration—and the modification of external power plants (i.e., existing ones). Fossil-fuelled power stations, and bioenergy with carbon capture and storage (BECCS) can both be outfitted with carbon capture devices. While integrating carbon capture facilities into fossil-fuelled power plants considerably diminishes the carbon dioxide output per kilowatt-hour, it does not ensure complete sequestration of emissions. The model posits that power plants utilising CCS technology can, on average, sequester roughly 90% of their emissions. This underscores the continued need for alternative carbon sequestration techniques, such as direct air capture (DAC) or external energy system carbon sinks. By 2060, CNS1 and CNS2 still possess 440 $MtCO_2$ and 580 $MtCO_2$, respectively, that mandate neutralisation via DAC or analogous carbon sink strategies. **Lastly, the financial burdens of DAC technology are significant.** In contrast to high-cost solutions like DAC, alternative carbon offset avenues like forestry carbon sinks emerge as more cost-effective. However, resorting to such alternatives compromises the attainment of internal carbon neutrality within the energy sector.

In conclusion, while CCS technology offers a pivotal mechanism towards achieving carbon neutrality, its inherent technical constraints caution against excessive reliance. Furthermore, large-scale CCS deployment should not be misconstrued as a rationale for postponing the essential transition away from fossil fuels. Embracing cost-effective and efficient strategies, such as advancing clean energy transitions and curtailing carbon emissions at their origin, is paramount.

Energy transformation is mutually beneficial to social-economic development and industrial upgrading

Per the CETO scenario setting, China's energy transformation not only ensures a steadfast and proficient foundation for socio-economic and environmental progress but also reciprocally catalyses industrial upgrading. This synergy drives a qualitative leap in economic dynamism and fosters the advancement of clean and low-carbon energy systems, culminating in an array of sustainable development outcomes.

From an industrial development perspective, the GDP proportion attributable to the power sector is markedly superior under CNS1 and CNS2 compared to BLS. This reflects the premise that an earnest commitment to energy transformation can propel high-calibre energy and electricity sectors to play a more substantial role in the economic and social fabric.

Considering shifts in the employment landscape, under the CNS1 and CNS2 scenarios, in contrast with BLS, envisage a significant upswing in job creation within the renewable electricity sphere. This surge offsets employment contractions in conventional sectors such as coal and thermal power, borne from the energy transformation. Whilst the equipment manufacturing, coal, and thermal power sectors experience a downturn in employment under carbon-neutral trajectories, a pronounced increase takes place in service industries and the renewable electricity sector. This transition, whilst fostering innovation, may lead to a reduction in employment due to automation in sectors like equipment manufacturing. Notably, while certain sectors may witness a dip in employment, their output and the overarching GDP are poised for growth, illustrating the multifaceted impacts of technological evolution.

From an environmental impact perspective, analyses of energy structure modifications under varying scenarios reveal a pronounced curtailment of major air pollutants, including $PM_{2.5}$, NO_x, and SO_2, as a result of the energy transformation. This strategic shift contributes to a reduction of over 90% in emissions by 2060 according to both CNS1 and CNS2 scenarios, furnishing essential impetus for the improvement of air quality.

The global energy crisis necessitates prompt transformation and enhancement of collaboration

CETO2023 presents the BLS scenario, which, for the first time in model research, introduces a net-zero emissions constraint. This scenario acknowledges the growing instability and uncertainty of the current international geopolitical climate, the COVID-19 pandemic, and the countermovement against economic globalisation. The volatility in energy market supply and demand, resulting from these factors, presents risks to worldwide initiatives aimed at tackling climate change and facilitating energy transition. Analysis within the CETO2023 scenarios indicates that during energy crises, high prices of fossil fuels expedite the shift towards low-cost renewable energy technologies. The energy security challenges, emerging from drastic fluctuations in the global oil and gas market, further hasten the demand for dependable electricity systems reliant on local renewable energy sources. This underlines the necessity for strengthened international cooperation to accelerate the low-carbon energy transition and establish a green, low-carbon, and resilient energy system in times of energy crisis.

The rapid proliferation of new and renewable energy sources propels the transformation of energy trade towards a more green-oriented approach. Due to the ripple effects of the COVID-19 pandemic, geopolitical uncertainties, and regional supply-demand imbalances, there has been a marked escalation and volatility in global fossil fuel prices. From 2021, a constrained global energy supply prompted a notable surge in China's medium-to-long term coal prices, escalating thermal coal prices. In 2021 and 2022, the long-term average price of thermal coal in China escalated by 16% and 10%, respectively, markedly diminishing the cost competitiveness of thermal power. In December 2021, China's comprehensive import landed price index for liquefied natural gas (LNG) surged by 223.2% year-on-year. The CETO scenarios suggest that the rapid development of renewable energy enables China to bypass a phase of high-speed and high-proportion development of oil and gas. Under the BLS scenario, the share of natural gas in total energy demand in 2060 falls to less than 7%; in the two CNS scenarios, it decreases further to 2%. The global energy trade pattern, traditionally dominated by oil and gas, gradually shifts towards a trade framework based on new energy. This transition necessitates a substantial increase in the proportion of green trade, providing diversified, low-cost clean energy technologies to the global market, reducing the global cost of green and low-carbon transformation, and accelerating the global shift towards sustainable energy solutions.

China solidifies its reputation as the world's largest green market, and the development of the clean energy manufacturing industry helps to reduce the cost of energy transition. In 2022, China's new photovoltaic capacity installation topped global charts for the tenth successive year, with its aggregate installed capacity leading for eight years. Research from International Renewable Energy Agency (IRENA) and International Energy Agency (IEA) indicates that between 2010 and 2021, the globally LCOE for newly integrated photovoltaic projects plummeted by 88%. Simultaneously, onshore wind energy witnessed a 68% reduction, while offshore wind energy experienced a 60% decrease. By 2021, the average LCOE for newly integrated photovoltaic and hydropower projects was 11% more cost-effective than the least expensive newly established fossil fuel power plants, with onshore wind energy being 39% cheaper. China Photovoltaic Industry Association (CPIA) data reveals that China's photovoltaic product output recorded a year-on-year growth of over 55% compared to the 2022 level. Distinctly, polycrystalline silicon output reached 827,000 tons, maintaining its top global position for twelve consecutive years. Silicon wafer annual production was at 357 GW, cell production at 318 GW, and module production culminated at 289 GW, sustaining its NO.1 global position for sixteen consecutive years. The marked decrease in the cost of global wind and photovoltaic power generation stands as a historic milestone for China's clean energy manufacturing industry. As per the CETO scenarios, the robust expansion of clean energy technology in China, aligning with the carbon-neutral pathway, cements the nation's status as one of the largest markets for green energy technology globally. China's clean energy manufacturing sector, benefiting from substantial economies of scale and the collaborative innovation of energy technology both domestically and internationally in an open setting, not only fosters China's extensive deployment of clean energy essential for achieving carbon neutrality but also substantially contributes to the global drive for low-cost, rapid, and low-carbon transformation.

Market-oriented reform stands as the bedrock of carbon neutrality

The success of any energy transformation strategy is intrinsically linked to market construction. The CETO scenarios reveal that to truly achieve carbon neutrality, a resolute commitment to market-oriented reforms is indispensable. Robust market competition facilitates optimal resource allocation, paving the way for the equitable inclusion of cost-efficient renewable energies. This competition spurs a gradual reduction in the prices of low-carbon technologies, thereby enhancing their competitiveness within the entire energy system. In a market-driven environment, diverse energy sources vie on an equal footing, invigorating the entry of more clean energy investors and providers. Absent a well-developed market and robust competition, the energy transformation may grapple with suboptimal resource distribution, inefficiencies, inability to optimise the energy mix, and challenges in leveraging declining new energy technology costs. Within the ambit of CETO scenarios, the energy market reforms essential for a carbon-neutral trajectory encompass the following elements:

- Based on the principles of technological neutrality and effective competition, improve the green power market, the electricity spot market and the ancillary services market, and promote the full participation of renewable energy, flexibility resources and distributed resources in market transactions. Accelerate the improvement of the construction of the electricity market, and through flexible price signals, create revenues for new modes of business such as demand-side response and smart, flexible technologies, and promote new types of energy storage and demand-side response to entering the stage of large-scale development.

- Accelerate the construction of a unified national power market system to promote the development of all types of resources in the power system. China's power flow pattern of sending power from the west to the east and supplying power from the north to the south continues to exist. Under the CETO 2023, the provision of electricity in China's eastern and central regions sees a substantial escalation, with the scale potentially doubling by the year 2060. To facilitate this growth, a nuanced equilibrium and harmonious exploitation of diverse power generation resources are imperative. This includes both centralised and decentralised energy systems, as well as the proficient distribution and absorption of clean and low-carbon energy within and among different regions.
- Promote scientific carbon pricing and the effective connection of green equity mechanisms. Optimise the market mechanism for green certificates and green electricity, make a good connection between the electricity market and the carbon market, and strengthen the synergy of policies and mechanisms.

Moreover, to realise carbon neutrality illustrated in the CETO scenarios, the following measures and policy elements are indispensable:

- Ensure adequate, diversified and sustained clean energy transition investments and green finance, with strong incentives for technological innovation.
- After the attainment of carbon peak, roll out more vigorous policy interventions to expedite the transition towards clean and low-carbon energy sources. It is essential that stable policy frameworks are established, alongside enduring incentives, to aid the transition of coal-fired power stations to roles as contingency backup units.
- Promote renewable energy substitution on both the supply and demand sides. The development of process technologies such as "green hydrogen instead of grey hydrogen" and green hydrogen coupled with carbon dioxide chemistry should be promoted on a large-scale, and the application of the "hydrogen and carbon sequestration" model in the production of different products should be promoted. Promote the use of heat pumps, electric heating, and other electrification technologies to replace fossil energy sources, meet the demand for medium- and low-grade heat, and upgrade the level of electrification.
- Reinforce policies for low-carbon transformation of end-use energy. Promote the circular economy as the new form of China's industrial development and the new direction of process change, promote the transformation of the process structure from primary resources to renewable resources, and promote the proportion of recycled aluminium, electric furnace steel and recycled plastics. Vigorously enhance the recycling of waste plastics and tyres and reduce the demand for basic chemical raw materials in line with the policy of reducing and banning plastics.

- Strengthen the process of popularising electric vehicles and reduce the number of models that still partly require fossil fuels, such as plug-in hybrids, as soon as possible.
- Strengthen the top-level design for the large-scale development of ultra-low-energy-consumption buildings, clarify the objectives of medium- and long-term development planning, and formulate plans, objectives, and implementation paths for sub-regional promotion in accordance with the differences in the levels of economic and technological development and industrial maturity in different regions. Explore pilot demonstrations of ultra-low-energy-consumption buildings constructed in an assembly-type manner, launch pilot projects for the promotion of ultra-low-energy-consumption buildings on a large-scale, improve incentive mechanisms, and encourage relatively economically developed regions and government-invested buildings to take the lead in implementing ultra-low-energy-consumption building and near-zero-energy-consumption building standards.
- Optimise the scientific planning, research, and layout of low-carbon infrastructure. Guarantee the development of new energy, green hydrogen, CCUS, electricity-to-fuel and other new energy infrastructure that matches regional economic development strategies.
- Champion targeted reductions of non-CO_2 greenhouse emissions in alignment with China's unique national conditions.
- Participate proactively in global energy and climate governance, safeguard energy supply chain security, create an open and efficient business environment, and promote synergistic energy and climate innovation cooperation.

Chapter 4

Energy transition of the end-use sector

4 Energy transition of the end-use sector

4.1 Key messages

- In the short to mid-term, the main transformative path for energy consumption in end-use sectors is marked by industrial restructuring and energy efficiency improvement. In the long term, the focus shifts towards deep electrification, facilitated by technological innovation and the substitution of low and zero-carbon fuels.
- Model analysis suggests that all three scenarios depict steady growth in end-use energy demand in the short to mid-term.[d] Specifically, under the CNS2 scenario, end-use energy demand is around 4.2 Btce by 2030, marking a 11.9% increase from 2020, and then gradually declining to 2.61 Btce by 2060.
- The ratio of electricity in the energy mix of end-use sectors steadily increases, while that of fossil fuels declines. By 2060, under the CNS2 scenario, electricity consumption in end-use sectors reaches approximately 14,000 TWh, accounting for 65% of total energy consumption, with fossil fuel consumption plummeting from the current 66% to 12%. By 2060, the industrial, building, and transportation sectors constitute 42%, 42%, and 12%, respectively, of electricity consumption, while other sectors like agriculture make up 4%.
- After 2030, clean hydrogen production from electricity experiences rapid proliferation. In the CNS2 scenario, by 2060, hydrogen production through electrolysis equals 3.1 Mtce, accounting for 11.9% of end-use energy consumption. Of this, 75% are allocated to industrial applications, and 25% to transportation.
- Regarding direct CO_2 emissions from end-use sectors during the energy transformation process, while achieving zero emissions is relatively easy in the building sector, it poses serious challenges in the industrial and transportation sectors. Under the CNS2 scenario, by 2060, direct CO_2 emissions from end-use sectors hover around 6.4 Mtce, a 92% reduction from 2020. Most of these emissions emanate from the chemical industry, accounting for about 5.4 Mtce, while steel and cement contributes 0.7 Mtce. These carbon emissions necessitate further offsetting through negative carbon technologies (emissions reductions from industrial CCUS are calculated separately).
- The short-term low-carbon transformation goal for the industrial sector is to peak carbon emissions as early as possible. This is achieved by promoting energy efficiency improvements and expediting industrial/structural adjustments. The long-term goal is to reach net-zero emissions by electrifying industrial production,

[d] Unless otherwise specified, this report incorporates the consumption of non-commercialized biomass energy in the building sector in its measurement of final energy consumption. The electrification rate of end-use energy is also calculated based on this methodology.

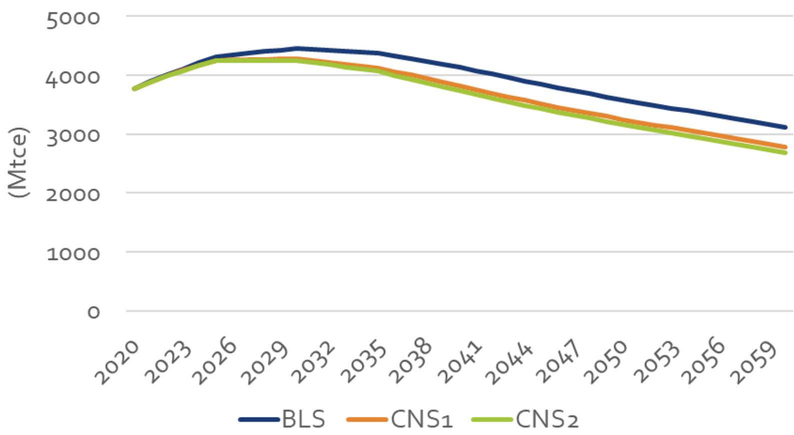
advocating resource recycling, substituting fossil fuels with low-carbon fuels represented by hydrogen in energy supply and feedstock, and employing carbon capture and storage (CCS) and other negative emissions technologies. In the CNS2 scenario, direct CO_2 emissions from the industrial sector are predicted to peak around 2025 and achieve net-zero emissions by 2060. By 2060, steel and cement production decreases by 40-60% compared to 2020 levels, energy consumption per unit of industrial value-added decreases by 85% compared to 2020, electrification rates gradually rises to around 55% from 25% in 2020, green hydrogen consumption accounts for approximately 18%, and the industrial sector achieves a high-quality low-carbon transformation.

- The transportation sector undergoes a low-carbon energy transformation through electrification and the promotion of low and zero-carbon fuels. In the short to mid-term, the transportation sector's energy demand continues to grow. Under the CNS2 scenario, the energy demand in the transportation sector peaks around 2030, a 17% increase from 2020, and by 2060, it decreases by about 30% from the peak level. By 2035, the market share of new energy vehicles reaches 100%, with 75% being electric vehicles. By 2060 under the CNS2 scenario, there is approximately 470 million electric vehicles, achieving an electrification rate of 51.4% in the transportation sector. In heavy-duty trucking, aviation, and shipping sectors, emissions are further reduced through green hydrogen, biofuels, and PtX fuels, supplementing the electrification efforts. By 2060, direct CO_2 emissions from the transportation sector decrease by 93% compared to 2020.
- Currently, direct carbon emissions in the building sector have plateaued. In the future, the building sector would achieve a low-carbon energy transformation primarily through energy efficiency improvements and electrification. Owing to the further expansion of building areas and continuous improvement of living standards, end-use energy demand in the building sector continues to grow in the short to mid-term. Under the CNS2 scenario, end-use energy demand in the building sector peaks by 2035, with a 17% increase compared to 2020. However, with the widespread adoption of ultra-low/near-zero energy buildings, deep retrofitting of existing buildings, ongoing improvements in electrification levels, and accelerated adoption of low-carbon and zero-carbon heating, the end-use energy demand in the building sector decreases by 22% by 2060 compared to 2035. The electrification rate in the building sector rises from 33% in 2020 to over 90%, and the remaining energy demand is met by other zero-carbon energy sources, leading to zero direct CO_2 emissions from the building sector by 2060.

4.2 Overall trends

End-use energy demand exhibits a consistent trend across all three scenarios, as depicted in Figure 4-1 and Figure 4-2. A peak in end-use energy demand across the three scenarios is reached between 2025 and 2030, followed by a consistent decrease owing to the retirement of obsolete capacity, improved energy efficiency, and enhanced electrification. By 2060, end-use energy demand under the BLS scenario diminishes to 3.09 Btce, while under the CNS1 and CNS2 scenarios, it falls to 2.71 and 2.61 Btce, respectively.

Figure 4-1 2020-2060 Total energy demand of end-use sectors

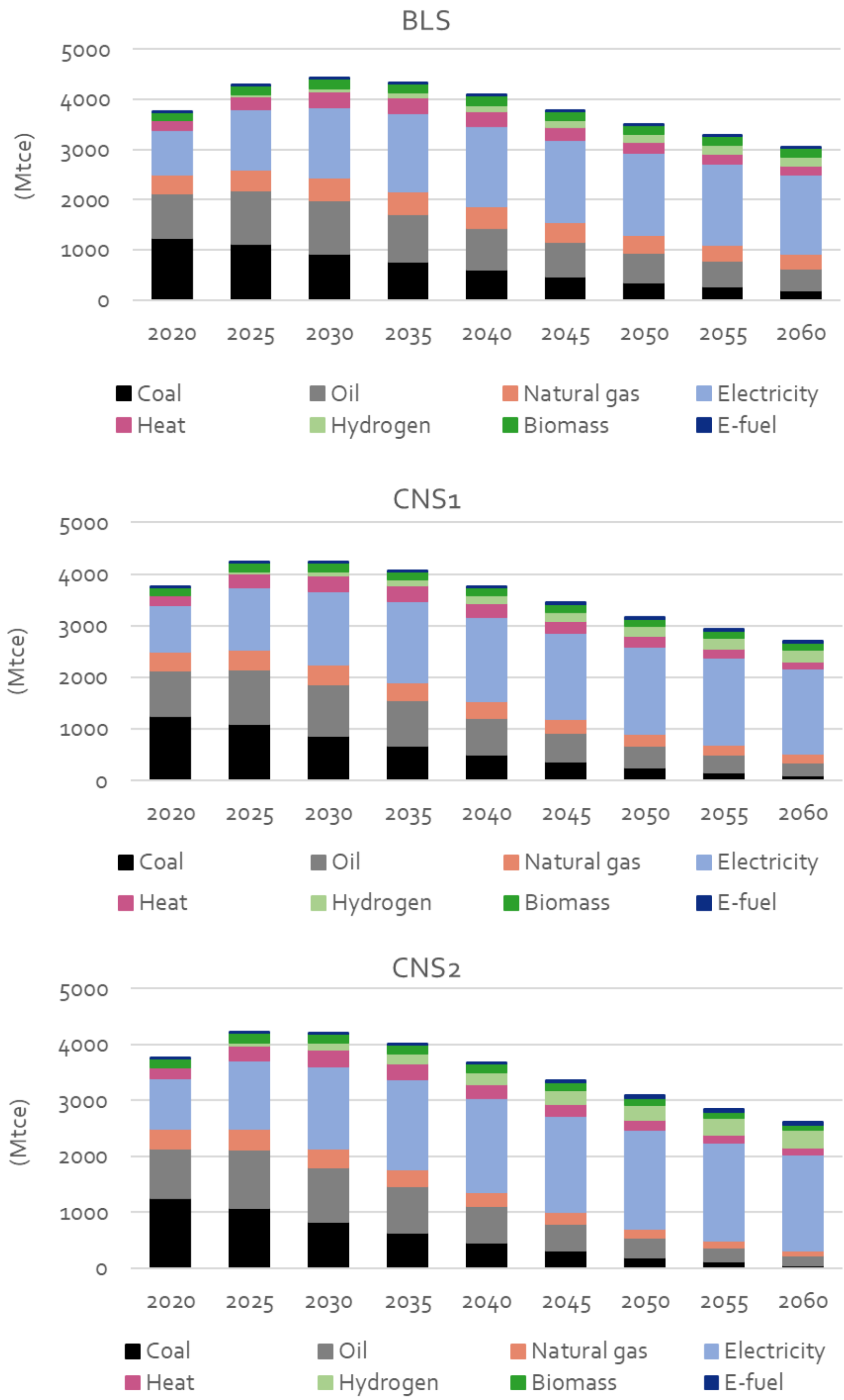


In all three scenarios, there is a growing share of fossil fuels in end-use energy consumption. In the BLS scenario, the coal consumption contribution contracts from 33.0% in 2020 to 6.6% in 2060. This share drops to 3.5% by 2060 in the CNS1 scenario and to 2.1% by 2060 in the CNS2 scenario.

In the BLS scenario, petroleum consumption share drops from 23.6% in 2020 to 14.1% in 2060. This share reduces to 9.5% by 2060 in the CNS1 scenario and to 6.2% by 2060 in the CNS2 scenario.

The share of natural gas consumption increases first then decreases in the BLS scenario, decreasing slightly to 9.8% in 2060. This share shrinks to 6.5% by 2060 in the CNS1 scenario and to 3.5% by 2060 in the CNS2 scenario.

Figure 4-2 2020-2060 Composition of energy types in end-use energy consumption



By 2060, the direct carbon dioxide emissions from the end-use sectors are reduced to only 970 and 640 Mtce, respectively, and can be mitigated through the utilisation of CCS or BECCS facilities in the CNS1 and CNS2.The residual carbon emissions in 2060 primarily originate from petroleum and natural gas uses in the transportation and industrial sectors. In the BLS scenario, approximately 1,750 Mtce of CO2 emissions by 2060. Decarbonisation within the industrial sector takes precedence in the medium term. With the gradual phasing out of coal consumption, along with electrification and fuel replacement, a considerable portion of carbon emissions can be reduced. Nevertheless, it remains challenging to fully supplant a certain amount of natural gas consumption in the industrial sector and petroleum products consumption in transportation with electricity or zero-carbon fuels.

The overall electrification rate in end-use sectors continues to rise in all three scenarios. In the BLS scenario, the share of electricity in end-use energy consumption increases from 23.9% in 2020 to 35.7% in 2035 and 51.4% in 2060. In the CNS1, this share to reach 38.6% by 2035 and 60.4% by 2060, while the CNS2 scenario has a share of 40.2% by 2035 and 65.8% by 2060.

The transportation sector undergoes rapid electrification, with electricity making up a growing proportion of energy consumption in the CNS1 and CNS2 scenarios. The electricity share in the transportation sector's energy consumption increases from the current 3% to 50.2% and 51.4%, respectively, by 2060, with vehicle electrification making the largest contribution. The present electrification rate in the building sector is 33%, but in the CNS1 and CNS2 scenarios, the building sector's electrification rate significantly increases, hitting 89.9% and 96.9% by 2060, respectively, building upon the current high level. In the industrial sector, the electrification rate steadily improves, propelled by the growth of intelligent manufacturing. The CNS1 and CNS2 scenarios foresee the share of electricity in industrial energy consumption rising from the present 25% to 46.4% and 52.2% by 2060, respectively.

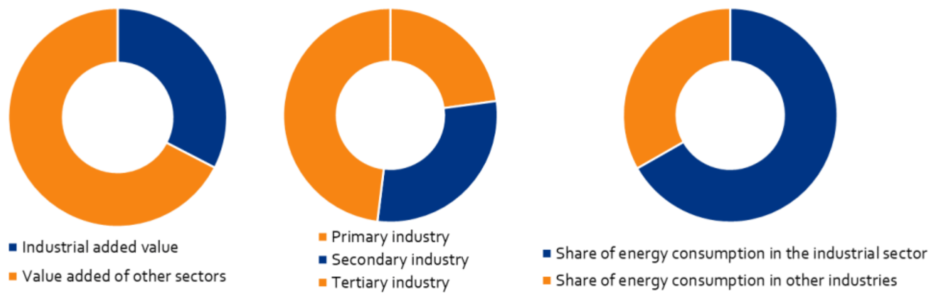
Energy consumption in specific end-use sectors is difficult to replace directly with electricity but can be replaced by hydrogen or other fuels produced from renewable electricity, which is equivalent to indirect replacement with electricity. In the CNS2 scenario, the overall electrification rate of the end-use sectors, considering both direct and indirect substitution by electricity, could reach 79.8% in 2060. Among them, the electrification rate of the industrial, building and transport sectors reaches 69.2%, 96.9% and 84.1%, respectively.

4.3 Industrial sector

End-use energy consumption in the industrial sector peaks before 2030

The low-carbon transformation of the industrial sector is crucial for achieving carbon peaking and carbon neutrality. Serving as the linchpin of China's national development, the industrial sector sustains rapid economic and social growth, contributing over 30% of the GDP and employment. However, it is also a significant source of energy consumption and carbon emissions, which necessitates strategies for carbon peaking and neutrality. A broad, comprehensive transition process is required to achieve deep decarbonisation in the industrial sector. This process requires extensive innovation in concepts, technologies, models, and pathways. Efforts need to be made in industrial upgrading, demand reduction, energy efficiency improvement, and energy substitution.

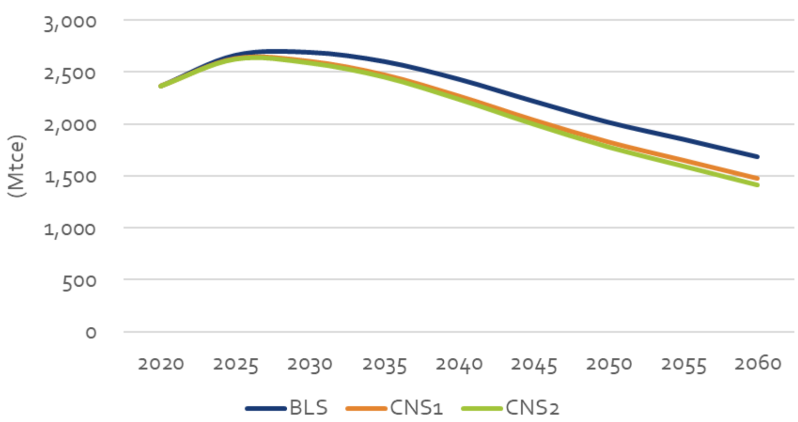
Figure 4-3 2020 Proportions of value added, employment, and energy consumption in the industrial Sector



Data Source: China Statistical Yearbook

In the BLS scenario, industrial energy demand increases from 2.37 Btce in 2020 to a peak of approximately 2.7 Btce by 2030 before declining to 1.68 Btce by 2060. In the CNS1 and CNS2 scenarios, industrial energy demand peaks around 2025 at approximately 2.63 Btce. By 2060, industrial energy demand declines to 1.47 billion and 1.42 Btce in the CNS1 and CNS2 scenarios, respectively.

Figure 4-4 2020-2060 Energy consumption demand of industrial sector



The industrial sector's low-carbon transformation significantly impacts China's industrial landscape and production structure. This transformation modifies existing production functions and factor supply conditions, restructuring regional comparative advantages and development patterns. Factors such as industrial iteration, escalating factor costs, and heightened environmental and carbon constraints accelerate the transfer of high-carbon capacity. As a result, the abundant renewable energy resources in China's central and western regions emerge as a notable comparative advantage in the era of carbon neutrality. These regions form crucial bases for resource/capital-intensive industries. By 2060, these regions have over 50% of electric arc furnace steel capacity, more than 60% of electrolytic aluminium capacity, and over 70% of synthetic ammonia and other chemical industry capacities. This facilitates the local utilisation of green electricity and green hydrogen resources, enabling deep decarbonisation of industrial products. In turn, this stimulates leapfrog development and low-carbon prosperity in relevant regions.

Four Pathways to Carbon Neutrality in the Industrial Sector

Gradual transition of the industrial economy towards high-end, intensive, and service-oriented development

China's industrial system has successfully weathered various pressure tests over the past decade, including international trade disputes and the COVID-19 pandemic. The country has emerged as a global model for high-quality industrial development and is committed to promoting industrial structural optimisation, scale reduction, and the evolution towards a service-oriented economy. By 2060, China's industrial sector embodies characteristics of high-end, intensive, and service-oriented development. The contribution of high-value-added industries such as pharmaceuticals, machinery manufacturing, and electronic products rises from less than 35% in 2020 to over 50%. In contrast, traditional energy-intensive industries like steel, cement, petrochemicals, and non-ferrous metals witness a decrease in their contribution from nearly 40% in 2020 to below 30%. Additionally, the production volumes of associated energy-intensive products gradually reach their peak during the *14th Five-Year Plan* period (2021-2025) and then reduce by 30% to 50% by 2060.

Figure 4-5 Comparison of 2020 and 2060 value-added structures in the industrial sector

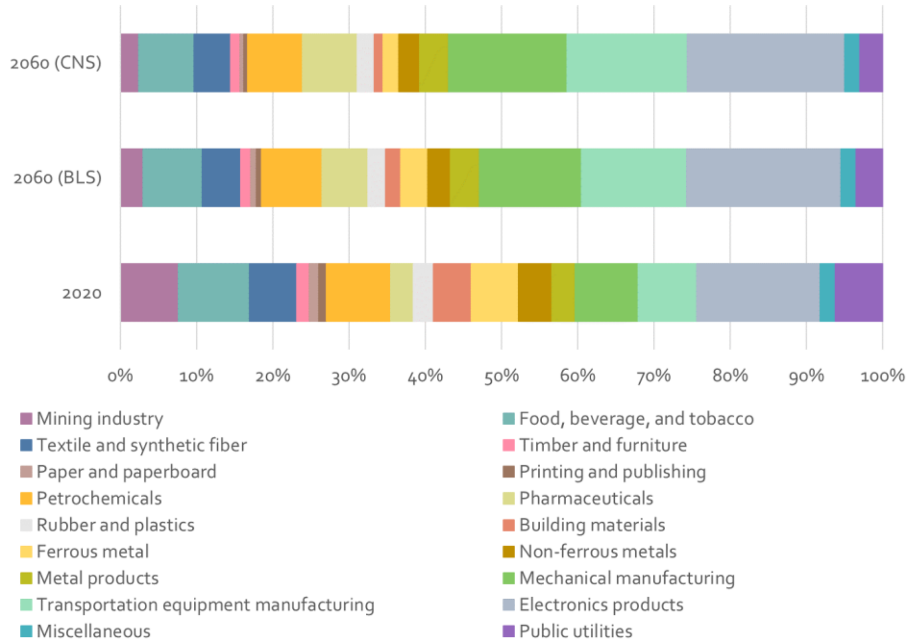
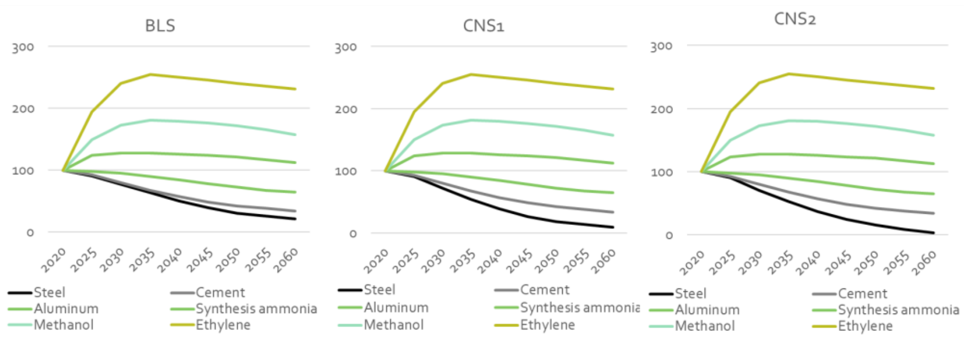


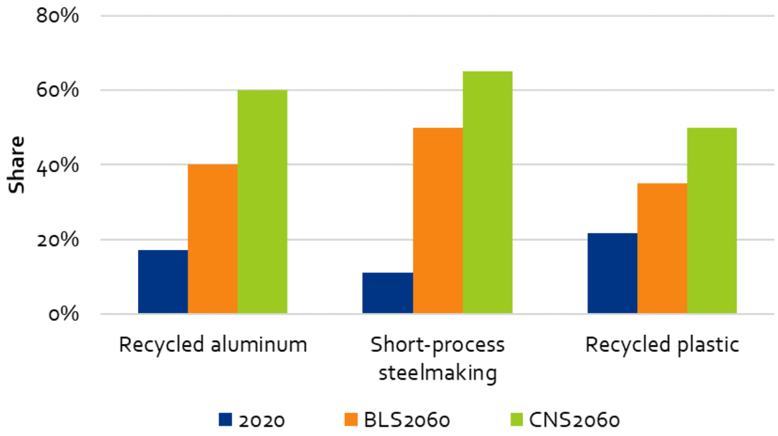
Figure 4-6 2020-2060 Index changes in the production volumes of major energy-intensive products



Circular coupling as a new form of industrial development and process transformation

China's industrial circular development system has made significant strides in recent years. The proportions of recycled aluminium, electric arc furnace steel, and recycled plastics reached 17%, 11%, and 22% respectively in 2020. During the *13th Five-Year Plan* period (2016-2020), the comprehensive contribution of the circular economy to carbon emissions reduction reached 25%. The circular economy is a new form of industrial development that embraces the principles of reduction, recycling, and reuse. It catalyses the transition of process structures from primary to recycled resources, thereby reducing waste and conserving resources. By 2060, under the BLS scenario, the proportions of recycled aluminium, electric arc furnace steel, and recycled plastics in total production increases to around 40%, 50%, and 35% respectively. Under the CNS scenarios, with more robust low-carbon policy efforts, these proportions further increase to approximately 60%, 65%, and 50% by 2060.

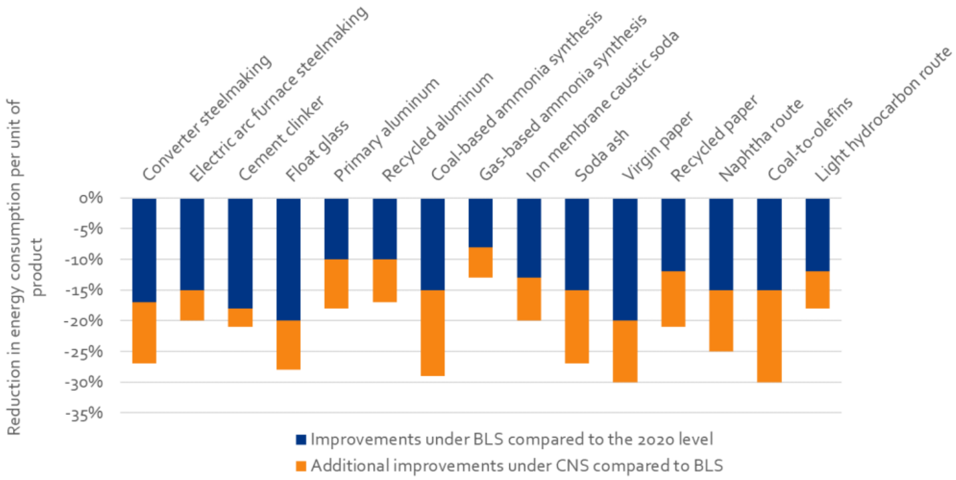
Figure 4-7 Proportions of recycled resources in major product processes in 2020 and 2060



Continuous improvement of energy utilisation efficiency through intelligent manufacturing and advanced production technologies

China has made significant progress in energy efficiency in the industrial sector. The energy efficiency levels of major energy-intensive products have improved remarkably, and this trend continues in the new wave of the industrial revolution, characterised by intelligence, digitization, and networking. Under the BLS scenario, the energy efficiency of major products increases by 15%-25% compared to the 2020 level by 2060. In the CNS scenarios, there is significant potential for further energy efficiency improvements through the deep application of intelligent manufacturing, advanced production technologies, equipment, and business models, particularly digital upgrades. By 2060, the energy efficiency of major products increases by an additional 10%-15% compared to the BLS scenario. This progress positions China as a leader in global industrial energy efficiency, establishing a cluster of world-class, energy-efficient factories.

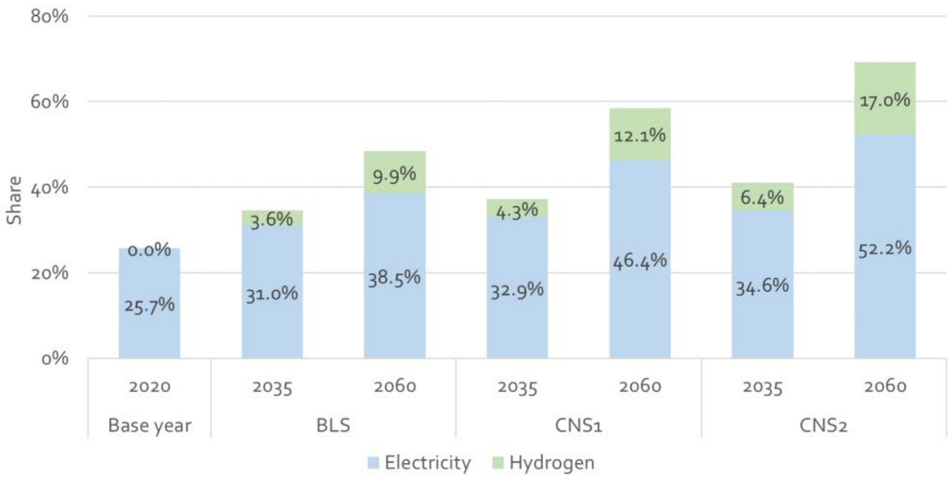
Figure 4-8 Decrease in per unit energy consumption of major product in 2060 compared to the 2020 level



Electrification and hydrogen poised to transform energy consumption in the industrial sector

Over the years, China has been diligently refining the energy consumption structure of its industrial sector, leading to a continuous reduction in the proportion of coal in the energy mix, which stood at 56% in 2021. The proportion of coal continues to decrease in the future, as the nation pivots towards utilising methods that are clean, efficient, environmentally friendly, and low in carbon emissions. Electrification and hydrogen spearhead a revolution in the industrial sector's energy consumption. Under the BLS scenario, by 2060, the rate of electrification and the proportion of hydrogen reach 38.5% and 9.9%, respectively. In the CNS1 and CNS2 scenarios, buoyed by the wide application of electric heating technology and a significant drop in the cost of green hydrogen, the electrification rate and the proportion of hydrogen surges even higher, reaching 46.4% and 12.1% under the CNS1 scenario, and 52.2% and 17.0% under the CNS2 scenario by 2060.

Figure 4-9 2020-2060 Proportions of electricity and hydrogen demand in the industrial sector



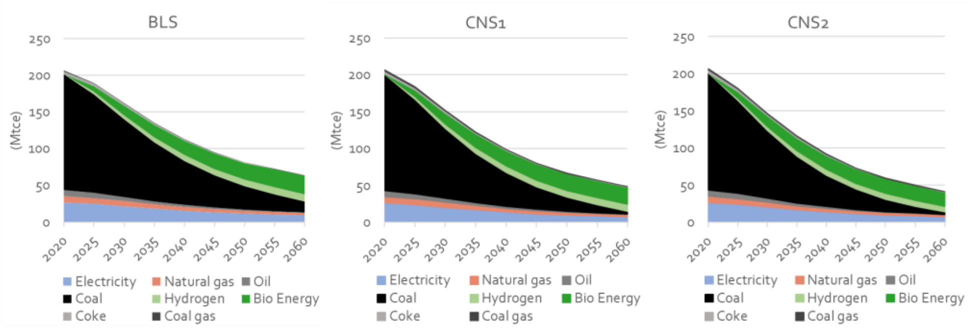
Deep decarbonisation pathways for typical industries

The cement industry: Moving towards near-zero coal consumption and emissions

The cement industry is an essential foundational industry in China's national economy and one of the highest carbon-emitting and energy-consuming industrial sectors. In 2020, the cement industry's carbon emissions reached almost 1.4 billion tons. Contrary to other industries, the bulk of the cement industry's carbon emissions originate from the production process itself, particularly limestone calcination to produce quicklime, contributing to 55%-70% of total carbon emissions during the total production process, while the energy activity of calcination only accounts for about 25-40% of the carbon emissions due to fuel consumption. Hence, deep decarbonisation of the cement industry presents substantial challenges.

The Chinese cement industry aims to achieve deep decarbonisation by adopting strategies such as utilising low-carbon clinker, accelerating the substitution of raw materials and fuels, and promoting the coordinated disposal of solid waste and hazardous waste in kilns. Under the BLS scenario, the energy consumption of the cement industry in 2060 is estimated to be approximately 63.4 Mtce, with biomass energy, hydrogen, coal and electricity contributing around 39.4%, 24.1%, 15.4%, and 14.2%, respectively. Under the CNS1 scenario, effective promotion of energy-saving technologies reduces the energy demand of the cement industry to 48.2 Mtce by 2060, with biomass energy, hydrogen, coal, and electricity contributing approximately 48.0%, 20.0%, 8.5%, and 16.0%, respectively. The CNS2 scenario, boosted by increased electrification, projects the energy demand of the cement industry in 2060 at 41.2 Mtce, with biomass energy, hydrogen, coal, and electricity contributing around 46.8%, 19.2%, 7.8%, and 19.0%, respectively.

Figure 4-10 2020-2060 Energy consumption demand of cement industry by fuel

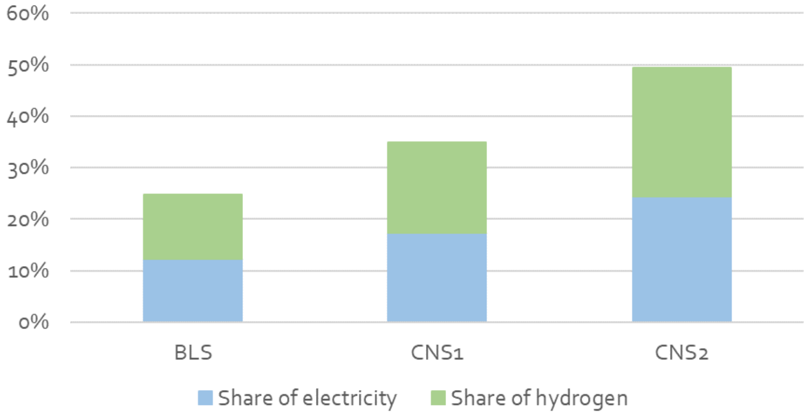


The petrochemical industry: Embracing circularity, carbon sequestration, and high electrification and hydrogen utilisation

The petrochemical industry, one of China's high-energy-consuming sectors, continues expanding to meet material demand and address supply-demand disparities. The production volumes of products like ethylene and methanol grow further, possibly until 2035 or beyond. Owing to the complex production processes and carbon emissions in the petrochemical industry, particularly the significant energy consumption and high-temperature heat demands, as well as emissions from industrial processes and non- CO_2 emissions, achieving deep decarbonisation requires comprehensive measures, including reduction, recycling, and energy and process transformation.

Deep decarbonisation in the petrochemical industry is driven by supply-demand dynamics. On the demand side, there is an urgent need to improve the recycling of waste plastics and tires, coupled with the implementation of plastic reduction and plastic ban policies to reduce the demand for basic chemical raw materials such as olefins and aromatics. In the CNS scenarios, the proportion of recycled plastics and tire production exceeds 40% by 2060. The application of digital technology and advanced equipment is also crucial to achieve precision management, "molecular refining," and cascading energy utilisation. On the supply side, there are several aspects to consider. Firstly, it is essential to promote the development of process technologies such as "replacing grey hydrogen with green hydrogen" and the coupling of green hydrogen with carbon dioxide in chemical processes, thereby facilitating the application of the "carbon sequestration through hydrogen" model in different production processes. Secondly, for medium and low-grade heat requirements, efforts should be made to replace fossil energy with electrification technologies such as heat pumps and electric heating, thus enhancing the level of electrification. Lastly, the utilisation of light hydrocarbons and hydrogen-rich raw materials should be steadily promoted. Figure 4-11 illustrates the electrification and hydrogen utilisation levels in the petrochemical industry in 2060 under different scenarios. It is worth noting that hydrogen plays a dual role as a zero-carbon raw material and zero-carbon fuel, marking a significant stride towards achieving deep decarbonisation in the petrochemical industry.

Figure 4-11 Proportions of electricity and hydrogen consumption in the petrochemical industry in 2060



4.4 Transportation sector

The future growth of the transportation sector hinges on the freight turnover and new demand for travel, both of which continue to fuel energy consumption and carbon emissions. A peak in this upward trend takes place around 2030. By 2060, the count of motor vehicles per thousand people surpasses 400, aligning with levels seen in moderately developed countries. Alongside this, the structure of transportation is further optimised, with high-speed rail playing a crucial role in intercity passenger transport. High-speed rail offers significant energy-saving and carbon efits compared to air travel. Even by 2060, sectors like aviation, maritime, and heavy-duty trucks continue to consume substantial amounts of oil. Nevertheless, innovations such as transportation electrification, electric synthetic fuels, and biofuels play a significant role in reducing carbon emissions within the sector. By 2060, electricity becomes the primary end-use energy source for transportation, with ammonia dominating the energy consumption structure of water transportation. Under the CNS2 scenario, the use of hydrogen becomes more widespread, significantly aiding in the reduction of carbon emissions within the transportation sector.

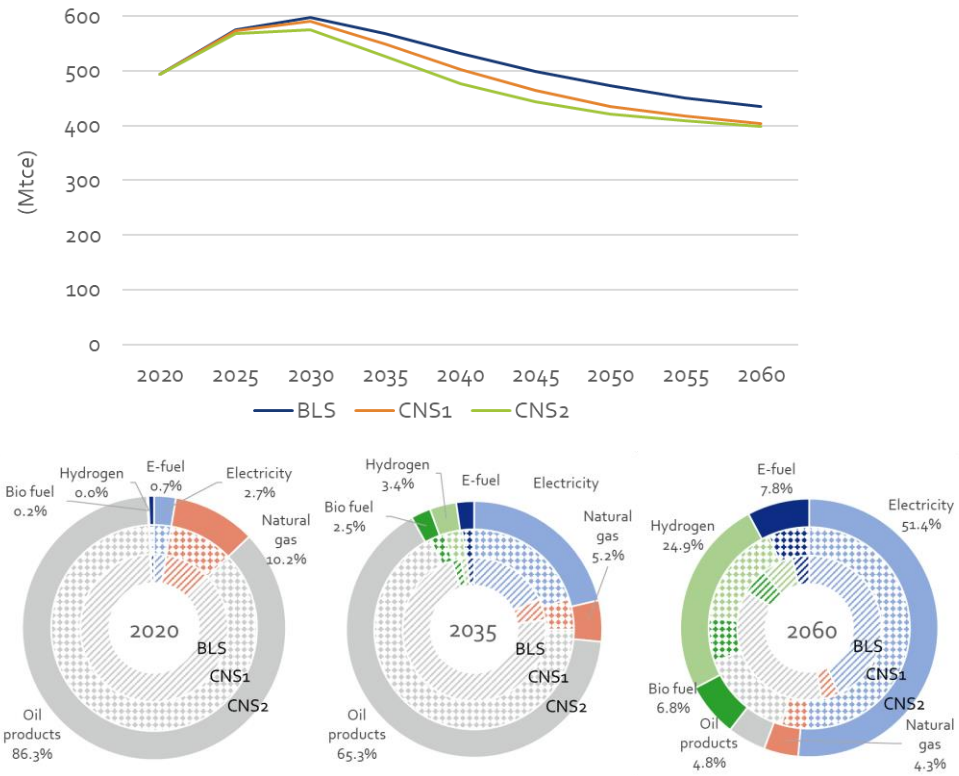
Transportation energy demand slowly declines after reaching its peak around 2030

In all scenarios, the end-use energy demand in the transportation sector peaks around 2030.

By energy type

Under the BLS scenario, the energy consumption of the transportation sector rises to its peak of approximately 598 Mtce by 2030 before falling to 435 Mtce by 2060. In the CNS1 scenario, peak energy consumption is around 590 Mtce by 2030, decreasing to 405 Mtce by 2060. The CNS2 scenario anticipates peak energy consumption at roughly 574 Mtce by 2030, dropping to 399 Mtce by 2060 (see Figure 4-12).

Figure 4-12 End-use energy demands and energy mix for transportation



Post-2035, electricity becomes the cornerstone of the energy mix. Under the CNS2 scenario, by 2060, electricity's share expands to 51.4%, while oil's share decreases to 4.8%. The share of biofuels rises to 6.8%, and hydrogen grows to 24.9%. PtX constitutes 7.8% of the energy mix.

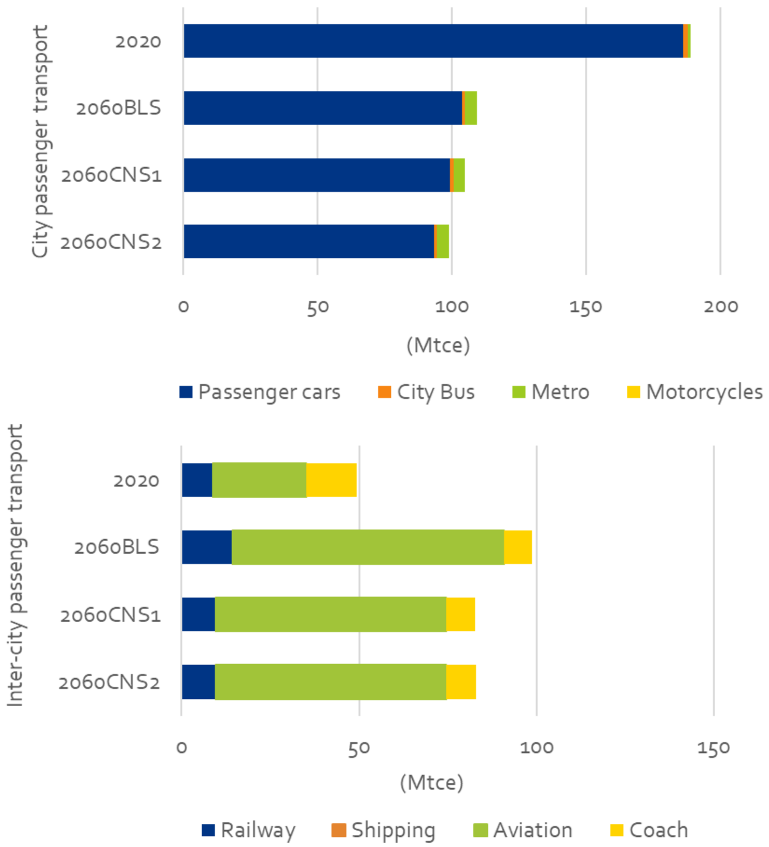
By transportation target

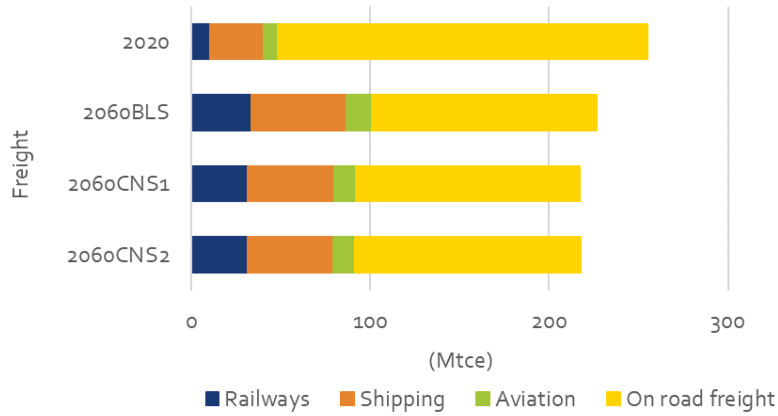
Under the BLS scenario, energy demand from passenger transportation decreases from 238 Mtce in 2020 to 208 Mtce by 2060. The CNS2 scenario estimates a drop to 182 Mtce (see Figure 4-13). Passenger cars, including private cars and taxis, continue to account for most of the energy demand during the forecast period, but their energy demand decreases in both scenarios due to increasing electrification rates.

Freight transportation's energy demand shows a different trend from passenger transportation. Freight energy demand rises gradually from 255 Mtce in 2020, peaking around 2030 at 285 million tons and 281 Mtce in the BLS and CNS2 scenarios, respectively, before declining. In both scenarios, energy demand drops to 227 and 218 Mtce, respectively, by 2060.

Road transport, primarily trucks, remains the dominant energy consumption entity of freight transportation. However, the proportion of total freight energy demand by trucks decreases from 81% in 2020 to between 55%-58% by 2060. Across all scenarios, steady growth is shown in the proportions of waterborne and aviation in the freight energy demand, increasing from 11.6% and 3.3% in 2020 to 22%-23% and 5.6%-6.2% by 2060, respectively. A significant increase in the proportion of railway freight energy consumption, rising from 4.9% in 2020 to between 14.4%-14.9% by 2060.

Figure 4-13 2020 and 2060 Energy demands for various modes of transportation

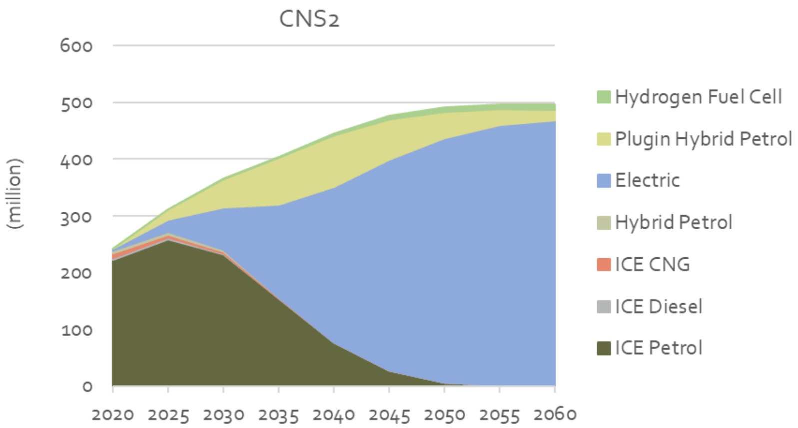




Growth in diverse travel demands

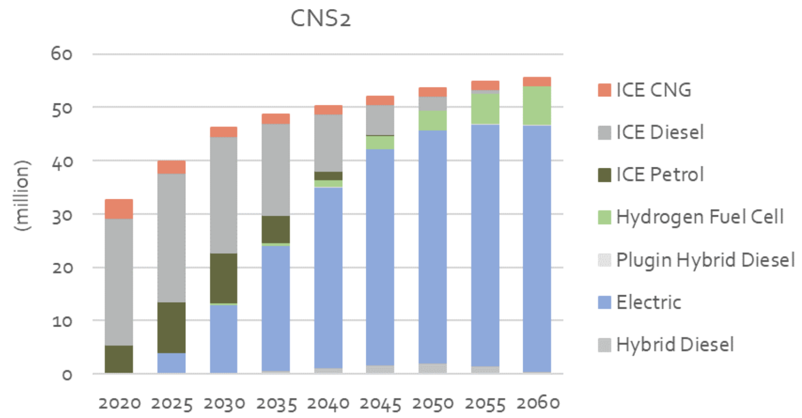
Mitigating the sharp rise in transportation energy demand necessitates controlling vehicle ownership growth. Current trends indicate that car ownership growth decelerates by 2035, with the growth in passenger car ownership slowing further and reaching saturation by 2050. By 2035, the number of passenger cars in China reaches 404 million (including 403 million private cars and approximately 1.6 million taxis). By 2060, the number of passenger cars increases to 497 million, nearly doubling the 2020 count (see Figure 4-14).

Figure 4-14 2020-2060 Passenger car stock in CNS2



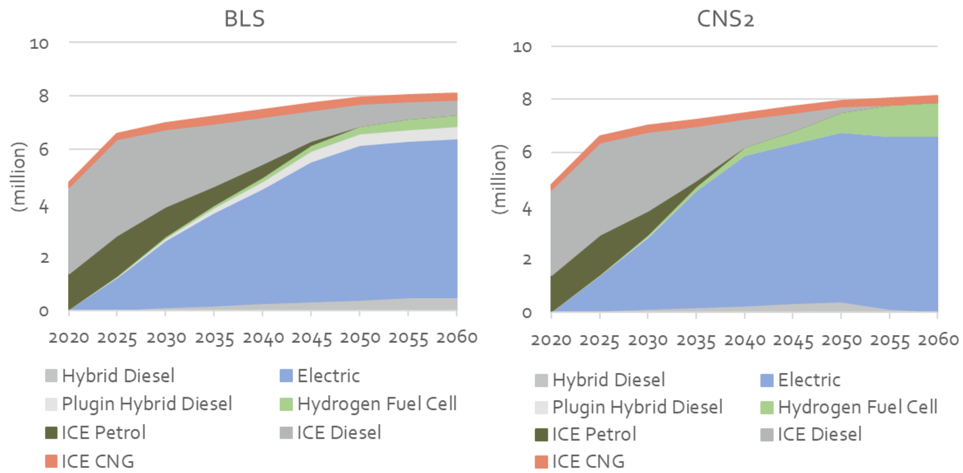
Although the number of trucks remains consistent across different scenarios, their energy consumption structures differ. In 2020, there were 32.61 million trucks, 73% of which were diesel trucks (23.8 million). By 2060, the proportion of diesel trucks drops significantly, reaching 7% in the BLS scenario and 2% in the CNS2 scenario. Conversely, the number of electric trucks increases, accounting for 75% in the BLS scenario and 83% in the CNS2 scenario (see Figure 4-15).

Figure 4-15 2020-2060 Truck stock in CNS2



Across all scenarios, truck ownership shows a gradual upward trend. In 2020, the truck count was 32.61 million, and it reaches 46.12 million by 2030 and 55.55 million by 2060. In terms of types, there are substantial differences in the medium-to-long-term increments for hydrogen fuel cell, plug-in hybrid, and electric trucks between scenarios. Under the BLS scenario, additional consumption for these three categories by 2030 are at 52,400 units, 94,800 units, and 2.5 million units, respectively. By 2060, these numbers increase to 428,000 units, 444,000 units, and 5.96 million units, respectively. Under the CNS2 scenario, hydrogen fuel cell and electric trucks play more significant roles, with consumption by 2030 at 72,600 units and 2.72 million units, respectively. The increments rise to 1.25 million units and 6.59 million units by 2060 (see Figure 4-16).

Figure 4-16 2020-2060 Number of incremental truck use

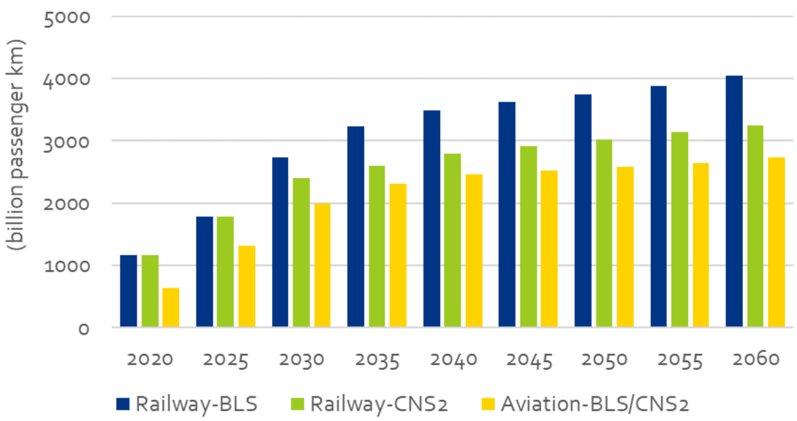


Energy-efficient and low-carbon modes are gaining increasing shares in the transportation structure

Promoting railway travel for personal commutes

High-speed rail plays a pivotal role in intercity passenger transportation. Non-road modes of transit, especially air travel, rapidly surge in passenger volume throughout the forecast period. As prosperity increases, both domestic and international air travel by Chinese individuals is predicted to rise. However, considering factors like better infrastructure, strategic high-speed rail station locations, superior luggage capacity, and quicker boarding processes, high-speed rail presents a competitive alternative to air travel for journeys approximately 800 kilometres in length. From an energy efficiency standpoint, travelling by high-speed rail is a preferable choice. Looking ahead, high-speed rail plays an even more prominent role in intercity transportation (see Figure 4-17).

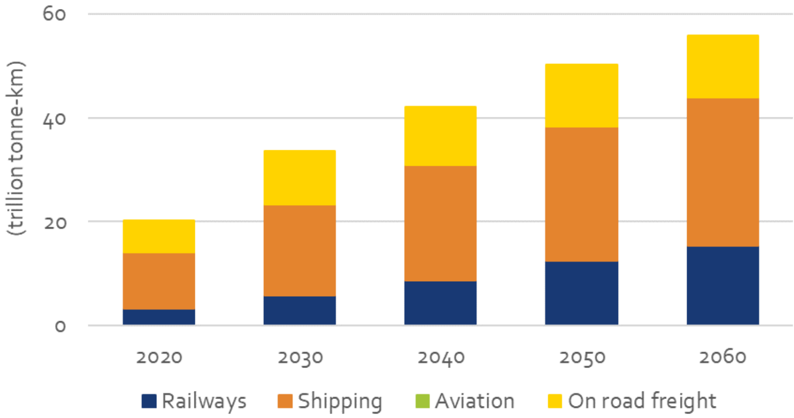
Figure 4-17 2020-2060 Growth of air and rail passenger turnover



Water transportation as the primary mode for freight transport

Freight transportation demand is intrinsically linked to economic development. By 2060, the total freight turnover reaches 56 trillion ton-kilometres, with water transportation accounting for 57%. As water transportation maintains its status as the predominant mode for freight, the proportion of road freight transportation remains relatively stable, with slow growth anticipated post-2040 through to 2060. Freight transportation shift towards more energy-efficient modes such as water and rail, with predicted increases of 160% and 385% respectively by 2060 compared to 2020 (see Figure 4-18).

Figure 4-18 2020-2060 Changes of freight turnover



Diversified development of transportation fuel structure reduces dependence on oil products

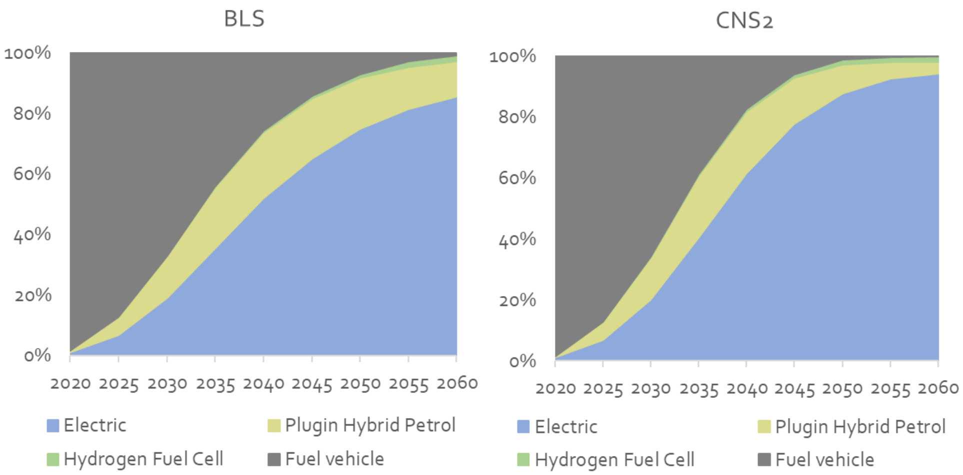
Accelerating the adoption of electric vehicles

Numerous Chinese cities have implemented policies to encourage the purchase of new energy vehicles, including facilitating license plate applications, exemptions from traffic restrictions, and reductions in vehicle purchase taxes. To accelerate China's carbon neutrality goals, the popularisation of electric vehicles needs to be further strengthened. Traditional hybrid vehicles, which still require fossil fuels to provide 100% of the fuel, should not be classified as new energy vehicles. In addition, plug-in hybrid vehicles, which still partially rely on fossil fuels and inefficient internal combustion engine technology for fuel supply.

With respect to future market share of private cars under different scenarios, a consistent trend is the gradual diminution in the proportion of gasoline vehicles, alongside a rapid surge in the proportion of electric vehicles. The percentage of plug-in hybrid vehicles initially sees an increase (from 2020 to 2040) before witnessing a decline (from 2040 to 2060). Under the BLS scenario, the proportion of electric vehicles and plug-in hybrid vehicles in 2060 stands at 85% and 12%, respectively. In contrast, under the CNS2 scenario, the proportion of electric vehicles is higher, attaining 94%, while plug-in hybrid vehicles are largely superseded, representing a mere 4%.

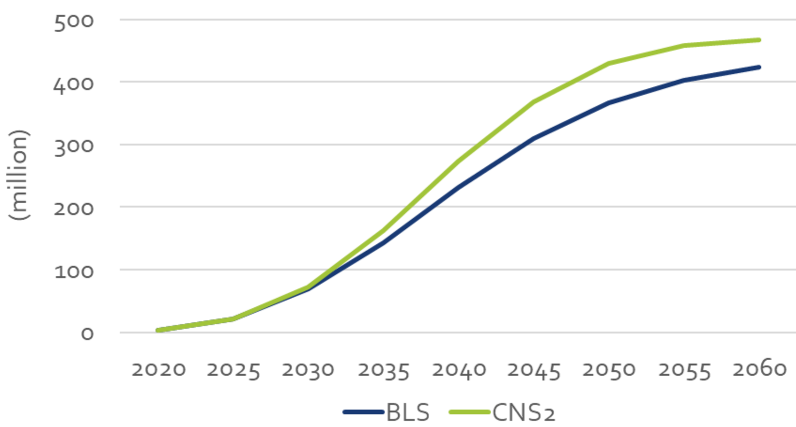
Moreover, under the CNS2 scenario, by 2060, gasoline vehicles are entirely phased out, replaced exclusively by new energy vehicles (see Figure 4-19).

Figure 4-19 Market share of private cars by fuel type



By 2060, in the BLS scenario, the number of pure electric cars reaches at 420 million units, while in the CNS2 scenario, it's to reach 470 million units (see Figure 4-20). Beyond that, there are also a small number of plug-in hybrid vehicles and a negligible number of hydrogen fuel cell vehicles.

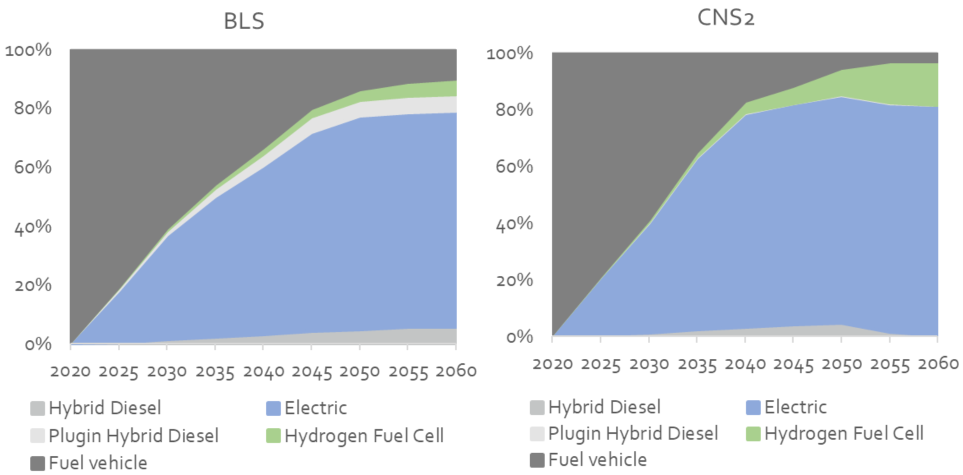
Figure 4-20 2020-2060 Ownership of electric vehicles



China's road freight vehicles increasingly adopt environmentally friendly fuels. Urban light-duty delivery trucks have already begun transitioning to pure electric vehicles.

By 2060, under the BLS scenario, pure electric trucks constitute the majority of vehicles (73%), with hydrogen fuel cell trucks and plug-in hybrid trucks each holding a market share of around 5%. Fuel trucks maintain approximately 10% of the market. The greening process is more profound under the CNS2 scenario. By the later phases of this scenario, the share of pure electric trucks rises to 81%, and hydrogen fuel cell trucks, fulfilling the needs of long-distance driving that pure electric vehicles can't meet, constitute 15% of the market by 2060.

Figure 4-21 2020-2060 Truck sales by fuel type



Application of P2X fuels in aviation and maritime

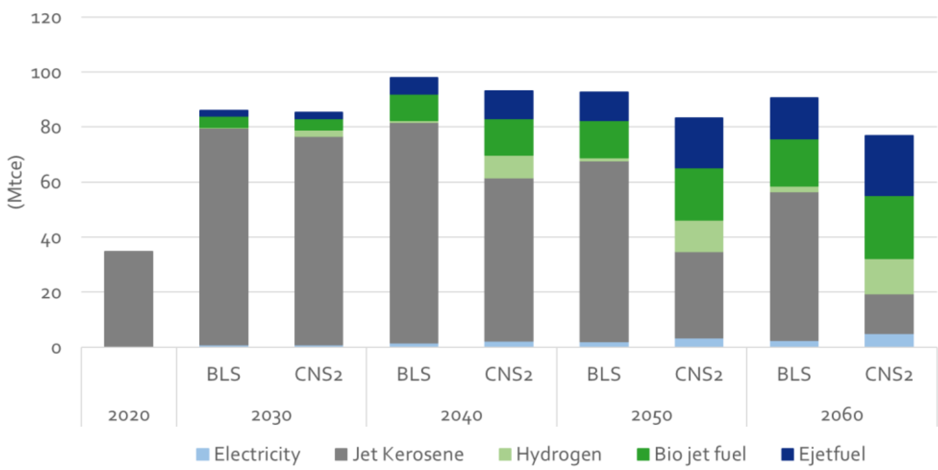
Aviation transportation has heavily relied on aviation kerosene as fuel since the advent of jet engines. Due to the stringent requirements for the volume, weight, and energy density of aviation fuel, achieving a low-carbon transformation presents significant challenges. At present, alternative aviation fuels are emerging, albeit with negligible market share. However, their proportion significantly increases with anticipated cost reductions.

Short-haul flights can benefit from pure electric technology, which, due to its lower maintenance needs, quickly becomes competitive. Under the BLS and CNS2 scenarios, the proportion of electric technology is 2.7% and 6.3% by 2060, respectively.

Longer domestic flights are likely to adopt biomass and hydrogen as alternative solutions. By 2060, the shares of biofuels and electrically produced fuels rise incrementally. Under the BLS scenario, the shares of biomass and electrically produced fuels increase from 4.9% and 2.4% in 2020 to 19.0% and 16.5%, respectively, by 2060. The share of aviation kerosene drops from 100% in 2020 to around 60% in 2060.

In the CNS2 scenario, a higher proportion of zero-carbon fuels is employed. By 2060, biofuels and electrically produced fuels are predicted to make up 28%-30% of the total, while hydrogen contributes around 17%. Aviation kerosene's share drops to less than 20%, further reducing reliance on fossil fuels (see Figure 4-22).

Figure 4-22 2020-2060 Aviation fuel demand (incl. passenger transport and freight)

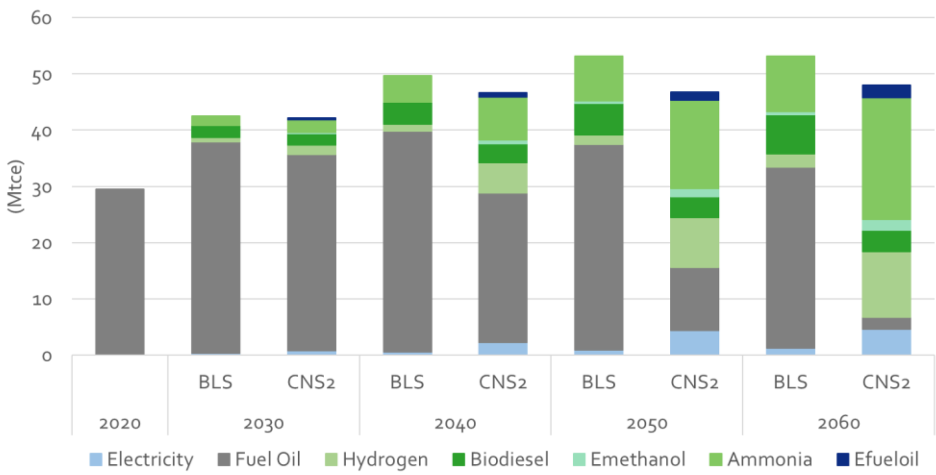


China, the world's largest maritime nation, consumes considerable amounts of petroleum products in transporting goods along major rivers and in international shipping. The volume of freight shipping activities grows, while passenger shipping activities remain relatively insignificant and can be largely overlooked.

The maritime industry also faces hurdles in achieving net-zero emissions. Yet, substantial emission reductions are achieved by low-carbon fuels such as biofuels, hydrogen, and ammonia. Pure electric technology is utilised for some short-haul maritime journeys. Diesel made from hydrogen can power older ships, while newer ships consume ammonia.

Under the BLS scenario, the use of electrically produced fuels, ammonia, and biodiesel gradually increases. By 2060, non-fossil energy sources substitute about 40% of current fuels. In the CNS2 scenario, the substitution rate for non-fossil energy sources is more robust, with ammonia, hydrogen, electrically produced methanol, and electrically produced fuel oil (Efuel oil) gaining larger market shares. Although petroleum products continues to represent over 57% of the total before 2040, by 2060, their proportion diminishes to less than 5%. In contrast, the shares of hydrogen and ammonia reach approximately 24% and 45%, respectively, thus satisfying a significant portion of maritime fuel demand.

Figure 4-23 2020-2060 Maritime fuel demand



Box 4-1 Hydrogen energy development in China's transportation sector

Current status of hydrogen energy utilisation in China's transportation industry

The transportation industry is a critical sector for hydrogen energy application. Despite China's swift progress in commercial vehicles and technological breakthroughs in aviation, maritime, and railway, overall utilisation of hydrogen energy in the transportation industry remains relatively limited, still in the demonstration and promotion stage.

The number of hydrogen fuel cell vehicles in China has grown steadily, reaching 8,939 vehicles in 2021, ranking third globally. By 2022, the cumulative number of hydrogen fuel cell vehicles exceeded 10,000. Recently, China's hydrogen fuel cell vehicles have developed alongside electric vehicles, primarily targeting commercial vehicles such as heavy-duty trucks, buses, passenger cars, logistics vehicles, and engineering vehicles. The application of fuel cell technology in heavy-duty trucks weighing over 31 tons appears especially promising. The government has greenlit the establishment of five demonstration city clusters for hydrogen fuel cell vehicles and implemented a "substitute subsidies with awards" policy to boost fuel cell vehicle sales in the Beijing-Tianjin-Hebei, Guangdong, Shanghai, Hebei, and Henan city clusters, which helps form a "3+2" demonstration model for fuel cell vehicle development nationwide. These regions, with robust hydrogen fuel cell industry chains and policy support, will expedite the advancement and application of hydrogen energy in the transportation sector.

Regarding hydrogen refuelling stations, China has built a total of 358 stations as of the end of 2022, reflecting a growth of 40% compared to 2021. In 2022, a total of 103 new stations were constructed. Expanding hydrogen refuelling station infrastructure facilitates the popularisation and promotion of hydrogen fuel cell vehicles.

China is also advancing several demonstration projects using hydrogen-based fuels in maritime and railway fields, which creates new demand for hydrogen. In 2022, Jianglong Shipbuilding completed the construction of "Hydrogen Boat 1," a hydrogen fuel cell-powered workboat for China Yangtze Power Co. This vessel is the first domestically built hydrogen fuel cell-powered vessel with a total rated output power of 500 kilowatts, scheduled for trial sailing in April 2023. China's first fuel cell locomotive was successfully developed by Southwest Jiaotong University in January 2013. In October 2017, CRRC Tangshan Co., Ltd. developed the world's first commercially operated hydrogen fuel cell tram. In 2019, the world's first commercially operated hydrogen-powered tram was officially launched in Foshan, Guangdong. Overall, hydrogen-powered rail transportation is still in its nascent stages, yet with tremendous potential for future growth.

Future trends of hydrogen energy utilisation in China's transportation sector

China has devised a top-level strategy for hydrogen energy development, necessitating the orderly promotion of hydrogen energy applications in transportation as per the *Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry*. The *Plan* emphasises the application of hydrogen fuel cells in heavy-duty vehicles, expanding the use of hydrogen fuel cells and other new energy vehicles in passenger and freight vehicle markets, and establishing a complementary development model between fuel cell electric vehicles and lithium-ion battery electric vehicles. It also encourages the exploration of fuel cells in ships, aircraft, and other fields, promotes the research and development of large-scale hydrogen-powered aircraft, and continually broadens the market size of hydrogen energy applications in the transportation sector.

Throughout the *14th Five-Year Plan* period, the transportation sector prioritises promoting innovative and demonstrative applications of hydrogen energy. This includes exploring demonstration applications for hydrogen fuel cell truck transportation and the application verification of vehicles equipped with 70MPa hydrogen storage cylinders in high operational intensity areas with fixed travel routes, like mining sites, ports, and industrial parks. In suitable locations, pilot applications of fuel cell commercial vehicles can be introduced in public service sectors such as urban buses, logistics delivery vehicles, and sanitation vehicles. Aligning the ecological and environmental protection needs of key regions with power infrastructure conditions, the *Plan* also aims to examine the demonstrative application of hydrogen fuel cells in ships, aircraft, and other fields.

Hydrogen fuel cell vehicles represent a significant area for hydrogen energy application in transportation. From 2021 to 2025, hydrogen fuel cell vehicles enter an introduction phase in China, with industry development driven by demonstration city clusters and vehicle popularisation supported by policies. By 2025, the number of hydrogen fuel cell vehicles ranges between 50,000 and 100,000, with 1,000 hydrogen refuelling stations. By 2030, fuel cell vehicles reach approximately 1 million, with 5,000 hydrogen refuelling stations. It is estimated that from 2021 to 2025, the compound annual growth rate (CAGR) of China's hydrogen fuel cell vehicle market reaches 68%, with a market size of around RMB 80 billion. After 2030, fuel cell vehicles will achieve commercial operation.

In the maritime sector, hydrogen can be widely utilised through fuel cells, internal combustion engines, and other methods. Between 2030 and 2060, the proportion of hydrogen energy consumption in the maritime sector increases from 2% in 2030 to around 20%, second only to ammonia.

In the aviation sector, the widespread use of hydrogen is a distant prospect. It is estimated that hydrogen-powered aircraft will not attain regular commercial use until after 2040. Liquid e-fuels derived from renewable energy sources align more closely with the aviation sector's decarbonisation goals, and by 2050, pure hydrogen accounts for approximately 4% of aviation energy consumption. By 2050, the share of pure hydrogen and hydrogen-based e-fuels in the aviation industry's energy consumption is around 17%.

Challenges and uncertainties in hydrogen energy application

Technological maturity is a prerequisite for the widespread application of hydrogen energy. The *Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry* also emphasises the continual improvement of key core technologies, such as improving the reliability, stability, and durability of fuel cells, advancing key core technologies in hydrogen energy infrastructure, and promoting the demonstrative application and industrialization of advanced hydrogen energy technologies, essential equipment, and major products.

Cost-effectiveness remains the most significant challenge for widespread adoption of hydrogen energy. Currently, fuel cell vehicles are considerably more expensive than traditional fuel vehicles and electric vehicles, lacking cost advantages. Subsidies alone are inadequate to bridge the substantial price gap. However, as production volumes grow and technology advances, the cost of fuel cell vehicles drops continuously. Some predictions suggest that by 2030, fuel cell buses, logistics vehicles, and heavy-duty trucks reach cost parity with conventional fuel vehicles, which facilitates the popularisation and promotion of fuel cell vehicles.

Figure 4-24 Total cost of using buses in China

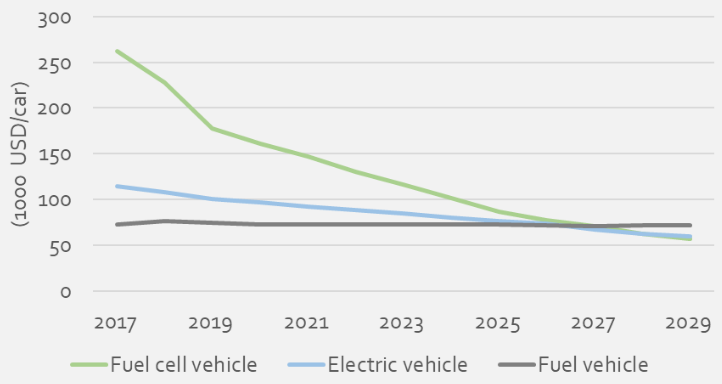


Figure 4-25 Estimation of gross profit rate of logistic vehicles in China

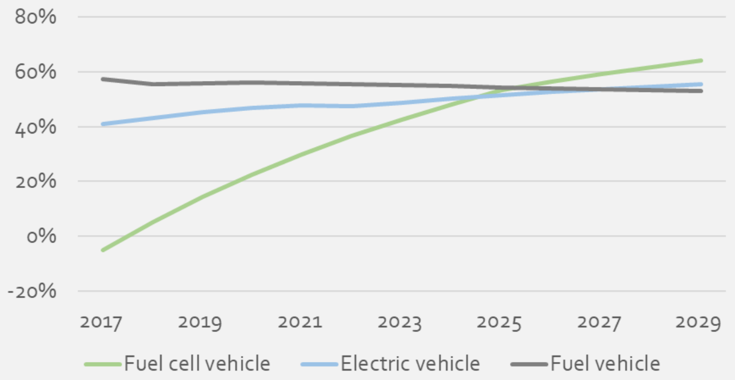
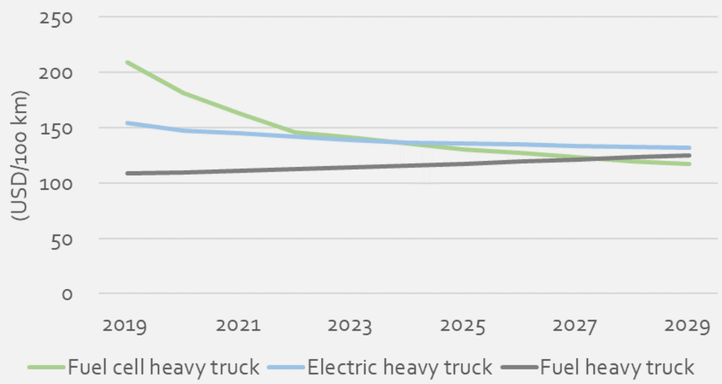


Figure 4-26 Total ownership cost of heavy-duty trucks



4.5 Building sector

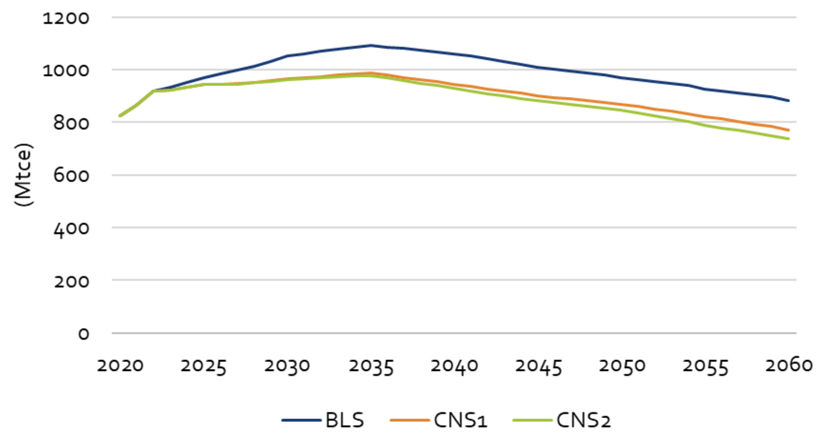
Energy consumption in the building sector shows a trend of initial increase followed by a decrease

Amidst continuous growth of the economy, ongoing urbanisation process, and a heightened focus on indoor environmental quality, energy demand within China's building sector climbs in the short to medium term. Nonetheless, the widespread adoption of energy-conservation technologies and products satisfies an increasing array of functional needs using reduced energy quantities over the long haul.

In line with the extant statistical benchmarks of the National Bureau of Statistics (NBS), the final energy consumption for the construction sector was reported at 680 Mtce in the year 2020. Yet, However, it is worth noting that there is approximately 140 million tons of non-commercialised biomass energy consumption in rural areas, which has not been included in the national energy consumption statistics. It is conceivable that this segment of energy usage may, in time, be assimilated into official energy statistics as it becomes commercialised. Additionally, industrial waste heat repurposed for building heating is derived as a secondary product of the industrial sector, with its energy utilisation already encapsulated in the industrial data. Consequently, this element should not be subjected to double-counting in the aggregation of total final energy consumption figures. However, in appraisals of the construction sector's final energy consumption, industrial waste heat is integrated as an auxiliary energy source and thereby included in its final energy utilisation metrics. In this vein, recalculating the final energy consumption for the construction sector in 2020 to encompass non-commercialised biomass in rural settings and industrial waste heat furnishes a figure of 820 Mtce.

In all three scenarios, the final energy consumption in the building sector first increases and then decreases, peaking around 2035. The peak values for final energy consumption in the building sector under the BLS, CNS1, and CNS2 scenarios are 1,090 Mtce, 990 Mtce, and 980 Mtce respectively, decreasing to 880 Mtce, 770 Mtce, and 740 Mtce respectively, by 2060. In the CNS2 scenario, the final energy consumption in the building sector in 2060 is 17% lower than that in the BLS scenario.

Figure 4-27 2020-2060 Total final energy consumption in the building sector



Scale development of ultra-low/near-zero energy buildings is key to reducing energy consumption in the building sector

To avoid the energy consumption lock-in effect, it is crucial that new buildings emphasise the development of ultra-low energy and near-zero energy buildings

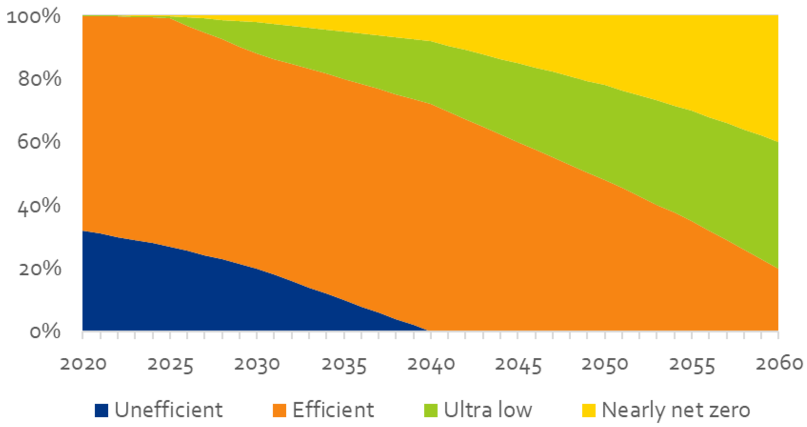
Ultra-low energy buildings and near-zero energy buildings achieve energy efficiency improvements of 50% and 60-75% or more, respectively, when compared to existing energy-saving standards for buildings. In the BLS scenario, the proportion of ultra-low energy and near-zero energy buildings in urban areas increases from less than 0.1% in 2020 to over 55% in future years. In the CNS1 and CNS2 scenarios, this proportion rises to over 75%. Currently, near-zero energy buildings are practically non-existent in rural areas. However, in the BLS scenario, the proportion of near-zero energy buildings in rural areas increases to 12% by 2060. In the CNS1 and CNS2 scenarios, this proportion reaches 25%.

The large-scale development of high-performance, energy-efficient buildings is paramount to reducing energy consumption in the building sector. In light of this, it is recommended that China bolster its top-level design for the development of ultra-low energy buildings, establish clear medium- and long-term development planning goals, and devise regional planning strategies, goals, and implementation paths that consider the differences in economic and technological development levels and industrial maturity across various regions. The exploration of pilot demonstrations of prefabricated ultra-low energy buildings should be encouraged, and large-scale promotion pilots for such buildings should be initiated. Incentive mechanisms ought to be improved to encourage the implementation of ultra-low energy and near-zero energy building standards in economically developed regions and government-invested projects. Furthermore, research and development of technical systems should be strengthened to provide industry support, with a particular focus on the localization of key components and equipment such as high-performance doors and windows, shading systems, insulation materials, and energy-efficient heat recovery ventilation equipment.

A shift from an "equal emphasis on construction and renovation" to a "renovation-first" mindset, coupled with the promotion of deep energy-saving and low-carbon refurbishments of existing buildings, is vital

Currently, approximately 36% of urban buildings in China are non-energy-efficient, with rural areas mostly comprised of similar buildings. The energy consumption for heating and cooling per unit of floor area in these buildings significantly exceeds that in energy-efficient buildings. Accelerating the transition to low-carbon in the building sector necessitates a deep energy-saving retrofit of existing buildings. In the BLS scenario, non-energy-efficient buildings in northern urban areas are eliminated before 2045. In the CNS1 and CNS2 scenarios, these buildings are phased out before 2040 (Figure 4-28).

Figure 4-28 2020-2060 Deployment of buildings with different energy efficiency Levels in northern urban areas (in CNS scenarios)



To this end, the concept and technologies of near-zero energy and ultra-low energy buildings should be incorporated into urban renewal, renovation of old neighbourhoods, and green rural housing construction while also strengthening the deep energy-saving retrofitting of existing buildings. Energy efficiency improvements, insulation of heating pipe networks, and intelligent control retrofits should be carried out on the user side in cold and severely cold regions. In regions with hot summers and cold winters or hot summers and mild winters, the retrofittingof shading systems in existing buildings warrants particular attention. For buildings with heating needs, the thermal insulation performance of the building envelope should be improved through energy-saving retrofitting, and simultaneous electrification should be implemented. Low-carbon and intelligent operation and maintenance retrofits of public buildings should be performed, and in rural areas, the promotion of clean heating should be combined with energy-saving retrofitting of rural housing.

Improving the thermal performance of rural housing and promoting passive rural housing construction are also critical

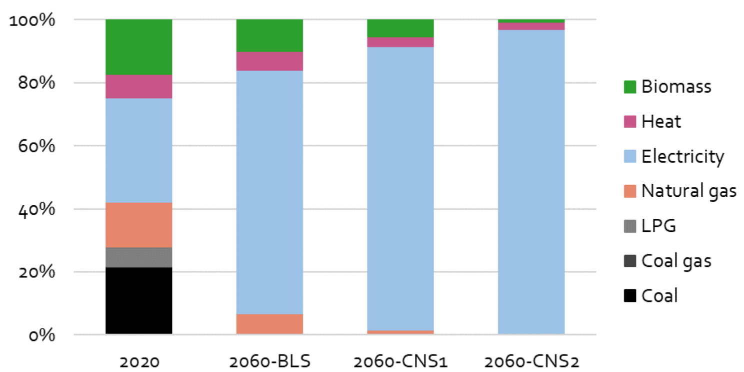
Compared to urban buildings, the thermal performance of low-cost rural housing is significantly inferior. At present, many rural buildings lack adequate heating systems, and those equipped with heating often only warm a portion of the space. As the economy grows and living standards continue to improve, the energy demand for heating in rural buildings inevitably rises. If rural buildings' poor insulation and thermal performance are not addressed, substantial energy wastage occurs. Since most rural buildings are single-family houses, promoting passive house construction in rural areas is an economically effective approach to energy conservation and carbon reduction. To achieve better comfort and energy efficiency, it is recommended to combine passive rural house designs with auxiliary heating sources such as heat pumps. Additionally, utilising various idle rooftops for installing rooftop photovoltaic systems and establishing rural direct current microgrids can effectively replace fossil fuel consumption (coal, gas, and oil) with renewable energy electricity, with the aim to achieve comprehensive electrification in such areas. By 2060, all rural energy needs are supplied entirely by zero-carbon electricity and renewable energy sources like biomass and solar energy.

Optimising the energy use structure in buildings to attain near-zero carbon emissions in the building sector as early as possible

Boosting the electrification rate and advancing electricity substitution tailored to regional specificities is paramount

In 2020, electricity consumption in China's building sector accounted for 30% of the total societal electricity consumption, with a per capita electricity consumption of 1,574 kWh. The proportion of electricity consumption in the building sector's end-use energy usage is 33.2%. The potential for growth in the sector's electrification rate is substantial. In the BLS scenario, the building sector's electricity consumption rises to 77.3% by 2060. In contrast, the CNS1 and CNS2 projections show this rate escalating to 89.9% and 96.9%, respectively (Figure 4-29).

Figure 4-29 2020-2060 Energy consumption structure in the building sector



To increase the building sector’s electrification leve, it is advisable for China to implement electrification simultaneously during the retrofitting process of existing buildings. This objective can be realised through the execution of building electrification projects, reserving adequate distribution network capacity, and replacing coal and gas with electricity for purposes such as residential cooking, sanitary hot water, and heating in line with regional conditions. Pilot programs and demonstrations showcasing novel building supply and distribution technologies, such as “distributed photovoltaic power generation systems, energy storage batteries, low-voltage DC distribution systems, and smart building electrical devices” (“solar, storage, DC, flexible power”), are to be encouraged. Furthermore, the use of renewable energy electricity for building heating (cooling), cooking, and hot water should be encouraged. Strengthening the demand-side response for electricity consumption is also crucial.

Improving the heat source structure and promoting low-carbon heating is another key factor

Heating represents the primary area of fossil fuel utilisation within the building sector, and enhancing energy use efficiency necessitates a swift transition to low-carbon and zero-carbon heat sources. Northern Chinese urban areas primarily use coal-fired combined heat and power (CHP) plants for heating, while a smaller portion relies on coal and gas boilers. Small coal stoves are still commonly used in rural areas for heating homes, presenting an urgent need for transitioning to low-carbon and zero-carbon heating solutions. Looking ahead, it is necessary to implement a differentiated low-carbon heating transition path. This approach must account for the diverse heating demands of different climatic zones and building types. In northern urban areas, fully utilising the existing centralised heating network resources is a key step in optimising the heat source structure. Substituting a portion of the coal-fired CHP and gas boilers with industrial waste heat and incorporating multi-energy complementary systems—such as sewage-source heat, geothermal energy, and solar energy—tailored to local conditions proves crucial for heating. Support should be directed towards transforming and upgrading traditional heating infrastructures while fostering the development of smart heating systems. For the northern rural areas, the promotion of clean heating practices should persist, and efforts to replace scattered coal with cleaner alternatives should be escalated. Alongside energy-efficient building insulation, initiatives like "coal-to-electricity" and "coal-to-biomass" that leverage renewable energy sources should be amplified. Heat pump technology, which extracts energy from air and geothermal resources for heating, emerges as the primary technical solution for ultra-low energy consumption buildings, in regions with hot summers and cold winters, and rural buildings. In the southern regions, decentralised heating methods should take precedence, with an emphasis on electricity as a gas substitute.

Currently, the contribution of industrial waste heat to heating in northern urban areas stands at about 1%. However, substantial market potential exists for supplanting coal and gas heating with industrial waste heat. In the BLS scenario, by 2060, the proportion of heating from industrial waste heat increases to 10%. In the CNS1 and CNS2 scenarios, these figures rise to 30% and 50%, respectively. In the BLS, CNS1, and CNS2 scenarios, by 2060, the proportion of rural heat pump heating in regions with hot summers and cold winters expands from the present 30% to 60%, 75%, and 100%, respectively.

Chapter 5

Transformation of the power sector

5 Transformation of the power sector

The decarbonisation of the power sector is pivotal for achieving net-zero emissions within the energy sector. On July 11, 2023, the Central Commission for Comprehensively Deepening Reform (CCDR) convened its second meeting and approved the *Guiding Opinions on Deepening the Reform of the Power System and Accelerating the Construction of a New Type of Power System*, underscoring the need for reforming the power system and expediting the establishment of a clean, low carbon, secure, efficient, coordinated, and intelligent new-type power system. Based on the CETO2023 study, the focus for this new system includes: 1) Expanding cost-effective, large-scale green electricity supply and consumption; 2) advancing flexible resources across diverse technological platforms and various time scales; 3) enhancing efficient and flexible electricity exchanges both interprovincially and interregionally; and 4) developing a robust power market system. This chapter delves into the essential technological pathways for constructing this new-type power system as illustrated by the EDO model. It addresses topics like clean transition of power supply and demand structure, ensuring adequate power supply through the exponential growth of wind and solar power, coal power transition, energy storage and demand response resources, and the supporting role played by power markets. This chapter also explores the necessity of deploying negative-carbon-emission power generation technologies.[e]

5.1 Key messages

- The power sector remains central to the future energy system. Transitioning into an eco-friendly, safe, and cost-efficient power sector is paramount for the goal of achieving net-zero emissions within the energy sector. Earliest by circa 2035, China is able to inaugurate this new-type power system, targeting an 50% above reliance on renewable energy in power generation, while ensuring both safety and reliability.
- A surge in electricity consumption is envisioned. All end-use sectors undergo substantial electrification. In CNS2, total electricity consumption reaches 16,200 TWh by 2035 and escalate to 20,200 TWh (incl. grid losses) by 2060. The electrification rate in end-use sectors hits 40% by 2035 and soars to exceed 65% by 2060.
- As the installed capacity for power generation grows, the power system witnesses a holistic clean transition. In CNS2, by 2060, China's cumulative installed capacity hits around 9,810 GW, reaching up to four times the present capacity, with non-fossil and renewable energy sources representing 99% and 98% of the total, respectively. In the total power generation, non-fossil energy and renewable energy accounts for 100% and 95%, respectively.

[e] The findings of this chapter are supported by the National Natural Science Foundation project (42201196).

- The cumulative installed capacity for wind and solar power surges, with both centralised and distributed projects being developed in equal emphasis. In CNS2, from 2025 to 2040, the average annual increase in new wind power installations in every five-year period reaches 100 GW, 150 GW, and 180 GW respectively. The average annual increase in new solar power installations in every five-year period stands at 120 GW, 210 GW, and 120 GW respectively. By 2060, the total installed capacity of wind and solar power reaches 4,200 GW and 4,800 GW respectively, with a combined total installed capacity of 9,000 GW, accounting for over 92% of total installed capacity.
- Both wind and solar power emerge as the most cost-effective electricity sources. By 2060, in CNS2, the levelised costs of electricity (LCOE) of onshore wind, offshore wind, and solar PV are 0.204 RMB/kWh, 0.211 RMB/kWh, and 0.143 RMB/kWh, respectively.
- By 2060, the retirement of all coal-fired power units takes place except to keep very small amount of system reserves. In CNS2, existing coal power units are either phased out or retrofitted into flexible power sources. Flexible coal power continues to play a significant role in power system regulation before 2040, after which their operating hours decreases to below 1,000 hours. In 2060, power system regulation no longer relies on coal power.
- Flexible resources witness widespread and diverse development. In CNS2, by 2035, total capacity of pumped storage, new-type energy storage and demand side response exceeds 1,400 GW, with flexible coal power and pumped storage still being the main regulating power sources. By 2060, total capacity of flexible resources reaches nearly 2,900 GW, with energy storage across multiple timescales, demand response, and electrolytic hydrogen production all becoming the mainstays of power system regulation.
- The new-type energy storage and demand side response both have entered the full-scaled-up development phase between 2025 and 2030. In CNS2, the average annual growth rate of EV smart charge, electrochemical storage, and electric boiler and heat pump capacity reaches 21%, 18% and 14%, respectively. By 2050, the capacity of EV-based flexible resources reaches the peak plateau, while the capacity of electrochemical storage continues to grow, whose installed capacity is doubled by 2060 in CNS2.
- Moving forward, the existing pattern of west-to-east and north-to-south power transmission in China persists. By 2060, East and Central China's electricity intake is twice today's levels. The grid persists as the pivotal link between electricity generation and consumption, ensuring synchronised planning between power infrastructure development and demand growth. This facilitates both centralised and distributed power usage, enable diverse power resources to be consumed

locally and across distances, and promote a more extensive distribution of clean, low-carbon energy.

- A unified national power market system is established to promote the development of various resources in the power system. Long and medium-term contract markets, spot markets and ancillary service markets are improved, with renewable energy, flexible and distributed resources fully participating in market transactions. The green certificate market mechanism is optimised to reflect the green premium of renewable energy power scientifically. Seamless coordination between power and carbon markets is strengthened through synergistic policies and mechanisms.
- Deploying negative-carbon-emission technologies such as carbon capture and storage (CCS) is an important means of achieving net-zero emissions in the energy system. In CNS2, the total installed capacity of biomass power CCS reaches 67 GW. Deploying CCS for thermal power is a necessary measure during the natural retirement period of coal power units, but its associated energy consumption and high costs should not be overlooked.

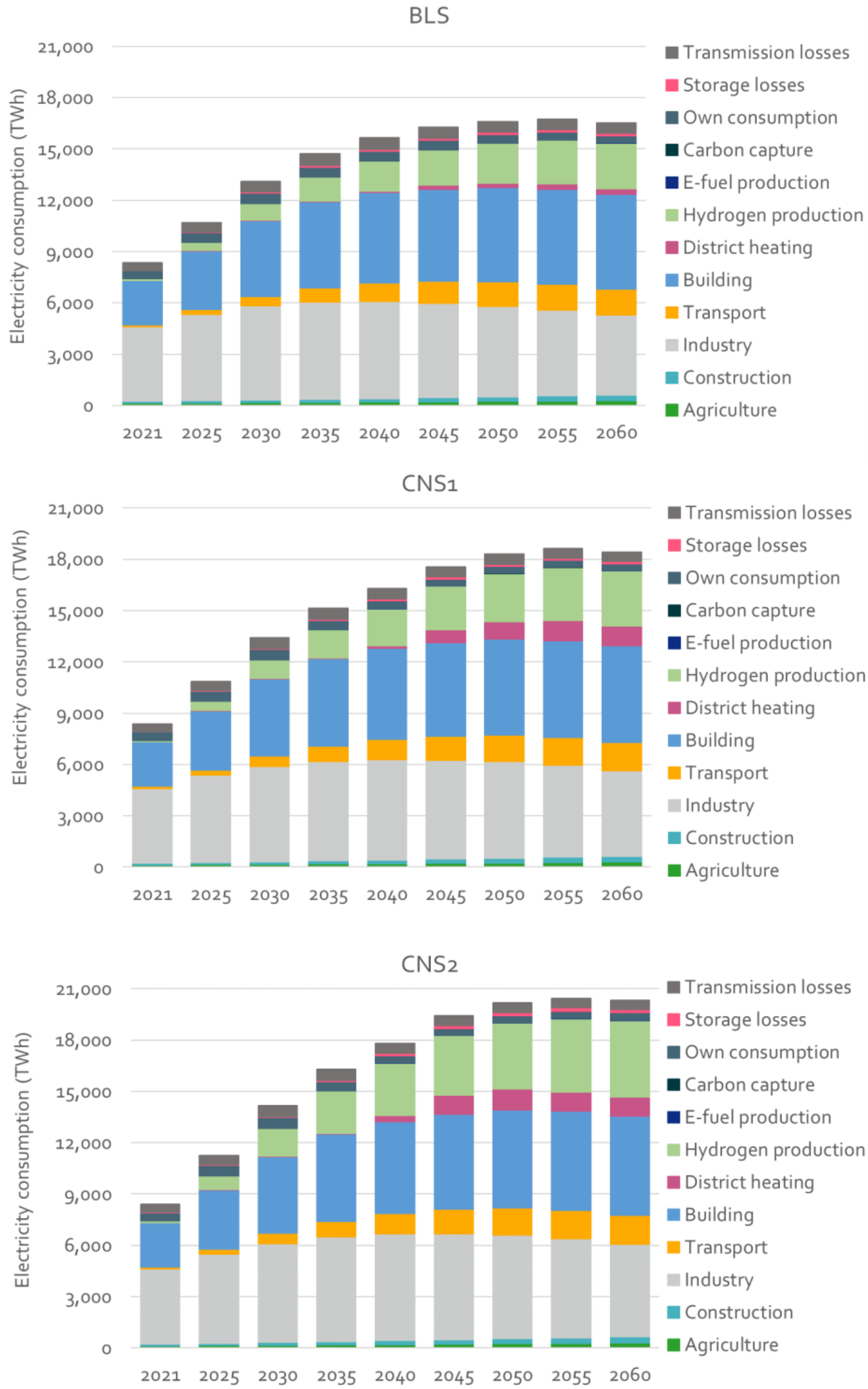
5.2 Transformation in power supply-demand structure

During the forecast period, China witnesses a significant surge in electricity demand and consumption. The surge in electricity consumption stems from several factors. Primarily, the drive is to bolster economic growth and cater to the enhanced demands for a high-quality life, in line with the vision of Chinese-style modernisation. Secondarily, the anticipated substantial rise in the electrification of end-use sectors renders the energy system more efficient and eco-friendly. Moreover, the modernisation and replacement of equipment to enhance energy efficiency curtail some electricity consumption. Notably, given the vast potential of electricity-driven hydrogen production, the uptick in electricity demand in the latter half of the forecast period intricately links to the diversified transformation and utilisation of electricity. In BLS, CNS1, and CNS2, there is 2,700~4,500 TWh of electricity are harnessed for hydrogen production by 2060.

Significant surge in total electricity consumption

Across all three scenarios, there's a discernible growth trend in the total electricity consumption, echoing the incessant enhancement in China's electrification rates. By 2035, the BLS, CNS1, and CNS2 scenarios anticipate the total electricity consumption to reach 14,700 TWh, 15,100 TWh, and 16,200 TWh, respectively. Ultimately, by 2060, the projections stand at 16,400 TWh, 18,300 TWh, and 20,200 TWh, respectively. When juxtaposed with CNS1, the total electricity consumption in CNS2 for 2060 is 10% more, and it overshadows BLS by 23%. The elevated electrification rates in end-use sectors coupled with the expansive development of electrically produced hydrogen predominantly spur the swifter rise in electricity consumption seen in CNS2.

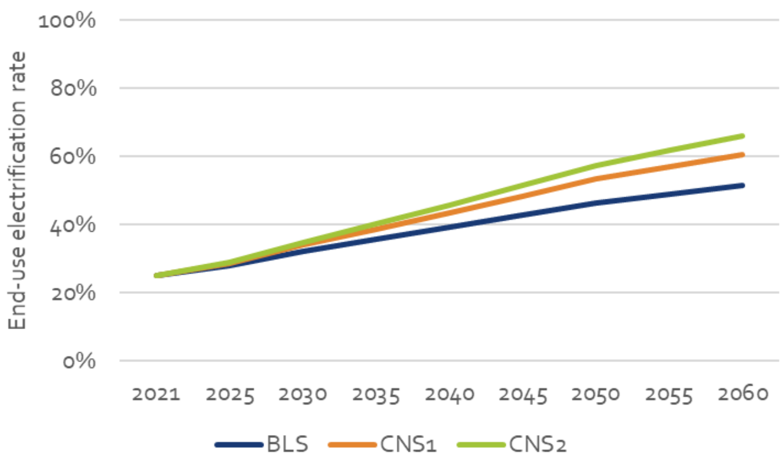
Figure 5-1 2021-2060 Total electricity consumption by sector



Steady growth in electrification rate

The pivot toward energy system electrification emerges as the cornerstone of transformational progress. As per CETO2023 findings, all of China's end-use sectors sustain heightened electrification rates across various scenarios. When juxtaposed—BLS, CNS1, and CNS2—the level of electrification progressively escalates. By 2035, the electrification rate of end-use sectors burgeons from 2021's 27% to 35.7%, 38.6% and 40.2% in BLS, CNS1, and CNS2 respectively. This trajectory further soars by 2060 to 51.4%, 60.4% and 65.8% respectively. CNS2 outstrips CNS1 by 5.4 percentage points and BLS by 14.4 percentage points. Refer to Chapter 4 for details on electrification development by sector.

Figure 5-2 2021-2060 End-use sector electrification rates



Green electrically produced hydrogen to play an increasingly important role in the mid to long-term

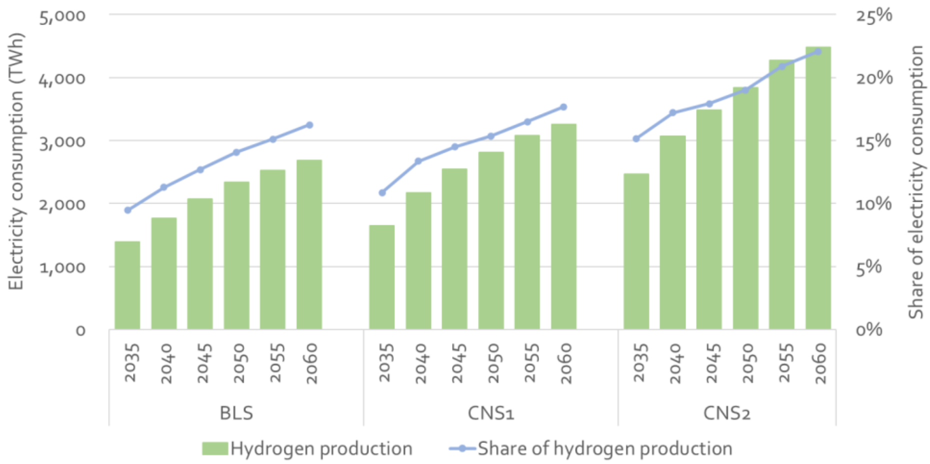
Post-2035, the electricity earmarked for hydrogen production becomes a pivotal contributor to the uptick in electricity demand. Within the industrial sector, hydrogen is envisioned as a coking coal substitute for raw steel production and an alternative to coal for ammonia synthesis. In the transportation sector, hydrogen holds the potential to supplant petroleum derivatives. Furthermore, certain electricity quotas fuel the production of other energy forms.

In all CETO2023's scenarios, hydrogen consumption perpetuates its growth, leading to a rising trend of electricity deployment for hydrogen synthesis. In BLS scenario, electricity consumption devoted to hydrogen production hits 1,400 TWh by 2035, ascend to 2,300 TWh in 2050, and then reach at 2,700 TWh in 2060. These figures represent 9.5%, 14.1%, and 16.2% of the total electricity consumption for each respective year. In CNS1 scenario, the projections indicate that electricity consumption for hydrogen production stands at 1,600 TWh in 2035, 2,800 TWh in 2050, and 3,300 TWh in 2060. These figures account for

10.9%, 15.4%, and 17.7% of the total electricity consumption for each of the mentioned years, respectively.

In contrast, the CNS2 scenario anticipates that by 2035, electricity consumption for hydrogen production already reaches 2,500 TWh, constituting 15.2% of the total electricity consumption—a percentage that surpasses the 2050 share for the BLS scenario (14.1%). By 2050, the consumption for hydrogen production in CNS2 scenario touches 3,800 TWh, making up 19.0% of the total end-use electricity. This is even higher than the CNS1's predicted share for 2060 (17.7%). By 2060, the electricity earmarked for hydrogen production surges to 4,500 TWh, a staggering 22.1% of the total electricity consumption, underlining the pivotal role of hydrogen as an intermediate energy source.

Figure 5-3 2035-2060 Electricity consumption for hydrogen production and its share in total electricity consumption



Renewable energies as the mainstay for installed capacity and electricity generation

Amid rising electricity demands, China's power generation capacity and actual electricity production are set for substantial growth to ensure a consistent power supply. Concurrently, with the advancement of the energy transition, the share of renewable energy in the electricity mix is progressively ascend, marking it as the predominant energy source—a distinguishing characteristic of China's power system overhaul. In the early phases of the *14th Five-Year Plan* period, with the rapid decrease in the capital cost and power generation marginal cost, onshore wind and solar PV have already demonstrated their competitiveness on the power generation side comparing to coal power. As the costs of offshore wind and solar PV continue to decline in the future, the market competitiveness of wind and solar PV strengthens.

Analysing the scenarios, there is a clear shift in power source capacities towards renewable energy as the primary installed capacity. Transitioning from the *15th Five-Year Plan* to the *16th Five-Year Plan* period (2026-2035), the capacity of renewable energy, spearheaded by wind and solar, is doubled. By 2035, in BLS, CNS1, and CNS2 scenarios, the total installed generation capacity is 5,370 GW, 6,270 GW, and 6,320 GW, respectively. By then, the share of non-fossil fuels amplifies to between 73% and 79%, and renewable energy comprises between 71% and 77%. In relation to the structure of electricity generation, the total output spans 14,700 TWh, 15,100 TWh, and 16,200 TWh, respectively, in BLS, CNS1 and CNS2 scenarios, where non-fossil fuels represent 63%~76%, and renewables account for 57%~71%. By 2035, non-fossil energy sources, in terms of both installed capacity and electricity generation, underpin China's power infrastructure. This shift results in the eclipse of coal power by renewable sources in the power hierarchy. Consequently, China is on the cusp of inaugurating a preliminary new-type power system.

As the power system undergoes a significant transformation towards low-carbon emissions, for the year 2060 indicate that the total installed capacity for power generation reaches 6,800 GW, 8,960 GW, and 9,810 GW, under the BLS, CNS1, and CNS2 scenarios, respectively. The total electricity generated touches 16,400 TWh, 18,300 TWh, and 20,200 TWh, respectively. To effectively satisfy the burgeoning demand for electricity, power plants and cogeneration initiatives that utilise biomass as a fuel source have been judiciously integrated into the power sector. Non-fossil and renewable energy's share in electricity generation surges to 92%-99% and 90%-98%, respectively. By then, the contribution of non-fossil and renewable energy sources to electricity generation oscillates between 86%-100% and 80%-95%, respectively. This signifies the maturation and completion of China’s new-type power system.

Figure 5-4 2021-2060 Installed capacity by power generation technologies

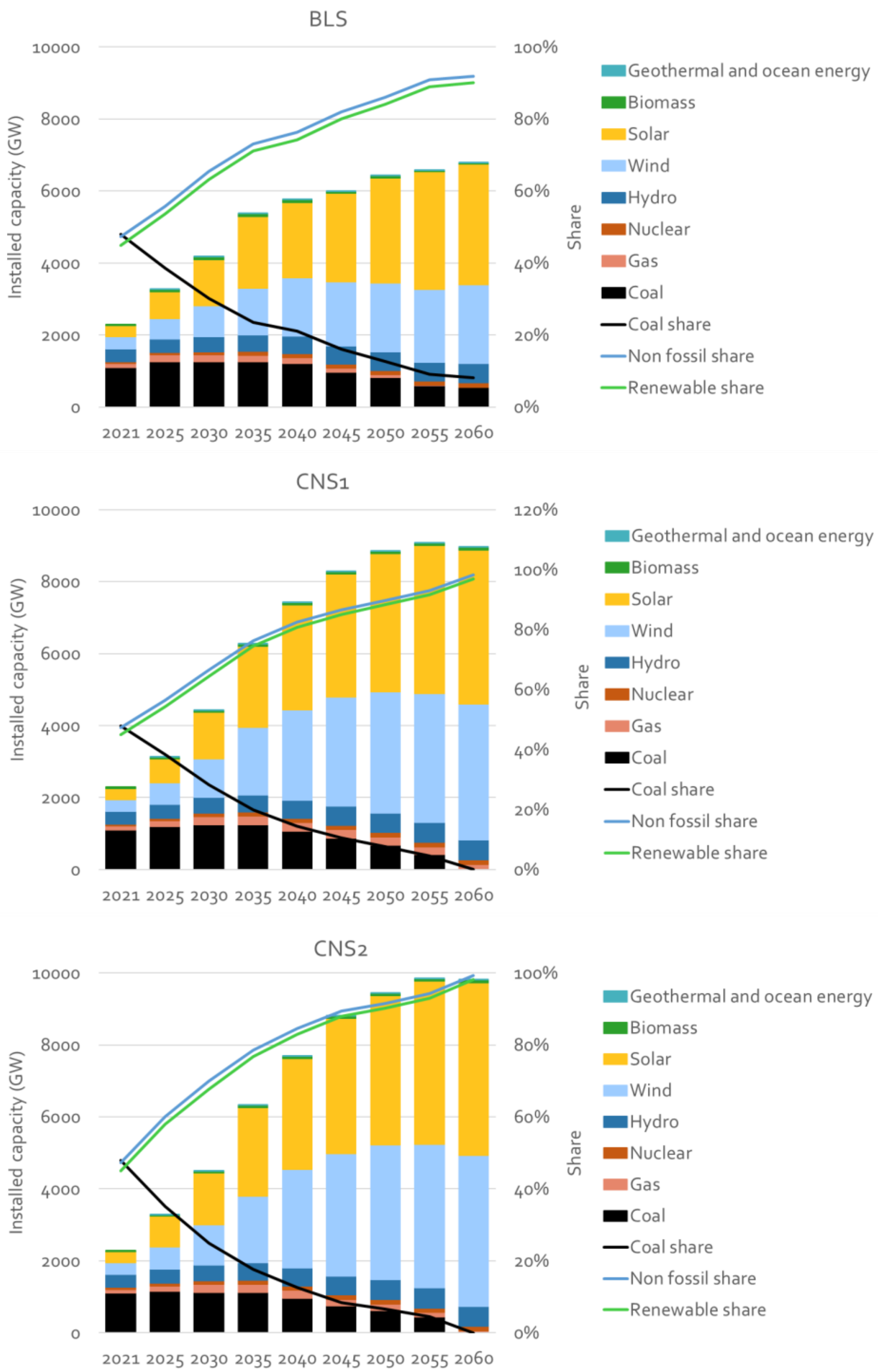
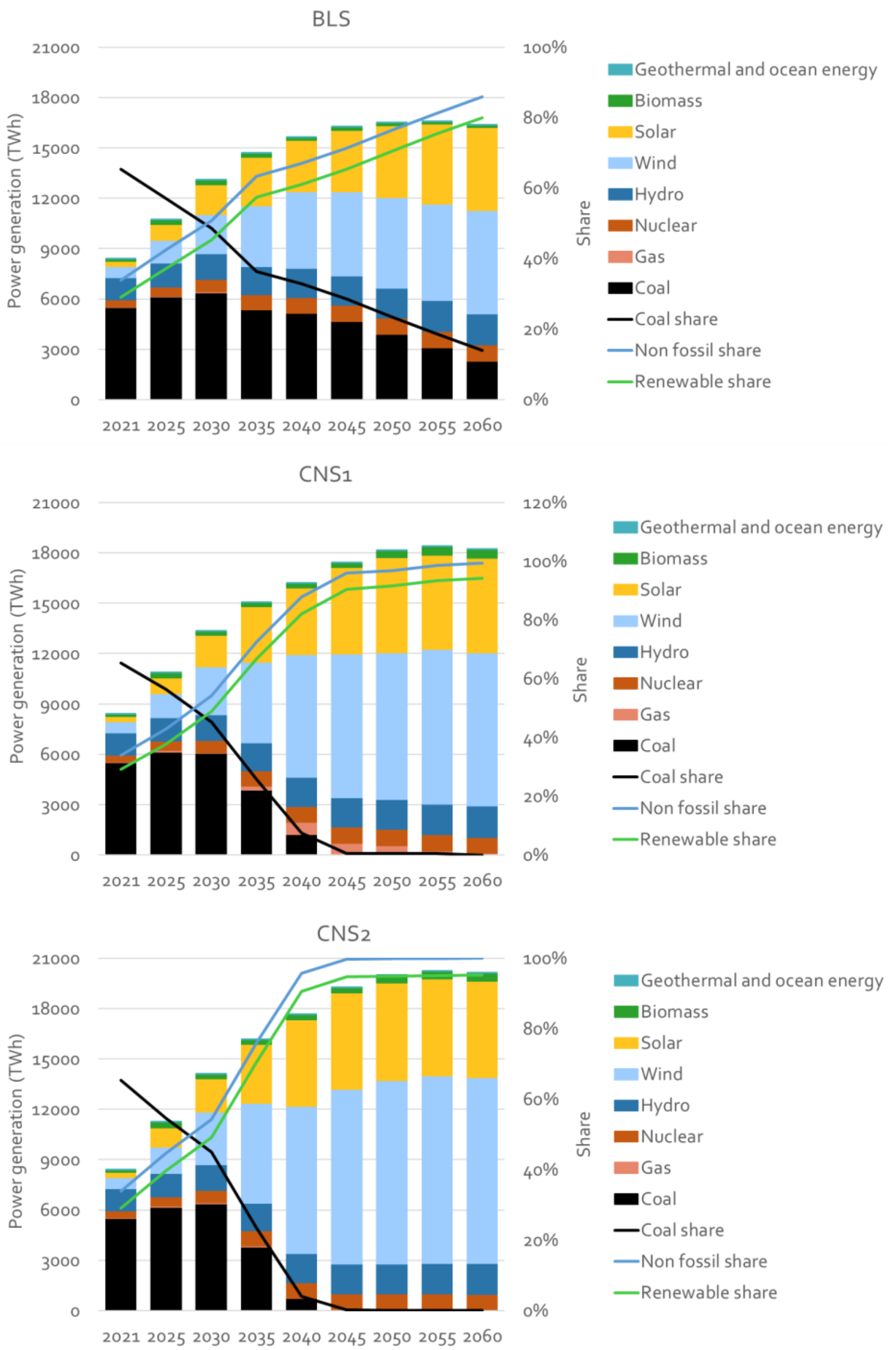


Figure 5-5 2021-2060 Electricity generation by power generation technologies



5.3 Development of wind and solar power in China

Considering the dual-carbon target, renewable energy in China is witnessing sustained and rapid growth. This surge is largely attributed to the combined influences of cost reductions and economies of scale, which have catalysed the expansive growth of the new energy manufacturing sector. This growth furnishes the foundation of equipment manufactures and cost benefits for the large-scale deployment of wind and solar power facilities. Initiatives that encourage both utility-scale and distributed wind and solar power, expedite the planning and construction of expansive wind power and solar PV bases in deserts, Gobi, and arid areas, and foster county-wide solar PV programmes have invariably cultivated a robust market demand for wind and solar power. In varied scenarios, the growth trajectories for wind and solar power capacity consistently outpace those of conventional power sources, enhancing their stake in the national power generation capacity.

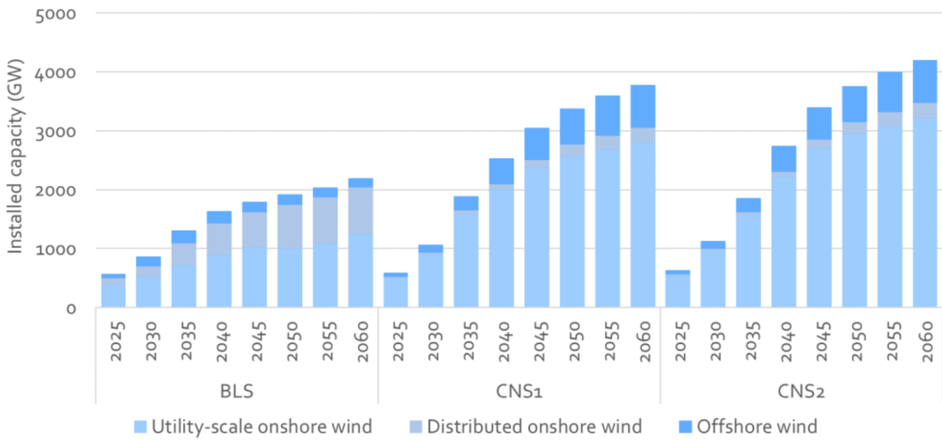
Concurrent advancements in low wind speed onshore wind and offshore wind technologies

The timeline leading up to 2040 is pivotal for wind power's ascendancy. The annual average growth rate of wind power capacity lies between 10% and 13%. Furthermore, the net increment in installed capacity experiences persistent surge, potentially peaking at 176 GW annually in the CNS2 scenario between 2035 and 2040. Predominantly, onshore wind power, buoyed by maturing technologies and consistent market competitiveness, is the major contributor to this net capacity augmentation. Concurrently, innovations in low wind speed turbines and the precipitous cost declines of offshore wind mechanisms have ushered in an era marked by expansive growth in low-speed utility-scale wind power, distributed wind power, and offshore wind power. Projections for 2040 across the BLS, CNS1, and CNS2 scenarios indicate that cumulative installed wind power capacities could reach 1,630 GW, 2,520 GW, and 2,730 GW respectively. Herein, onshore wind energy could potentially represent 83%~88% of the total. In terms of offshore wind power, a sequential augmentation takes place across the BLS, CNS1, and CNS2 scenarios, with capacities touching 190 GW, 420 GW, and 420 GW in that order. Post-2040, the cumulative installed capacity of wind power persistently demonstrates an upward trajectory, although the rate of new installations shows a gradual decrease. By 2060, under the BLS, CNS1, and CNS2, the aggregate installed capacity of wind power reaches 2,190 GW, 3,770 GW, and 4,190 GW, respectively.

Table 5-1 Average annual net increment of wind power capacity

Scenario (GW)	2026-2030	2031-2035	2035-2040	2041-2045	2046-2050	2051-2055	2056-2060
BLS	60	88	66	32	25	23	32
CNS1	93	165	128	105	65	43	37
CNS2	99	146	176	132	72	47	41

Figure 5-6 2025-2060 Total installed wind power capacity by technology



In terms of regional distribution, onshore wind power has been established across all six regions. It presents a more balanced distribution compared to solar power. The "Three North" regions (North China, Northwest China, and Northeast China) have the most significant proportion of total onshore wind power capacity, attributed to their substantial single-unit capacity and consolidated layout. By 2040, CNS2 projects that onshore wind power capacity in the "Three North" regions comprises 68% of the total. The Central and South regions have a smaller share, with a cumulative installation share of 24%. Meanwhile, Eastern China prioritises the development of offshore wind power, with onshore wind installations comprising the smallest regional share at 8%. By the year 2060, leveraging the cost efficiencies of low wind speed turbines, the "Three North" regions intensify the deployment of centralised low wind speed wind power projects. In CNS2, this results in the "Three North" regions increasing their share of onshore wind power installations to 71%, with a corresponding reduction in the combined installation shares across the Central, Eastern, and Southern regions.

Given China's maritime landscape, offshore wind power predominantly finds its home in the East and South China regions. The East China region, boasting a more extended coastline and superior engineering construction conditions, leads offshore wind power development. By 2040, CNS2 projects that offshore wind power installations in the East China region comprises 81% of the total, with the South China region contributing 11%. The shares in North China and Northeast China are less than 5% each. Moving forward to 2060, CNS2 shows a more equitable distribution of offshore wind power installations, in order to serves the burgeoning electricity demands of the coastal provinces. The East China region's share decreases to 58%, the South China region sees its share increase to 24%, and the North and Northeastern regions expand their contributions to 10% and 8%, respectively, reflecting a strategic diversification of offshore wind power development across the country.

Figure 5-7 Regional deployment of onshore wind power capacity in CNS2

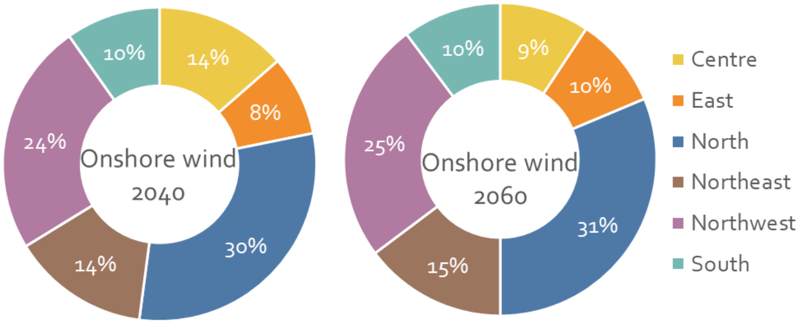
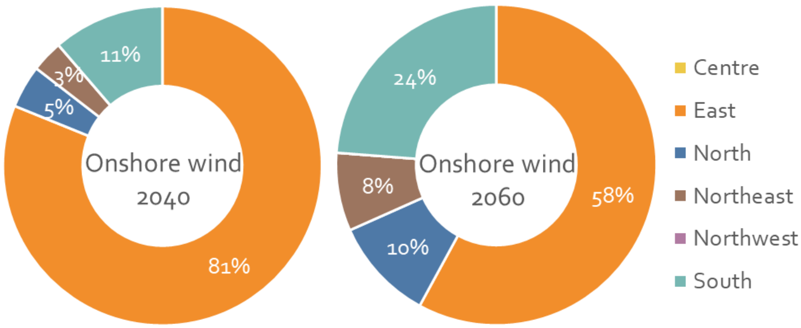


Figure 5-8 Regional deployment of offshore wind power capacity in CNS2



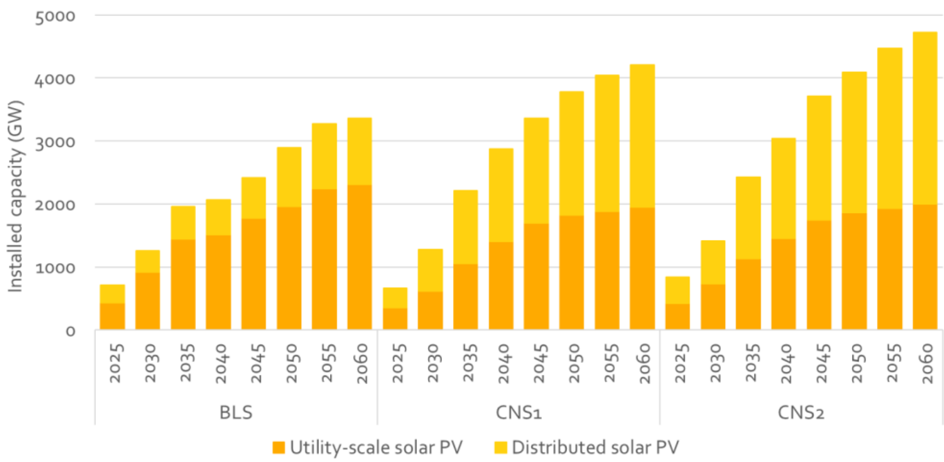
Utility-scale and distributed PV develop in parallel

Compared to wind energy, solar power generation, predominantly through photovoltaic (PV) systems, characterised by a more extended period of mass deployment and boasts a higher average annual increase in installed capacity. Between 2021 and 2040, the annual average growth rate of solar PV capacity spans 12%~14%, with a peak annual increase of 206 GW occurring in the CNS2 scenario between 2031 and 2035. Within the domain of solar PV, while utility-scale solar PV capacity maintain a lead, distributed solar PV capacity grow at a faster annual rate, driven by continually reducing costs and the expansion of county-wide solar PV projects. By 2040, the cumulative installed capacities of solar power generation under BLS, CNS1, and CNS2 reach 2,070 GW, 2,910 GW, and 3,080 GW, respectively. Among them, the utility-scale solar PV capacity reaches 1,400 GW to 1,450 GW, while distributed solar PV capacity reaches 1,460 GW to 1,590 GW. Post 2040, the installed capacity for solar PV experiences further expansion. By 2060, under the BLS, CNS1, and CNS2 scenarios, the cumulative installed capacity of solar power generation hits 3,360 GW, 4,28 GW, and 4,800 GW, respectively. It underscores solar power's significant role in the future energy mix, driven by technological advancements and policy support.

Table 5-2 Average annual net new solar power capacity

Scenario (GW)	2026-2030	2031-2035	2035-2040	2041-2045	2046-2050	2051-2055	2056-2060
BLS	108	142	20	71	95	75	18
CNS1	125	189	134	100	86	54	35
CNS2	118	206	124	136	77	79	52

Figure 5-9 2025-2060 Total installed solar PV capacity by technology



Regionally, following the initiation of the *14th Five-Year Plan* period, China is pivoting towards constructing large-scale solar PV plants in the North and Northwest regions. These areas, rich in solar resources and unused land prone to desertification, serve as ideal locations. Concurrently, with a focus on hydropower development and grid connection capabilities, efforts are on in Xinjiang, Ningxia, and Gansu to explore large-scale solar power generation bases integrated with hydropower or wind power. In the future, the "Three North" regions remain primary zones for large-scale solar endeavours. Under CNS2, by 2060, their cumulative solar PV capacity ranges between 3,110 GW, constituting 66% of the national total. The Central-East-South areas develop both utility-scale and distributed solar PV, projecting a cumulative installed capacity of 1,620 GW, or 34% of the national total.

From a technological perspective, the "Three North" regions, replete with sunlight, conducive land conditions, and advantages for inter-provincial transmission grid construction, predominantly deploy utility-scale solar PV. Post 2040, under the CNS2, these regions account for 68% of total utility-scale solar PV capacity, over half of which is located in the Northwest.

Industrial and commercial rooftop distributed solar PV offers benefits such as load proximity, spatial flexibility, and modest power transmission requisites. This creates a solid foundation for the scaled-up deployment of solar PV in central and eastern regions. By 2040, CNS2 projects that 84% of distributed solar PV capacity is in the Central-East-South and North China regions, and the Central-East-South region covers nearly 60% of this distribution. In contrast, the Northwest and Northeast jointly holds around 16%. By 2060, there is a more concentrated spread of distributed solar PV across regions. In CNS2, the Northwest and Northeast see their share climb to 47%, whereas the Central-East-South and North China regions recede to 53%.

Figure 5-10 Regional deployment of utility-scale solar power generation in CNS2

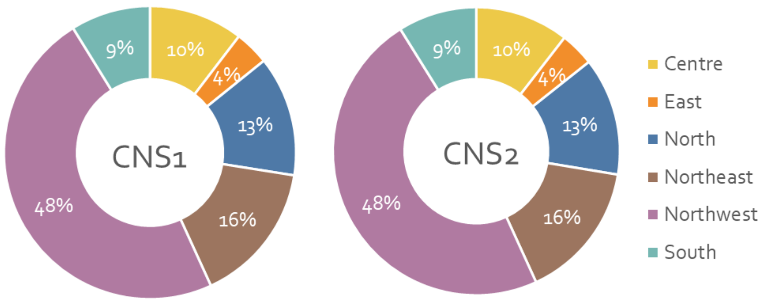
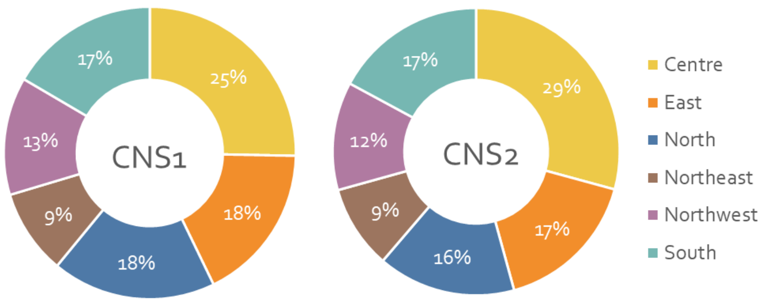


Figure 5-11 Regional deployment of distributed solar power generation in CNS2

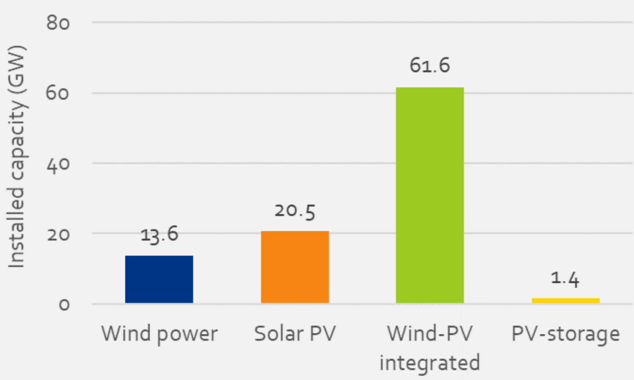


Box 5-1 Large-scale wind and solar PV bases in deserts, Gobi and arid regions

During the *14th Five-Year Plan*period, the development of large-scale wind power and solar PV bases, primarily in deserts, Gobi and arid regions, has become crucial to China's energy development and power infrastructure. Speeding up the construction and activation of these bases—some catering to local consumption while others channel electricity to central and eastern regions through ultra-high voltage power grids—will meet the escalating electricity needs in these areas. This initiative will mitigate power scarcities during peak times in regions like Central, East, and North China. Consequently, it will bolster China's power supply reliability and enhance its capability for inter-provincial and inter-regional power adjustments.

On October 26, 2021, the State Council released the *Action Plan for Peak Carbon Emissions by 2030*, underscoring the urgency to expedite the construction of wind power and solar PV bases. The *Plan* accentuates the robust development of renewable energy sources and the swift construction of the bases. By 2030, the cumulative installed capacity for wind power and solar PV aims to surpass 1,200 GW. To realise this national directive, the National Development and Reform Commission and the National Energy Administration collaboratively announced the *Notice on Printing and Distributing the List of Large-Scale Wind Power and Solar PV Base Construction Projects Focused on Desert, Gobi, and Arid Regions (First Batch)* on November 24, 2021. This initiative spans 19 provinces, boasting a total capacity of 97.05 GW across 50 projects. These projects are slated for completion between 2022 and 2023. Furthermore, in 2022 and 2023, the National Energy Administration sequentially released the second and third batches of these mega base project lists.

Figure 5-12 Distribution of project types in the first batch of wind power and solar PV large base projects



Source: National Energy Administration

Box 5-2 County-wide (-city or -district) rooftop distributed solar PV development

China ardently advocates the fusion of distributed grid-connected solar PV systems with architectural rooftops. This advocacy stimulates the assembly of such systems atop urban public facilities, commercial edifices, industrial parks, factories, and residences in suitable regions. The primary objective is to channel solar PV development towards sectors with economic feasibility.

In June 2021, the General Affairs Department of the National Energy Administration released the *Notice on Submitting Pilot Schemes for County-wide (-City or -District) Rooftop Distributed Photovoltaic Development*. Subsequent to this document, county-wide distribution of solar PV has proliferated throughout numerous Chinese provinces. This county-centric strategy for distributed solar PV zeroes in on two pivotal challenges: 1) streamlining the use of rooftop spaces to navigate the predicament of plentiful yet dispersed and diminutive rooftop resources in residential areas; and 2) assuring the upgrading and rebuilding of distribution grids to cater to the voluminous connection needs of distributed solar PV in trial regions. In 2021 alone, a total of 676 counties devised and tabled their execution blueprints. By the close of the year, these trailblazing counties boasted a combined capacity registration of 46.2 GW. Predominantly, these ventures were clustered in the provinces of Shandong, Henan, and Zhejiang. This is largely fuelled by collaborative investment and development models that involve central enterprises, local state-owned entities, and private firms, which constitute over 60% of all project developers.

Table 5-3 Progress in county-wide solar PV development

Region	Province	Count	Region	Province	Count	Region	Province	Count
North 154	Shandong	70	Central 127	Henan	66	East 138	Jiangsu	59
	Hebei	37		Hubei	19		Zhejiang	30
	Shanxi	26		Chongqing	16		Fujian	24
	Inner Mongolia	11		Hunan	12		Anhui	17
	Beijing	6		Jiangxi	8		Shanghai	8
	Tianjin	4		Sichuan	6			
Northwest 116	Gansu	46	South 105	Guangdong	32	Northeast 27	Liaoning	15
	Qinghai	32		Yunnan	28		Heilongjiang	11
	Shanxi	26		Guangxi	22		Jilin	1
	Ningxia	7		Guizhou	13			
	Xinjiang	5		Hainan	10	Tibet		9

Source: National Energy Administration (NEA)

5.4 The role of flexibility resources in power system regulation

Trends in the development of flexibility resources

As the new-type power system evolves, flexibility resources in China are displaying an array of diversified and expanding developmental traits. Based on the EDO model, the Chinese power system's flexibility resources can be categorised into four main types: flexible coal power, pumped storage, new-type energy storage, and demand-side response. New-type energy storage encompasses both electrochemical energy storage and vehicle-to-grid (V2G) technology. In contrast, demand-side response involves smart charging for electric vehicles, industrial demand response, electric boilers, and heat pumps. When juxtaposed with BLS and CNS1, CNS2 exhibits a rapid progression in renewable energy adoption, necessitating an increased reliance on flexibility resources for stable operation of the power system. To encapsulate CNS2's need for the widespread deployment of flexibility resources, the cost reduction curves for flexibility technologies are accentuated in the CETO 2023 scenario configurations.

By 2035, the growth trajectory for other flexibility resources, such as pumped storage, new-type energy storage, and demand-side response, remains consistent across BLS, CNS1, and CNS2, reaching a combined installed capacity of about 1,400 GW. Conventional flexibility resources like flexible coal power units and pumped storage maintain their significance, backed by ongoing policies, which include coal power unit flexibility retrofits and medium and long-term development plans for pumped storage. By 2060, the total potential capacity for flexibility resources (excluding flexible coal power units) in BLS, CNS1, and CNS2 stands at 2,610 GW, 2,700 GW, and 2,870 GW, respectively. In both CNS1 and CNS2, coal-fired power units are either completely phased out or transformed into reserve units, predominantly depending on pumped storage, new-type energy storage, and demand-side response as low-carbon flexibility assets for grid regulation.

Additionally, it is worth noting that by 2060, in CNS1 and CNS2, the share of electricity consumption for hydrogen production ranges between 18%~22%. This projection implies that electrolysers emerge as a pivotal flexibility resource in the intermediate to distant future. With renewable energy generation poised to become the primary power source, the implementation of electrolysers can bolster the capacity of renewable power consumption, simultaneously promoting green hydrogen output. The CETO research team intends to delve deeper into the resource dynamics for electrolyser-driven green hydrogen production in 2024, examining the potential contributions of this technology to system regulation.

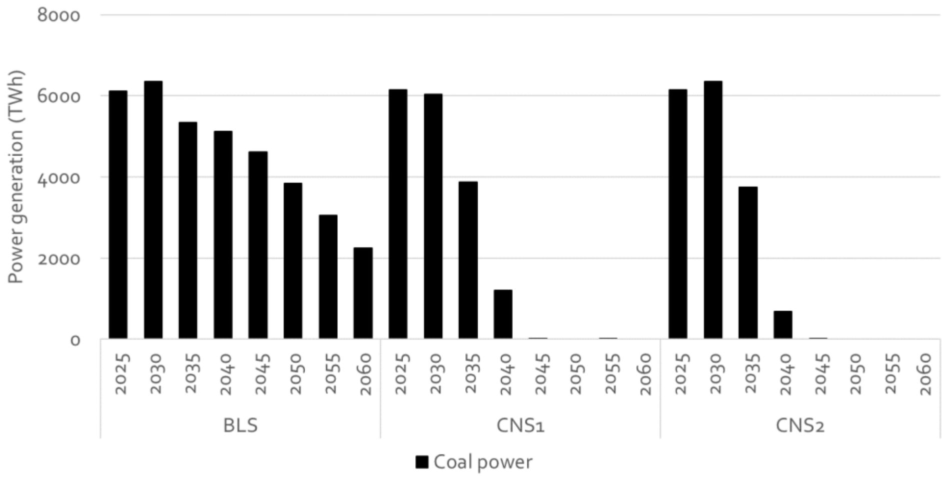
New positioning for coal power units

The transition and development of coal power are pivotal in propelling China towards net-zero emissions within its energy sector. As outlined in the *Opinions on Fully Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality* released by the State Council in 2021, China has set its sights on rigorously managing the surge in coal consumption during the *14th Five-Year Plan* period. During the subsequent *15th Five-Year Plan* period, there is a progressive decrease in coal consumption. The EDO model's simulation outcomes, under the presumption of consistent fuel prices, suggest that the total installed coal power capacity in CNS1 and CNS2 touches roughly 1,250 GW of plateau during the *14th and 15th Five-Year Plan* periods (2026-2035), post which there is a steady decline. BLS reflects a parallel downward trajectory in coal power installations; however, by 2060, it has not yet reached "zero" installed capacity, attributed to prevailing policies that are in execution.

Post-2035, CNS1 and CNS2 both envisage an accelerated coal-fired power plants natural retirement. Compared with that in CNS1, the LCOE for wind and solar PV in the CNS2 scenario sees a more pronounced reduction, thereby gaining a considerable edge over coal-fired power in terms of cost-competitiveness. Nevertheless, the CNS2 scenario's more extensive integration of wind and solar PV heightens the need for flexible resources to manage the variability of these renewable sources. This increased demand for flexibility, paradoxically, decelerates the decommissioning of coal-fired power units. These units remain integral to the power system's stability, fulfilling essential load-balancing functions. By 2060, under both the CNS1 and CNS2 scenarios, coal-fired power is retired completely.

During the holistic process of the natural retirement of coal-fired power units, the currently operational coal-fired power units are gradually being decommissioned or transitioning from a base load power source to a more flexible power source. Between 2025 and 2040, flexible coal-fired power units serve a crucial modulatory function. In a collaborative move in October 2021, the National Development and Reform Commission and the National Energy Administration jointly released a directive advocating the revamp and enhancement of coal-fired power units across the nation (*Notice on Transformation and Upgrading of National Coal-fired Power Units*). This directive mandates the flexible upgrade of 200 GW of coal-fired power units within the *14th Five-Year Plan* period. As the ratio of these flexible units amplifies, the annual utilisation hours of coal power shrink from 4,600 hours in 2021 to 3,100 hours in CNS1 and 3,400 hours in CNS2 by 2035 – marking a reduction of 33% and 26% respectively. Notwithstanding, coal power remains instrumental in fortifying energy security. Even though certain decommissioned coal-fired units are retained as standby assets with requisite upkeep, they primarily serve as a buffer for supply guarantees and emergency reserves. Beyond 2040, the annual utilisation hours of coal power in both CNS1 and CNS2 dips below 1,000 hours. In 2060, coal power is no longer a significant pillar in China's power system regulation.

Figure 5-13 2025-2060 Annual coal power generation



Pumped storage to embrace a new era of opportunities

Pumped storage stands out as the foremost mature and cost-effective low-carbon flexibility solution, holding the greatest potential for scaled development, in the power system. Yet, its developmental pace trailed behind projections by the close of the *13th Five-Year Plan* period, stemming primarily from imperfections of market and pricing mechanisms. The government's vision of crafting a new-type power system rejuvenated interest in pumped storage. In its pursuit of structured growth for pumped storage in the medium to long run, the National Energy Administration unveiled the *Medium and Long-term Development Plan for Pumped Storage (2021-2035)* in September 2021. This directive demarcates the overarching development-available resource capacity for pumped storage and publish a specific project list, furnishing a meticulous roster of projects after factoring in resources, environmental, and technological aspects. Targets set within the plan peg pumped storage's total installed capacity at 62 GW by 2025, stretching to 120 GW by 2030. Meanwhile, to align with the requirements set out in the *14th Five-Year Plan for Renewable Energy Development*, there is an emerging trend towards diversification and integration within the renewable energy sector. This trend is characterised by the development of various hybrid systems that combine hydro, wind, solar, and energy storage capabilities. Moreover, wind and solar power plants are increasingly being equipped with supplementary peak-shaving features, and there is a gradual shift towards the establishment of distributed pumped storage stations, evolving from the traditional pumped storage models. In both CNS1 and CNS2, the installed capacity of pumped hydro storage mirrors that of BLS, with a consistent increase up until 2035. After this point, the rate of new pumped hydro storage installations begins decelerating, continuing at a more modest pace through to 2060.

From a geographical lens, the locus of pumped storage progression transitions from the eastern to the western regions. In upcoming years, Central and East China remain to be the pivotal epicentres for pumped storage development, with the "Three North" regions witnessing an uptick in developmental vigour. Conversely, the southern territories experience a deceleration, shifting the project epicentre towards the Southwest. These recalibrations emanate from the government's blueprint of erecting nine onshore clean energy bases during the *14th Five-Year Plan* period. The Northwest channels its energies towards pioneering vast wind and solar installations in desert regions and the Gobi, considering pumped storage as an indispensable peak-load regulation tool. The Southwest sculpts integrated hydro-wind-solar-storage bases, capitalising on native hydropower resources. The construction of these clean energy bases underscores the mounting appetite for pumped storage initiatives.

The medium to long-term role of new-type energy storage and demand-side response

Both new-type energy storage and demand-side response experience scaled development and span till 2060. The *14th Five-Year Plan* period witnesses these technologies transition into their full-fledged developmental stages. In CNS2, between 2025 to 2035, their compound annual growth rates (CAGR) stand at 64% for new-type energy storage and 18% for demand-side response. As per the EDO model, the power system prioritises leveraging pre-existing flexibility resources. Consequently, with the electric vehicle count surging and the infrastructure to support them gaining ground, EV smart charge emerges as the most rapidly advancing flexibility solution. In CNS2, its CAGR from 2025 to 2035 is pegged at 21%. Other technologies like electrochemical energy storage, and electric boilers and heat pumps witness a consistent and brisk upward trend, with CAGRs of 18% and 14%, respectively. The electric vehicle-to-grid (V2G) technology is slated for a breakthrough around 2030. By 2050, both EV smart charge and EV V2G attain their zenith, subsequently plateauing in the following decade. Meanwhile, in the CNS2 scenario electrochemical energy storage perpetuates its growth projecting a doubling of its total capacity between 2050 and 2060. Electric boilers and heat pumps are on track for unwavering expansion until they crest between 2035 to 2050, boasting a CAGR of 12%. By then, new-type energy storage, demand-side response, and pumped storage collectively supplant coal power, emerging as the primary conduits for grid regulation services.

It is worth noting that a high resource capacity does not necessarily mean a large capacity for real-time system regulation. Taking electric vehicles as an example. Under CNS2 scenario, while 80% of the demand-side response resources by 2060 are earmarked for intelligent EV charging, only 50% of these EVs are available for this service at specific moments. Hence, the actual real-time participation in regulation may fall considerably short of the total resource capacity.

Table 5-4 2035-2060 Cumulative resource capacities for new-type energy storage and demand-side response

(GW)	Scenario	2035	2040	2045	2050	2055	2060
New-type energy storage	BLS	97	246	420	564	565	565
	CNS1	97	246	420	565	565	566
	CNS2	101	261	435	600	633	638
Demand-side response	BLS	877	1,123	1,368	1,405	1,444	1,440
	CNS1	870	1,141	1,482	1,533	1,579	1,564
	CNS2	870	1,242	1,548	1,598	1,612	1,547

Note: New-type energy storage envelops both electrochemical storage and EV Vehicle-to-Grid (V2G) technologies, whereas demand-side response encompasses EV smart charge, industrial demand response, electric boilers, and heat pumps.

From a regional deployment perspective, new-type energy storage and demand-side response resources nest in Central, Eastern, and Southern China, mirroring the regional proliferation of distributed renewable energies and EVs. In CNS2 projections, the Central-East-South regions account for 57% of new-type energy storage capacities by 2035, escalating to 60% by 2060. For demand-side response resources in the same regions, the aggregated capacities for EV smart charging and industrial demand response are 53% by 2035 and surge to 61% by 2060. Conversely, electric boilers and heat pumps find their primary hubs in the "Three-North" regions, owing to the dominance of district heating systems. However, a notable regional shift is on the horizon. Between 2035 and 2060, the "Three-North" regions' contribution to electric boiler and heat pump capacities recedes from 77% to 58%. This migration is spurred by the expedited growth of distributed renewable energy in Central-East-South regions, thereby amplifying the deployment of distributed and standalone electric boilers and heat pumps. Consequently, these regions see their share in the said capacities jump from 23% in 2035 to 42% in 2060.

Figure 5-14 Regional deployment of new-type energy storage and demand-side response resource capacities in CNS2 in 2035

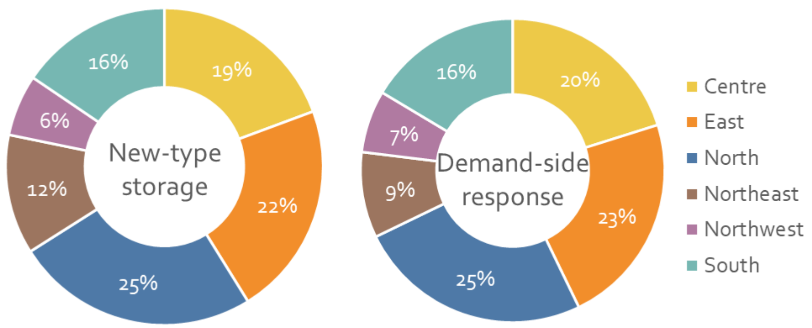
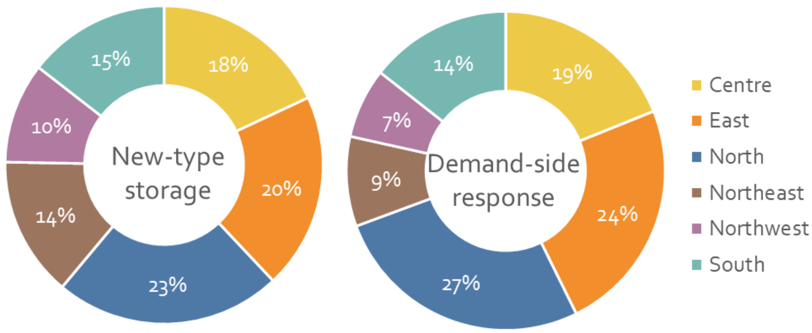


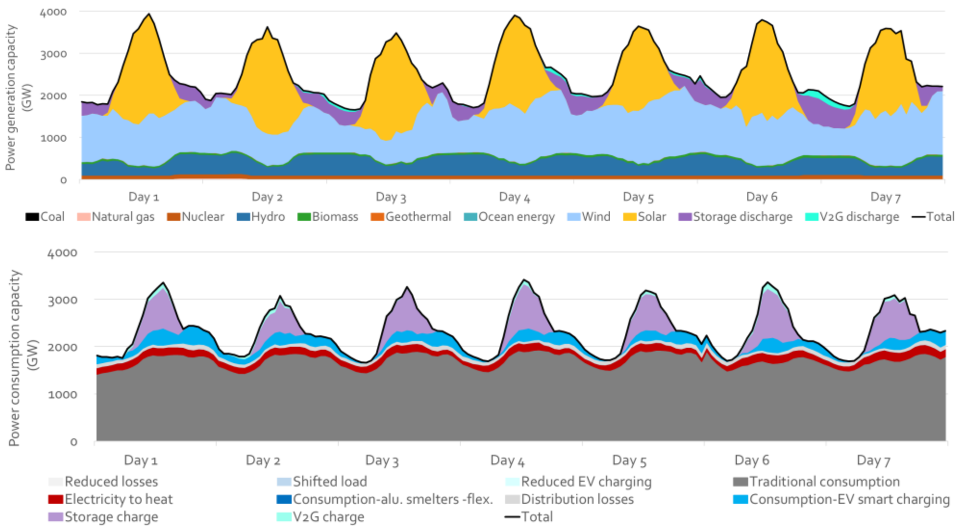
Figure 5-15 Regional deployment of new-type energy storage and demand-side response resource capacities in CNS2 in 2060



Power balance simulation of the new-type power system

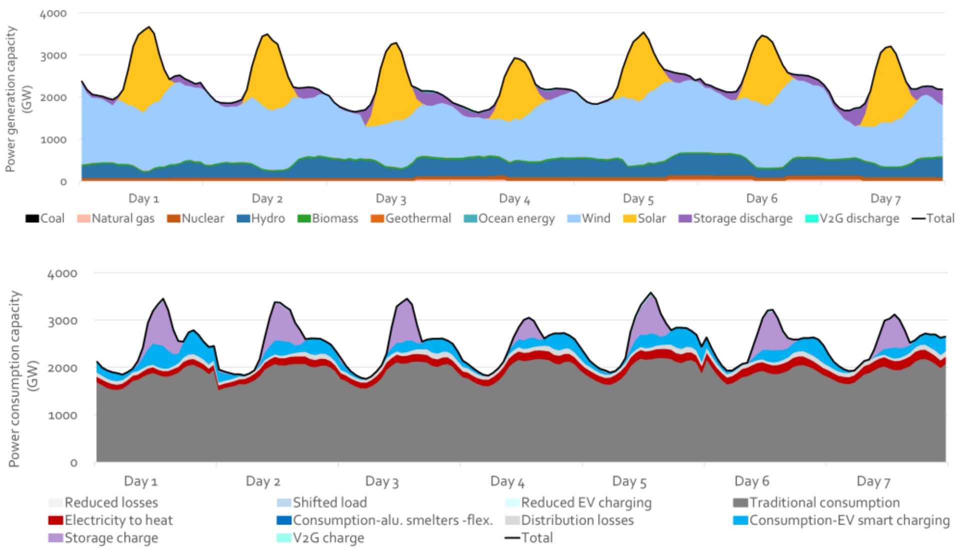
By 2060, diverse timescale energy storage and demand-side response resources eclipse coal power, asserting themselves as the linchpins of power system regulation. Taking a typical summer week in CNS2 as an example. There is ample sunlight during the day, leading to a rapid increase in solar PV generation. Particularly at noon, when the total generation capacity far exceeds existing power load (as shown in Figure 5-16, Day 1), pumped hydro storage, electrochemical storage, and electric vehicles undergo substantial charging, accounting for 37% of the total load. Electric vehicles, following an orderly charging process, utilise V2G technology to absorb excess electricity from the grid. In the evening, solar PV output declines while wind power increases. During periods of significant wind power generation (as shown in Figure 5-16, Day 1), electric vehicles' smart charging plays a more substantial role, reaching 16% of the total power load. Conversely, during periods of insufficient wind power (as shown in Figure 5-16, Day 6), pumped storage, electrochemical storage, and EV V2G discharge a considerable amount of electricity, contributing to 38% of the total generation capacity.

Figure 5-16 Hourly power balance of the national power system for a week in summer 2060 under CNS2



Note: Storage charge encompasses pumped storage and electrochemical storage.

Figure 5-17 Hourly power balance of the national power system for a week in winter 2060 under CNS2



Note: Storage charge encompasses pumped storage and electrochemical storage.

5.5 Inter-regional power mutual aids and grid optimisation

The large-scale development of renewable energy not only alters the production and consumption dynamics of electricity but also establishes more stringent demands for power transmission. As China continues its transformative journey towards energy, electricity supersedes fossil fuels as the principal energy source. This shift substantially elevates electricity's share in energy trade. Consequently, the epicentre of China's inter-regional energy trade transitions from coal transportation to power mutual aids across regions. It's worth noting that, in contrast to commodities like oil and liquefied natural gas, which enjoy a broad global market, electricity remains a predominantly regional commodity. China's energy resources and consumption demands are inversely proportioned, leading to power flow from west to east and north to south. By 2060, the amount of electricity received by the eastern and central regions surges to roughly double its current levels.

Regarding the pathways for inter-regional power transmission, projections for 2035 highlight primary routes: Northwest to Central China, Northeast to North China, and North to East China. By 2060, these exchanges become more regular. Beyond the three traditional pathways that channel power from the "Three North" regions to the load centres in the central and eastern regions, the significance of power transfer routes between central and south-eastern regions, such as from East to Central China, from Central to East China, and from South to Central China, are rised, fortifying regional power cooperation.

Moreover, addressing the anticipated demand for large-scale renewable power transmission necessitates a re-evaluation of the power grid's role as a conduit between electricity production and consumption. Grid planning should evolve in tandem with power generation trends and consumption patterns, adapting to substantial and recurring shifts in both supply and demand sides. Such evolution ensures both centralised and distributed resource utilisation, fostering a harmonious blend of localised and inter-regional energy integration. Concurrently, this would expedite the optimal distribution of clean, low-carbon energy across a more extensive range.

Comprehensive grid planning should align with a national vision, gradually shaping a multi-tiered interconnected system. This system should prioritise intra-provincial stability, elevate to regional synchronisation, and culminate in a balanced national integration. Efforts should focus on creating a continuous interconnection framework for the electrical grid that facilitates power transmission from West to East, East to West, North to South, and ensures mutual power exchange between the North and South. The interconnected grids' expansion should be anchored in a pattern that emphasises bi-directional power flow. Within this configuration, the Northwest grid primarily becomes an expansive clean energy exporter, the Central China grid transforms into an interlinking hub, while the North, East, and Southern grids emerge as primary consumers. The Northeast grid, while catering to its consumption, also serves as a partial power exporter.

By harnessing cutting-edge control technologies, inter-provincial and inter-regional conduits can maximise their continuous transmission capacities, further enhancing the architecture of the emerging power system.

Figure 5-18 Inter-regional power transmission in 2035 (TWh, BLS-left, CNS1-mid, CNS2-right)

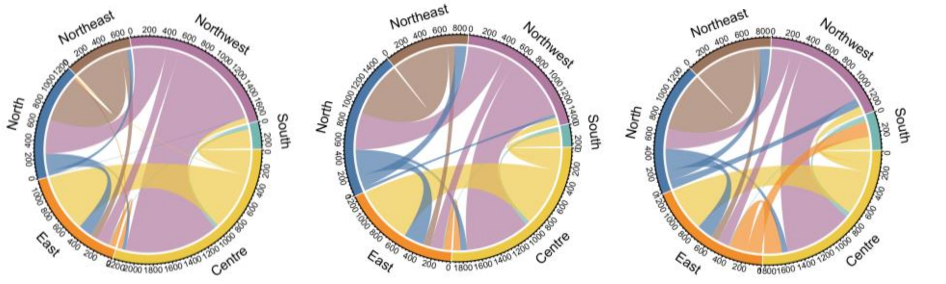
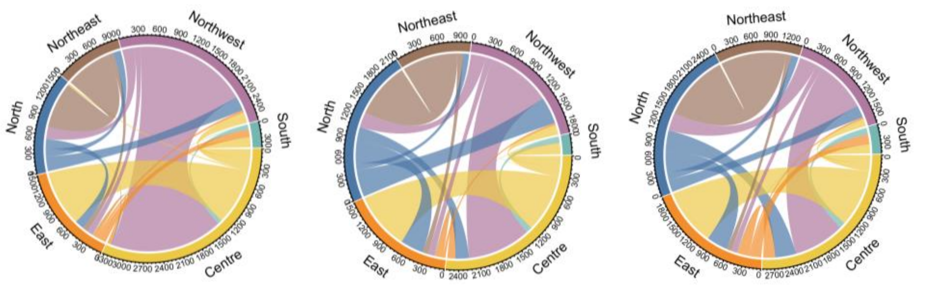


Figure 5-19 Inter-regional power transmission in 2060 (TWh, BLS-left, CNS1-mid, CNS2-right)



5.6 Power market reform

New-type power system catalyses the rapid evolution of the power market

The carbon peak and carbon neutrality goals have presented new requirements for accelerating the development of the power market. In 2022, China's power market achieved unprecedented milestones in trading volume and the number of active market participants. Plans for electricity generation and consumption were systematically liberalised, leading to the full regional deployment of medium to long-term and ancillary service markets. Six spot pilot areas, including Shanxi, embarked on the trial phase of continuous long-term settlements. The Southern region initiated its trial operations, and both inter-provincial and inter-regional market-driven transactions witnessed consistent progress.

From a macro perspective on the power market's performance, data from transaction settlements reveal that the cumulative market transaction volume in 2022 nationwide soared to 5,250 TWh. This signifies a 39% surge from the previous year, accounting for 60.8% of the total electricity consumption. Of these transactions, market-driven trading spanning provinces and regions surpassed 1,000 TWh, reflecting an impressive 50% year-on-year growth. The count of market participants enlisted with power trading establishments eclipsed 600,000, marking a 29% yearly upswing. Nationally, the average trading price for coal power plants settled at 0.449 RMB/kWh, offering an approximate 18.3% margin over the national average baseline electricity price, thereby easing the fiscal strain on thermal power companies. In terms of the pilot operations for inter-provincial and inter-regional exchanges, the integrated Sichuan-Chongqing peak-shaving market streamlined the use of an additional 4.5 GWh of off-peak hydropower in Sichuan and bolstered peak-shaving with a maximum 200 MW of inter-regional power aid. The Southern region's market pilot facilitated unprecedented "point-to-point" medium to long-term deals of 20 GWh between power producers in Hainan and power vendors in Guangdong. The regional frequency regulation market incurred costs close to RMB 1.11 billion, underpinning 29 collaborative thermal power-storage integrated frequency regulation projects. Additionally, a regional spot market was inaugurated for non-settlement trial operations on July 23, 2022.

Throughout the formation of the national unified power market and the rejuvenated power system, the discourse on comprehensive integration of renewable energies into market trading structures has taken central stage. Aiming to amplify resource efficiency, the Chinese government unveiled the *Guiding Opinions on Accelerating the Construction of a National Unified Power Market System (NDRC Institutional Reform [2022] No. 118)* in January 2022. This directive outlines benchmarks for the establishment of a national unified power market system by 2025 and 2030. The vision for 2030 encompasses "the holistic realisation of a national unified power market system. This system adheres to the requests of the new-type power system, synchronise the national market with provincial and regional markets, seamlessly incorporate renewable energy into market transactions, guarantee a level playing field and autonomy for market players, and refine the allocation of power resources on a national scale."

The policy underlines the Importance of adapting to the nuances of the new-type power system, especially focusing on the comprehensive integration of renewable energy into market transactions. It distinctly advocates for "amplifying the power market's adaptability to elevated proportions of renewable energy, refining market mechanisms that cater to these high proportions, methodically advancing the inclusion of renewable energy in power market transactions and formulating medium and long-term power trading protocols consistent with the idiosyncrasies of renewable energy. There should be a notable push for renewable energy to engage in longer contract durations during the execution of medium to long-term contracts, and to participate competitively in the spot market. Notably, any electricity left unsold from unsuccessful bids is not classified as curtailed wind or solar power. Moreover, there is a thrust towards enhancing peak-shaving services within the spot market and introducing novel ancillary services like ramping up, especially in areas heavily reliant on renewable energy." These directives underscore that the design and enhancement of China's power market mechanisms ought to proactively evolve in tandem with the rising prominence of variable renewable sources, such as wind and solar.

Box 5-3 Progress in spot power market development

Mid and long-term contracts still dominate China's power market system, the amount of spot power trading is limited. Currently, coal power generation enterprises and industrial and commercial users are the main participants of the spot power market. Due to the different power source and load characteristics, the spot power market presents different characteristics in various places. For example, Inner Mongolia has better wind and solar irradiance resources, thus the average price of the spot market in western Mongolia is relatively low, which can attract more production enterprises to settle down. Solar PV power generation accounts for a large proportion in Shandong, and its spot power market sees a period of negative electricity price during the day. The peak-and-valley price difference widens, fully reflecting that the supply and demand of the spot market determine the electricity price.

Reflect real-time power supply and demand changes

By the requirements of the *Notice on Further Deepening the Marketisation Reform of Coal Power Feed-in Tariff Mechanism (NDRC Pricing [2021] No. 1439)*, the government imposes no upper or lower limit on the price formed through the spot power market. Spot transactions reflect the power supply and demand relationship in a timelier manner, and different time-sharing and regional prices are formed through market competition. Taking the spot power market in Gansu as an example, from May to December 2021, its monthly average spot price increased by 87%, providing a significant reference for subsequent medium and long-term contract transactions. At the same time, affected by market-oriented price fluctuations, more users have changed from "demand-based electricity consumption" to "price-based electricity consumption", and the new user-side peak shaving capacity is nearly 2 GW, accounting for about 12% of the peak load in January 2022. Comparing the load curves of the Gansu Power Grid on a particular day in January 2021 and 2022, its peak load is shifted from 18:00 to 11:00, which not only reduces the pressure of the evening peak hours but also increases the consumption capacity of renewable energy.

Initial realisation of energy cost transmission

Meanwhile, according to the requirements of the *NDRC [2021] No. 1439* document, starting from October 2021, all coal power generation is priced through market-based transactions, to reflect changes more flexibly and truly in the cost of coal power generation. In the winter of last year, affected by the tight coal supply, the medium and long-term coal prices in the State Grid's operating areas rose sharply, and the spot prices of electricity in Shanxi and Gansu rose accordingly, with the maximum increases of the monthly average day-ahead and intraday prices exceeded 60%, preliminarily realised the primary and secondary energy price transmission. This summer, the spot power price in many places has risen due to factors such as high temperature and increased demand for electricity. For example, the real-time clearing price of the Shanxi spot power market once reached 1,600 RMB/MWh on August 26, which truly reflected the cost of local gas power units participating in peak shaving when the power supply was tight.

Green power certificate to enter a new stage of development

In 2017, China initiated its Green Power Certificate system with a voluntary subscription market. Initially, the dominant trading type was the substitution of subsidized green certificates. Given their high pricing, the volume of green certificate subscriptions remained modest. By the end of June 2021, the green certificate's cumulative trading volume stood at a mere 75,800. However, post the *14th Five-Year Plan* period, China's pivot towards price-parity (i.e., subsidy-free available) in renewable energy development triggered a price drop for these subsidy-free project-based green certificates. The aggressive dual-carbon target bolstered the demand for green electricity, causing a substantial upswing in green power certificate demand. In 2022, a staggering 20.6 million green certificates, equivalent to an electricity output of 20.6 TWh, were released — a 135% hike from 2021. Transaction figures touched 9.7 million, translating to an electricity volume of 9.7 TWh, marking a 15.8-fold surge from the prior year. By the end of 2022, the cumulative tally of issued green certificates nationwide approximated 59.5 million, accumulating over 10.31 million transactions. By the end of June 2023, the cumulative transactions further increased to 34.6 million, this significantly furthered the shift towards a greener, low-carbon developmental trajectory.

For the year 2023, in alignment with the dual-control mandates concerning carbon emissions and intensity, the government authorities are ardently championing refinements to the green power certificate system, aiming to elevate green electricity consumption levels. Primary measures include:

1) The revision of the *Notice on Advancing in Full Coverage of Renewable Energy Green Power Certificates and Promoting Renewable Energy Power Consumption* in July 2023, elucidating the authority, distinctiveness, ubiquity, and primacy of green certificates. This also involves broadening the issuance and trading range, expanding trading platforms, ensuring complete issuance coverage, and facilitating integration with the carbon market. It also transparently delineates the rights and responsibilities of principal green certificate market stakeholders, like the issuing entities and trading platforms. Concurrently, a system to administer green certificate accounts is crafted, along with detailing procedural steps for issuing and trading.

2) The amendment of green power trading regulations by the electricity exchanges centres according to the green certificate policy.

3) Enhancements to the renewable energy power consumption assurance mechanism based on green certificates. This aims to guide prudent consumption and harnessing of national renewable energy generation, escalate green electricity consumption levels.

The green value of renewable energy needing to be further manifested

CETO 2023 studies indicate that achieving a high proportion of renewable energy in a carbon-neutral scenario necessitates a technologically neutral, efficient, and competitive power market. Presently, the Chinese power market grapples with issues such as incomplete functionality and inconsistent transaction rules. Medium to long-term markets are dominant, while spot markets represent only a small share of transactions. This structure hinders the effective incentivization of flexibility resources on both the supply and demand sides, undermining power security. Additionally, obstacles remain in cross-provincial and cross-regional trading markets.

The green value of renewable energy sources like wind and solar needs further manifestation. Currently, the green electricity trading market is merely a module within the medium to long-term power market. In 2022, the green electricity premium for wind and solar power in China was relatively modest. For example, Guangdong Power Trading Centre data reveals that the average transaction price for renewable energy electricity in November 2022 stood at 0.5065 RMB/kWh, with the average environmental premium only at 0.0267 RMB/kWh. In some pilot provinces, green electricity prices even dipped below those of coal electricity. When green electricity is on par or even cheaper than coal electricity, the green power market price then largely depends on green power market dynamics and benchmark product prices. It is crucial that the green electricity premium encapsulates the environmental externalities mitigated by green electricity. With all renewable electricity available for issuance of green certificates and most of it tradable, the supply of green certificates would increase substantially in a short period of time, which can lead to a continued decline in the price of green certificates. Therefore, it is necessary to improve the relevant premium and external pricing mechanisms.

Box 5-4 The green power market mechanism

China launched the green power market in 2021. Price parity wind power and solar PV projects became the major players. In August 2022, the government included all renewable energy sources, such as hydropower, biomass, and geothermal power, in the scope of green certificates and green power trading; in February 2023, the government clarified the rules of green power trading for subsidised renewable power projects, aiming to improve the green power market mechanism.

Green power market trading mechanism

The power generation of renewable power projects contains two parts: guaranteed electricity and market-based electricity. Guaranteed electricity, i.e., the power grid uniformly buys a certain number of hours of power generation, and the price is the local baseline price of coal power; market-based electricity is the power generation beyond the guaranteed amount, and the power generation enterprises directly participate in the power market transaction, and the transaction price is determined by the market, which is mainly medium and long-term contracts at present.

After the launch of the green power market, the amount of guaranteed electricity and market-based electricity can freely choose to participate in the general power market or green power market. In the trading of guaranteed electricity, the amount of the transaction price higher than the coal power baseline price can be seen as a green premium; in the trading of market-based electricity, the part of the transaction price higher than the price obtained by participating in the general power market can be seen as green premium.

For grid parity projects, the green premium revenue goes to all power generation enterprises. For subsidised projects, the green premium goes to the government and is used as subsidy funds, but the subsidy the project ultimately receives remains unchanged. When the subsidised project's green power trading amount accounts for more than 50% of its annual feed-in electricity and is higher than the average proportion of green power trading volume in the region, the government prioritises granting subsidies.

Enhancing coordination between the electricity and carbon markets is imperative. Both the green electricity and carbon markets aim to foster the clean and low-carbon transformation of China's power sector. Although their reform trajectories are aligned and there is some overlap in their initiatives, a comprehensive and synergistic plan is missing. A notable gap exists between China Certified Carbon Emission Reductions (CCER) and green electricity certification. The carbon market allows companies to use CCERs to offset a part of their carbon emissions, but most CCERs are sourced from green power projects like existing wind farms and solar PV plants. This can result in double counting. Another issue is the disconnection between implicit carbon pricing tools and carbon trading. Although current policies promoting renewable energy development and carbon reduction inevitably incur costs associated with carbon emission reduction—evidenced by mandatory energy conservation targets, energy efficiency standards, renewable energy quotas, environmental taxes, resource taxes, and fuel taxes—these are often seen as implicit carbon pricing tools. However, quantifying the carbon costs produced by these policy tools and comparing them to carbon prices in the carbon trading market is a complex task. This complexity makes it difficult to accurately evaluate the cumulative emission reduction costs borne by businesses.

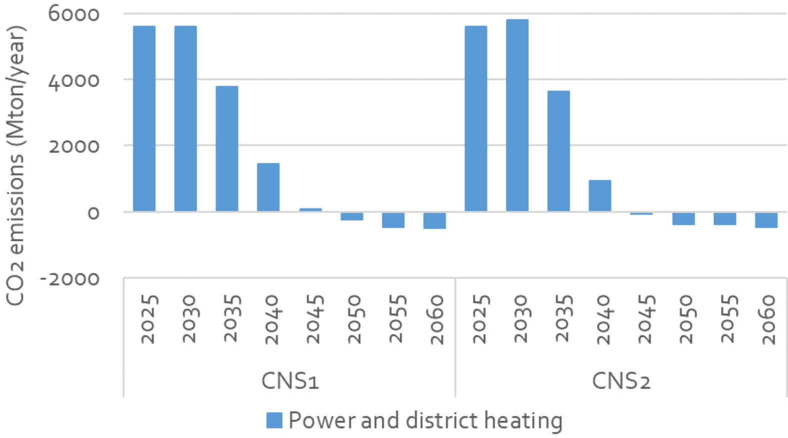
CETO contends that to attain a net-zero emissions trajectory, it is essential to enhance new energy participation in the market. This should include flexible and distributed resources, fortifying the connection between the spot market and the medium to-long-term and auxiliary service markets, and amplifying the synergy between electricity and carbon markets and policy mechanisms.

5.7 The necessity of carbon capture and storage (CCS) and negative carbon technologies

Carbon capture path for the power industry

EDO's simulation results indicate that the power industry, inclusive of district heating, reaches net-zero emissions by 2050 in CNS1, and by 2045 in CNS2. As the power sector strides towards net-zero emissions, the transitional phase necessitates the judicious integration of gas-fired units to supplement the gradual decommissioning of coal-fired plants. In crafting the CETO2023 scenario, we have instituted stringent installation parameters for CCS mechanisms on the remaining coal-fired and gas-fired units within the energy system. Nonetheless, it is pertinent to acknowledge the significant initial investment and operational costs associated with thermal power plants equipped with CCS. Moreover, such plants, despite their advancements, still emit a residual amount of carbon dioxide—around 10% compared to traditional thermal units. These residual emissions mandate compensation through additional negative carbon technologies. Moreover, the adoption of CCS technology brings with it increased energy requirements and consequent costs. Hence, while thermal power CCS is a critical component in the transition towards a lower carbon footprint within the power sector, the energy and financial implications of CCS technologies themselves are non-trivial and must be carefully considered.

Figure 5-20 2025-2060 Carbon dioxide emissions in the power industry (including district heating)



Limitations of negative carbon technologies

The CETO 2023 scenarios project that the energy system seeks to attain net-zero emission around 2055 in CNS1 and before 2055 in CNS2. However, simulation results of the LEAP model suggest that end-use sectors like industry, transportation and building persistently emit carbon dioxide through 2060 in both CNS1 and CNS2. This implies a requirement for negative carbon technologies in such fields as electricity, district heating, and power-to-x production to counterbalance these emissions. Presently, three primary negative carbon technologies are recognised:

- Bioenergy is perceived as carbon-neutral [f], leading to the conclusion that the Bioenergy with Carbon Capture and Storage (BECCS) technology results in negative emissions.
- Direct Air Capture (DAC) is a method that actively absorbs carbon dioxide directly from the atmosphere, which is then stored.
- Finally, carbon offsetting can be extended beyond the energy sector to encompass carbon sequestration in agriculture and forestry.

Resource constraints of bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) stands as the preeminent selection for negative emission technologies. Within the parameters of the EDO model, it is mandated that for both CNS1 and CNS2 scenarios, the integration of CCS technology is compulsory for all new biomass power generation units at specified junctures in their implementation. By 2060, both CNS1 and CNS2 project the total installed capacity of BECCS to reach 67 GW. Nevertheless, the inaugural simulation results from CETO2023 highlight a significant caveat: China's limited biomass resources make an exclusive reliance on BECCS inadequate for counterbalancing the residual carbon dioxide emissions in the energy sector. This shortfall underscores the importance of integrating DAC and other offset technologies.

The big uncertainty of Direct Air Capture (DAC) technology

Based on the current technological level, the Direct Air Capture (DAC) technology consumes large amount of energy and creates high cost during carbon capture process. Owing to the intrinsic uncertainties associated with DAC as a negative emission technology, its adoption has emerged as an unavoidable option. Consequently, we require utilising carbon offset strategies beyond the energy sector as an alternative to DAC for carbon sequestration.

[f] Biomass combustion is typically viewed as carbon-neutral since the carbon dioxide emitted during the burning process is offset by the absorption from newly planted trees. However, with the incorporation of carbon capture equipment on biomass power generators, the biomass combustion effectively becomes carbon negative. This means that the carbon dioxide absorbed by the new trees effectively contributes to a net reduction in atmospheric carbon, resulting in what can be termed as negative emissions.

Chapter 6

Socio-economic impact assessment of China's energy transition

6 Socio-economic impact assessment of China's energy transition

6.1 Key messages

- This chapter presents research findings on the socio-economic impact evaluation of China's energy transition, highlighting the potential differential changes in economic and social development that may arise from three distinct energy transition scenarios in China. The chapter is divided into three parts.
- Evaluation methodology, in which CETPA, a Chinese multisectoral dynamic computable general equilibrium model suitable for evaluating China's energy transition policies, is constructed.
- Impact evaluation of energy transition on socio-economic development, focusing on changes in industrial structure, economic growth drivers, economic growth quality, employment, wage income, environmental quality, and other factors.
- A local case study of energy transition, examining the impact on socio-economic development based on the energy transition history in Beijing.
- The evaluation results of the model indicate that China's energy transition provides safe and efficient energy security for socio-economic development, and that it also promotes industrial upgrading during the transformation process, enhancing the quality of economic growth and the development of clean and low-carbon energy. This ensures the achievement of sustainable development goals such as carbon peak and carbon neutrality, and contribute to building a beautiful China.

6.2 Evaluation methodology

To systematically evaluate the potential impacts of energy transition on China's socio-economic development and examine the macroeconomic effects of different energy transition policies and pathways, we developed a Computable General Equilibrium (CGE) model, or CETPA[9], for evaluating the socio-economic impacts of energy transition in China.

CETPA is a dynamic multisectoral CGE model specifically developed for China. CETO 2023 constructed a social accounting matrix using the most recent input-output table data, import-export data, and other pertinent statistics released by the National Bureau of Statistics (NBS). The CGE method was then used to quantify the socio-economic effects of China's energy transition in support of achieving carbon peak and carbon neutrality objectives. While constructing the CETPA model, we consider the research needs of evaluating the socio-economic impacts of China's energy transition in terms of variable settings, equation combinations, and model closure conditions, as well as

[9] CETPA is the abbreviation of China Energy Transformation Policy Assessment.

requirements for integration with two other models in this project (EDO and LEAP). The development process drew upon methods from OECD Development Centre's GREEN Model[h] and Tsinghua University's TECGE Model.

The CETPA model includes four agents and three production factors. The four agents are households, enterprises, government, and foreign entities, where households include both rural residents and urban residents. The three production factors are labour, capital, and energy, where energy includes coal, oil, natural gas, and electricity which can be further divided into thermal power generation, hydroelectric power generation, nuclear power generation, and non-hydro renewable electricity.

Assumptions of the CETPA model

Under the assumptions of the computable general equilibrium analysis method, all domestic producers and consumers are homogeneous, and residents are composed of numerous homogeneous consumers in the country. The technological development level of producers in each economic sector is also synchronous. Furthermore, the CETPA model makes the following fundamental assumptions:

1) Producers make decisions based on profit maximisation, while consumers make decisions based on utility maximisation. The market is perfectly competitive, and when making decisions, producers and consumers treat prices as exogenous variables. In any given year, the existing capital stock in each sector is fixed and cannot flow between sectors; between years, capital in each sector increases or decreases through investment and depreciation. Changes in capital for each production sector are realised through dynamic recursion to achieve dynamic changes in capital stock. Labour can migrate across production sectors at any time, and wages for each sector remain constant during every period with wage change rates being consistent across different years; hence, labour markets are not fully employed.

2) Production factors, such as coal, oil, natural gas and electricity, have substitutability among them which together form energy combination factors; capital and labour have substitutability among them which together form value-added factors; energy combination factors have substitutability with value-added factors. There is no substitution among other non-energy intermediate inputs which along with energy combination factors and value-added factors are used for output production by production sectors. Different products of the electric power sector have substitutability with one another, which together form an electric power element - For example, with energy transition policies implemented alongside environmental protection policies, thermal power may gradually be replaced by hydroelectricity, nuclear power, or other renewable electricity.

[h] The GREEN model has been widely used for socio-economic impact assessment of climate change mitigation, with high international recognition.

3) Most goods involve two-way trade imports/exports where imported goods do not completely substitute domestically produced products due to product differentiation.

4) The allocation of total investment among various sectors depends partly on the proportion of each sector's capital income in total capital income and is also influenced by investment inertia and government investment policies.

5) If a carbon tax policy is adopted, the carbon tax will be levied on energy users, including energy demand in both production and consumption sectors. Carbon tax revenue is recorded as part of fiscal income.

6) If a renewable energy subsidy policy is adopted, the subsidy comes from government finance and is used for the production of renewable electricity.

Sectoral division of the CETPA model

To depict China's energy transition using a model that controls complexity within the range of obtainable data for constructing social accounting matrices, can be solved by desktop computers, and produces interpretable results, the CETPA model divides China's national economy into 16 sectors. The non-energy sectors are suitably integrated, while the level of detail in the energy sectors is increased. The model consists of a total of 7 energy sectors and 9 non-energy sectors, including coal, oil, natural gas, thermal power generation, nuclear power generation, hydroelectricity, and non-hydropower renewable electricity. The non-energy sectors comprise agriculture, heavy industry, light industry, equipment manufacturing, construction, transportation, commerce, accommodation and catering services, medical and health care, and other services. The relationships between these sectors and the sectors listed in input-output tables are presented in Table 6-1.

Table 6-1 Sectoral division of the CETPA model

Sector No.	Sector Name	Sector No. in Input-Output Tables (IOT)
1	Agriculture	1-5
2	Heavy Industry	8-11, 43-66, 100
3	Light Industry	12-40
4	Equipment Manufacturing	67-97
5	Construction	101-104
6	Transportation	107-117
7	Commerce, Accommodation and Catering	105-106, 119-120
8	Medical and Health Care	141
9	Other Services	118, 121-140, 142-149
10	Coal	6, 42

11	Oil	7, 41
12	Natural Gas	7, 99
13	Thermal Power	98
14	Nuclear Power	98
15	Hydroelectricity	98
16	Non-hydropower Renewable Electricity	98

Structure of the CETPA model

The CETPA model is composed of 11 modules (Table 6-2) that reflect the operational logic and interrelationships of production, factor demand, prices, income, consumption, investment, capital accumulation, foreign trade, market equilibrium, energy and environmental characteristics, and welfare in the national economic system. Each module contains a set of equations that describe the interrelationships between demand, input, and output within that module. In total, there are 95 equations across all 11 modules. Due to space limitations in this report, we do not include these equations or their explanations. Instead, we will describe the main features of the CETPA model based on its structural relationships.

Table 6-2 Module composition of the CETPA model

Module No.	Module Name
1	Production Module
2	Factor Demand Module
3	Price Module
4	Income Module
5	Consumption Module
6	Investment and Capital Accumulation Module
7	Foreign Trade Module
8	Energy Environment module
9	Market Equilibrium module
10	Analysis of Energy Consumption Changes module
11	Welfare Index Analysis module

The CETPA model primarily employs CES functions in its production functions, while the combination between non-energy intermediate inputs and between capital-labour-energy and non-energy intermediate inputs uses the Leontief (Leontief) production function (Figure 6-1, Figure 6-2). Within the intermediate inputs, coal, oil, natural gas, and electricity are substitutable with each other to form an energy factor group. There is also substitutability between capital and labour, which together form a capital-labour factor group. There is also substitutability between energy and capital-labour factors, which together form the energy-capital-labour group. Other non-energy intermediate inputs are not substitutable with each other, but they combine with capital-labour-energy groups to form total output.

Most goods have two-way trade flows of imports and exports. For imported goods, the CETPA model adopts Armington's assumption that imported products do not have complete substitution with domestically produced goods due to product differentiation. Domestic consumers choose a combination of imported products and domestic products according to CES function to form composite goods. The situation for exports is similar to imports; changes in the ratio of product sales between domestic sales and exports are caused by changes in relative prices of market commodities at home or abroad. The degree of conversion between domestic sales and exports can be measured by price conversion elasticity, as shown in Figure 6-3.

Figure 6-1 Production structure of non-energy sectors

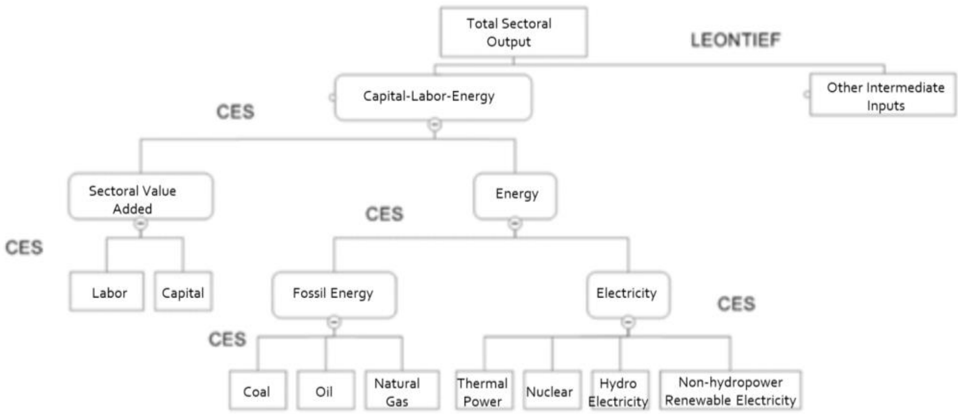


Figure 6-2 Production structure of energy sector

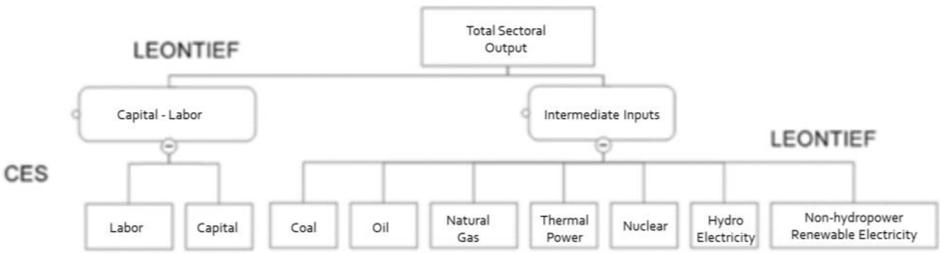
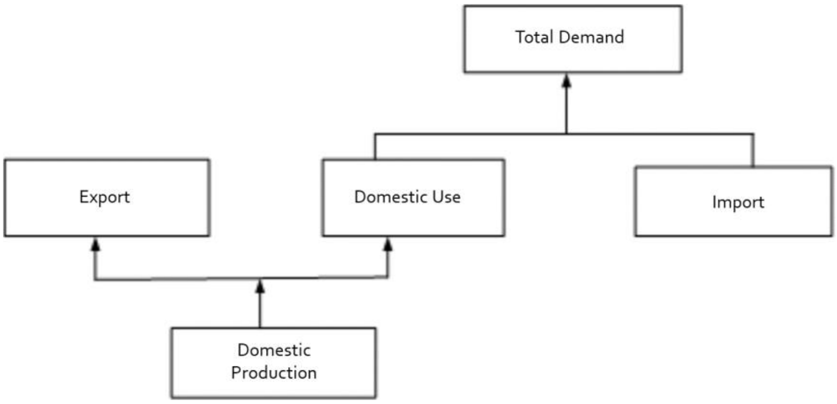


Figure 6-3 The substitution relationships between commodity imports and exports and domestic products



The CETPA model incorporates four types of equilibrium relationships:

1) Commodity market equilibrium, where the total composite supply of a commodity equals the quantity demanded by society as intermediate inputs for the product, final consumption by residents, government consumption, demand for investment goods by enterprises, and inventory increase. The equilibrium in the commodity market indicates that the total composite product supply of each sector equals domestic total demand.

2) Labour market equilibrium, where labour supply equals labour demand. In the model, labour is homogeneous and can flow freely between sectors. Labour can reach full employment level where the sum of all sectors' equilibrated labour force equals the exogenously given total labour force quantity. There may be unemployment where the sum of all sectors' equilibrated labour force is less than the exogenously given total labour force quantity.

3) Capital market equilibrium, where the model assumes that capital cannot flow freely between sectors in the short-term but uses dynamic recursion to adjust it in the long-term.

4) Import-export trade balance, where the import-export trade surplus or deficit equals net foreign borrowing plus net inflow/outflow foreign exchange plus foreign savings after deducting trade deficits.

In addition to these four types of equilibria conditions mentioned above, there are other local scope balance conditions involved in this model, such as energy existing as a sectoral product with its own supply-demand balance, the government budget needing to achieve balanced revenue-expenditure, and savings-investment needing to achieve an overall balance, among others. However, these other conditions are not listed here one-by-one.

6.3 The impact of China's energy transition on socio-economic development

CETO 2023 has been categorised into three scenarios: the Baseline Scenario (BLS), Carbon Neutrality Scenario 1 (CNS1), and Carbon Neutrality Scenario 2 (CNS2). Definitions of these three scenarios align with those provided in the preceding chapters of this report. Utilising the results of the EDO and LEAP models' simulations for China's energy transition from 2023 to 2060, we have compiled key data on China's primary energy consumption, energy consumption structure by type, total electricity production, and power source structure for these three scenarios. We conducted an analysis of the social and economic impacts of China's energy transition under these three scenarios using the CETPA model.

Changes in Industrial Structure

The energy transition contributes to modifications in the industrial structure. Figure 6-4 illustrates the industrial structure under the BLS scenario. It shows that the proportion of primary industry in China gradually decreases from 7.5% in 2020 to 3.5% in 2060. The proportion of secondary industry also gradually decreases from 39.5% in 2020 to 25.2% in 2060, with a faster decline from 2020 to 2040 when it drops from 39.5% in 2020 to 27.4%. Meanwhile, the proportion of tertiary industry gradually increases from 53.1% in 2020 to 71.4% in 2060, with a faster increase from 2020 to 2040 when it increases from 53.1% in 2020 to 67.7%. Additionally, the proportion of output in the energy sector in gross domestic product (GDP) gradually decreases from 5.9% in 2020 to 2.3% in 2060, and the proportion of electricity in the gross domestic product (GDP) decreases from 2.2% in 2020 to 2.1% in 2060.

Figure 6-4 Trends of changes in industrial structure under the BLS scenario

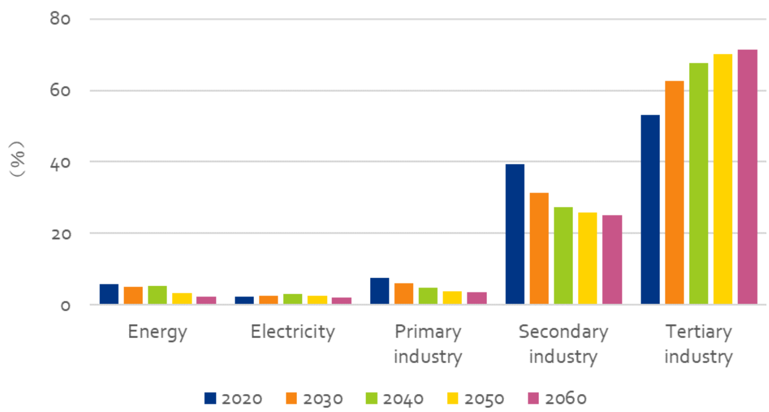


Figure 6-5 illustrates the proportion of various industrial sectors in China's macro economy in GDP under the BLS scenario. It shows that the proportions of agriculture, heavy industry, light industry, construction, coal, oil, natural gas, and other sectors gradually decrease in GDP. However, the proportions of equipment manufacturing and hydropower and other sectors fluctuate while increasing over time. Additionally, the proportions of transportation industry, commercial catering industry, medical health care industry, other service industries, and non-hydropower renewable energy sector gradually increase in GDP.

Figure 6-5 Proportion of various industries in GDP under the BLS scenario

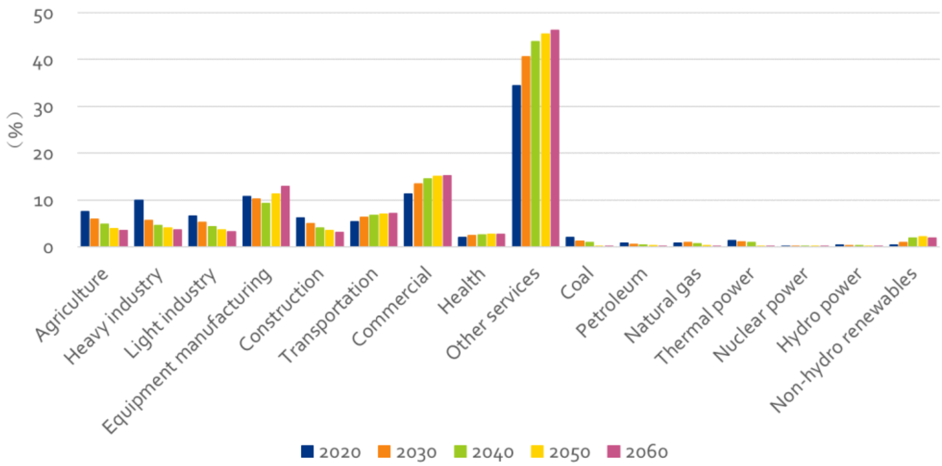
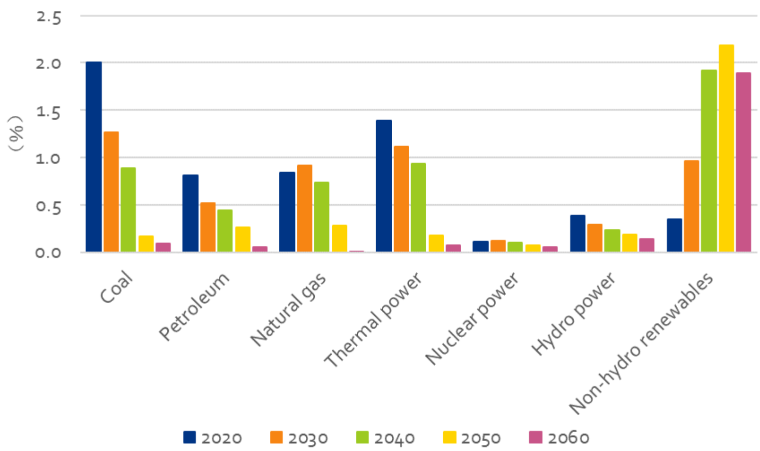


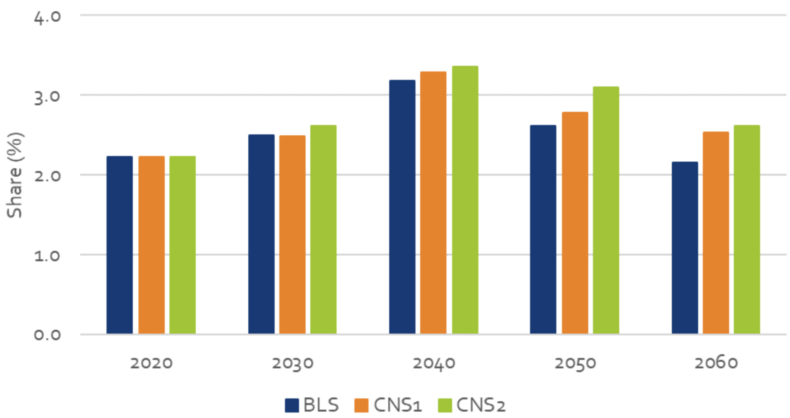
Figure 6-6 illustrates changes in the proportion of value added by energy industry under the BLS scenario. The proportion of coal, oil, natural gas, thermal power, hydropower and other sectors in GDP gradually decreases, with a faster decline from 2020 to 2050. The proportion of nuclear power first rises and then slowly declines while that of non-hydropower renewable energy increases rapidly.

Figure 6-6 Changes in the proportion of value added by energy industry under the BLS scenario



The changes in the GDP share of the electricity industry under different scenarios are shown in Figure 6-7. Compared with the BLS scenario, CNS1 and CNS2 have higher shares for the electricity industry's GDP which reflects that promoting energy transformation can make high-quality energy contribute more to economic and social development.

Figure 6-7 Trends of changes in the GDP share of the power industry



Changes in employment structure

Figure 6-8 illustrates the employment trend within China's three industrial sectors in the BLS scenario. The total employment remains relatively stable, declining from 789 million in 2020 to 786 million in 2035, and further reducing to 698 million by 2060. Influencing factors include the rate of economic growth, adjustments in industrial structure, energy structure transformation, and fluctuations in labour supply. Among the three industries, the primary industry's employment steadily decreases from 114 million in 2020 to 47 million in 2060. Employment in the secondary industry also declines from 255 million in 2020 to 147 million in 2060. Conversely, employment in the tertiary industry initially rises from 419 million in 2020 to 522 million in 2035, before gradually decreasing to 503 million in 2060.

Figure 6-8 Trend of changes in employment levels for the three industries under the BLS scenario

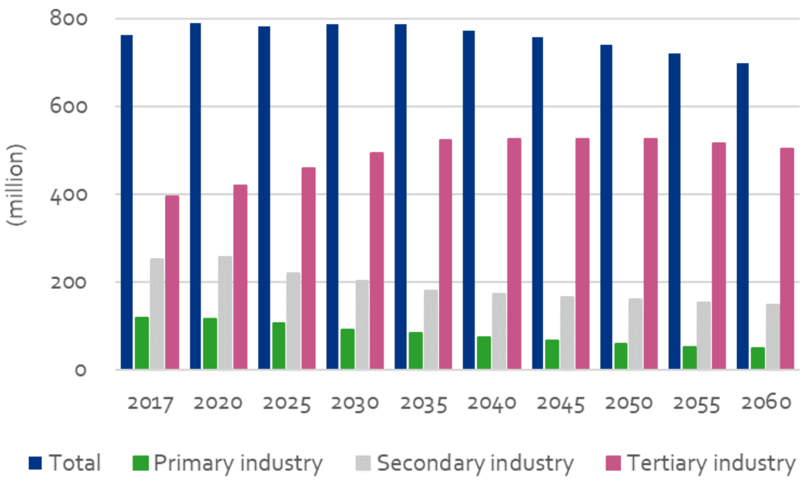


Figure 6-9 presents the employment levels for various industrial sectors under the BLS scenario. As per the projection, employment levels for agriculture, heavy industry, light industry, construction industry, coal, thermal power generation, and other related sectors gradually decrease over time. In contrast, the employment levels of transportation, commercial catering, medical healthcare, other service sectors, natural gas, and non-hydropower renewable electricity experience a gradual increase, reaching their peak before eventually decreasing again. The employment level for equipment manufacturing experiences a gradual upward trend with some fluctuations.

Figure 6-9 Trend of changes in employment levels for industrial sectors under the BLS scenario

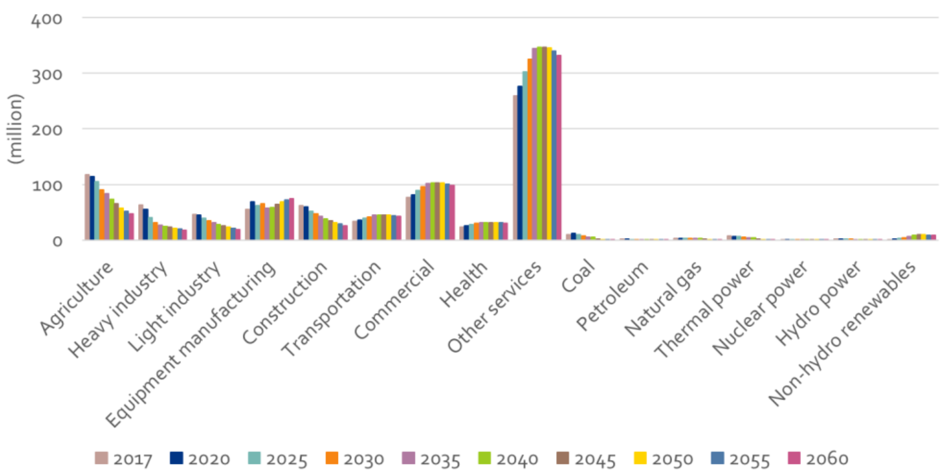


Figure 6-10 illustrates the trend of changes in employment in the energy sector under the BLS scenario. As per the projection, employment levels of coal, oil, thermal power generation, and hydropower generation gradually decrease. In contrast, employment levels of natural gas, nuclear power, and non-hydropower renewable electricity gradually increase, reach their peak, and continue to occupy the first place in the energy sector in terms of employment level by 2060. Under the carbon neutrality scenarios CNS1 and CNS2, non-hydro renewable electricity generates more job opportunities compared to the BLS scenario. These new employment opportunities offset the job losses in traditional industries such as coal and thermal power caused by energy transition.

Figure 6-10 Trend of changes in employment levels for energy-related sectors under the BLS scenario

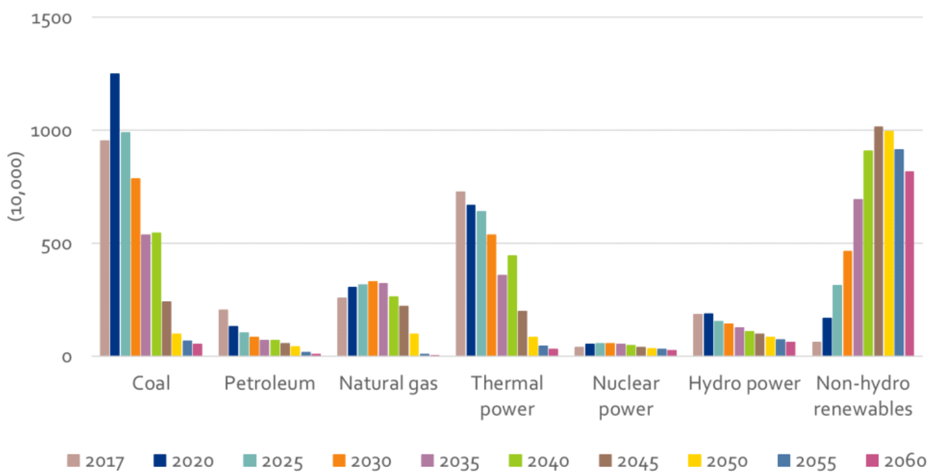
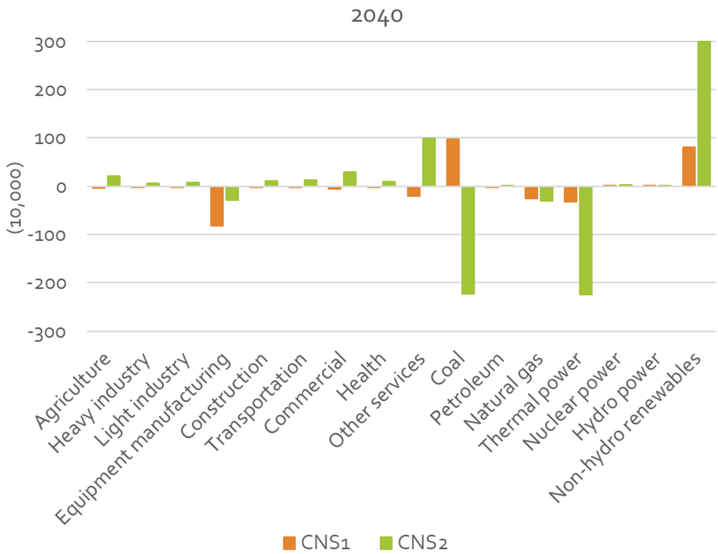
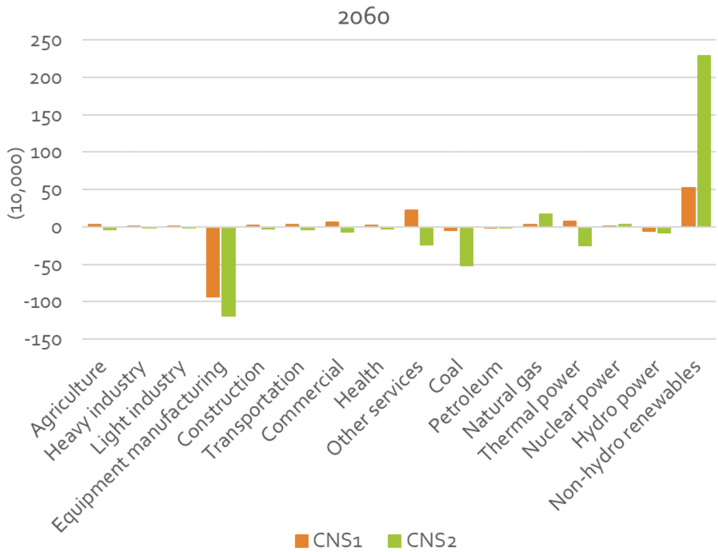


Figure 6-11 illustrates the changes in employment levels of various sectors under the CNS1 scenario and CNS2 scenario in 2040 and 2060 compared to the BLS scenario. Employment levels of equipment manufacturing, coal, and thermal power significantly decrease under both CNS1 and CNS2, while employment levels of other service industries and non-hydro renewable electricity sectors increase significantly. This is consistent with the analysis of energy transition and structural adjustment results, where changes in output lead to changes in employment levels within the energy sector. As energy transition promotes innovation and leads to accelerated technological progress in sectors such as equipment manufacturing, technological substitution leads to a decline in employment. It is noteworthy that although there is a decline in sectoral employment levels, sectoral output and GDP still increase, confirming the effect of technological progress yet from another angle.

Figure 6-11 Comparison of changes in employment by sector between carbon neutrality scenarios and BLS scenario





Driving factors for economic growth

Figure 6-12 illustrates the changes in capital investment by various sectors under the BLS scenario. Except for coal, oil, thermal power, and hydropower, all other sectors show an increase in capital investment. Heavy industry, light industry, equipment manufacturing, transportation, commercial catering, and other service industries have relatively large capital investments with higher added value. The capital investment of coal, oil, thermal power, and hydropower shows a process of growth-reaching peak-decline.

Figure 6-12 Changes in capital investment by sector under the BLS scenario

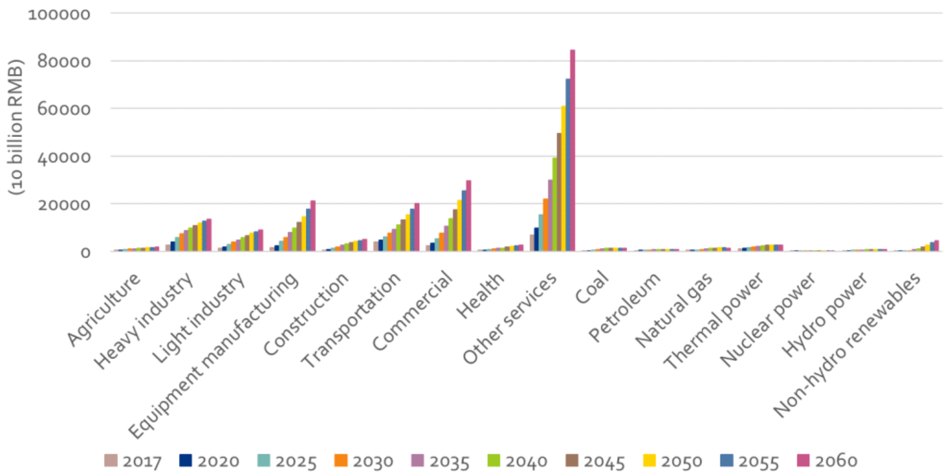


Figure 6-13 Changes in capital investment by various energy-related sectors under the BLS scenario

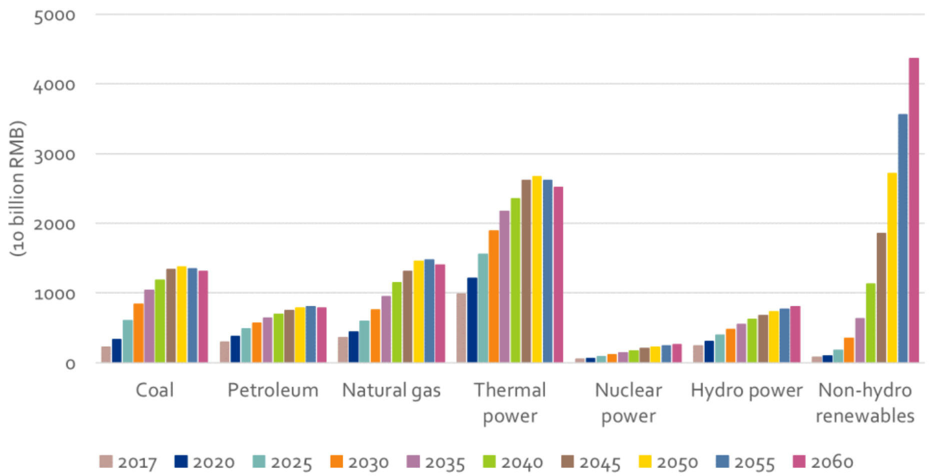


Figure 6-13 displays the changes in capital investment by various energy sectors under the BLS scenario. The capital investments of coal, oil, natural gas, and thermal power generation first increase to reach their peak values before declining again. In contrast, nuclear power, hydropower, and non-hydropower renewable electricity sectors maintain continuous growth.

Figure 6-14 illustrates the changes in capital investment across various sectors under the CNS1 scenario in comparison with the BLS scenario. Capital investments in the nuclear power, hydropower, and non-hydropower renewable electricity sectors see an increase. Among these, the non-hydropower renewable electricity sector registers the highest growth rate, with capital investment rising by 6.5% in 2060 compared to the BLS scenario. Conversely, capital investments in equipment manufacturing, natural gas, and thermal power experience a downturn. By 2060, these sectors show declines of 1.2%, 4.0%, and 0.5% respectively when compared to the BLS scenario.

Figure 6-14 Comparison of capital investment by various sectors under CNS1

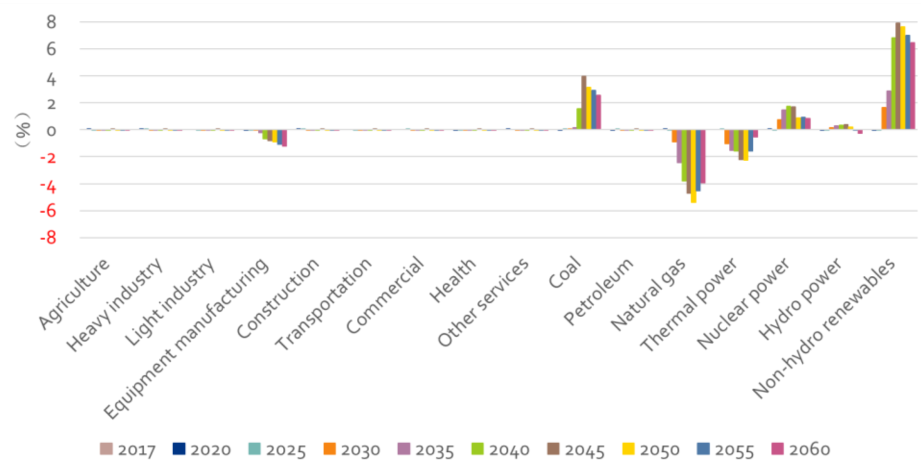


Figure 6-15 Comparison of capital investment by various sectors under CNS2

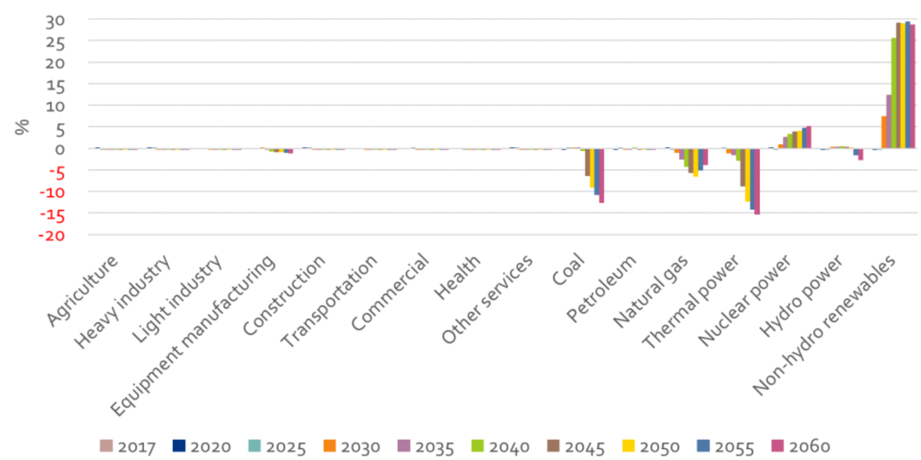
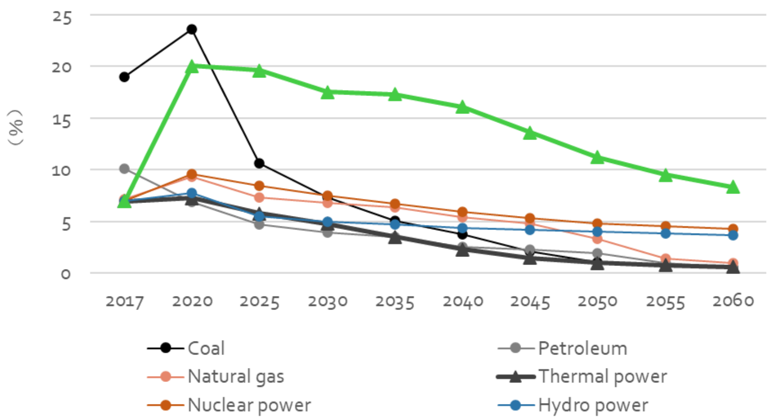


Figure 6-15 shows the shifts in capital investment across various sectors under the CNS2 scenario relative to the BLS scenario. Both the nuclear power and non-hydro renewable electricity sectors are predicted to see increases in capital investment, with the latter demonstrating the most pronounced growth. By 2060, capital investment in the non-hydro renewable electricity sector exceeds the BLS scenario by 28.7%. In contrast, the sectors of equipment manufacturing, coal, thermal power, and natural gas witness declines in capital investment, with reductions of 1.1%, 12.5%, 15.3%, and 3.8% respectively by 2060 compared to the BLS scenario. This denotes a more significant shift in investment structure under the CNS2 scenario than the CNS1 scenario.

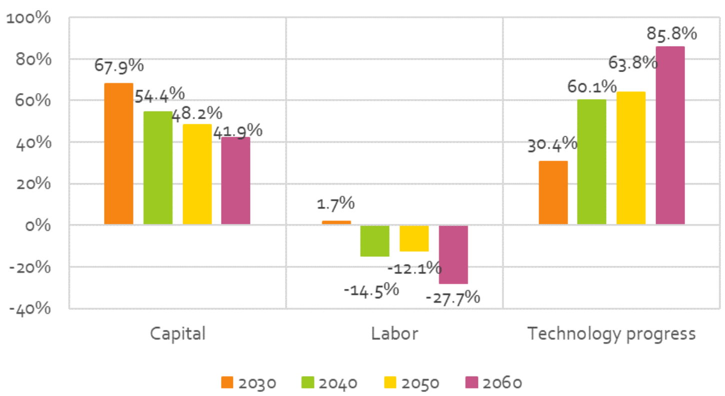
According to model results, the changes in capital investment for various sectors affect the capital return rates accordingly. Figure 6-16 illustrates the capital return rates for various energy sectors under the BLS scenario. All energy sectors show a decline in capital return rates, with coal experiencing the fastest decline. However, non-hydropower renewable electricity and nuclear power still have relatively high returns on investments compared to other energy sources. By 2060, their respective capital return rates are 8.3%, 4.3%, and 3.7%.

Figure 6-16 Changes in capital return rates of energy-related sectors under the BLS scenario



The contribution rates of economic growth factors in future years under the BLS scenario are shown in Figure 6-17. The contribution rate of capital is gradually decreasing, from 67.9% in 2030 to 41.9% in 2060. The contribution rate of technological progress is steadily increasing, from 30% in 2030 to 86% in 2060. This indicates that future economic growth relies on technological progress followed by capital investment. Due to population decline and aging, as well as the reduced working population, the contribution rate of the labour force to economic growth gradually declines.

Figure 6-17 Contribution rates of economic growth factors in future years under the BLS scenario



Changes in environmental quality

Based on the changes in energy structure under different scenarios and considering the emission factors of different pollutants, the changes in $PM_{2.5}$, SO_2, and NO_x emissions are calculated. It is found that the emissions of major atmospheric pollutants such as $PM_{2.5}$, NO_x, and SO_2 significantly decrease with energy transition, as it helps to achieve source reduction of air pollutants. With the attainment of net-zero carbon emissions in the energy system, both CNS1 and CNS2 fully address the issue of atmospheric pollutant emissions by 2055. This pivotal development provides essential support for enhancing air quality and contributing to the construction of a beautiful China.

The emission trends of atmospheric pollutants $PM_{2.5}$, SO_2, and NO_X in three scenarios are depicted in Figure 6-18, Figure 6-19, Figure 6-20, respectively.

Figure 6-18 Trends in future $PM_{2.5}$ emissions

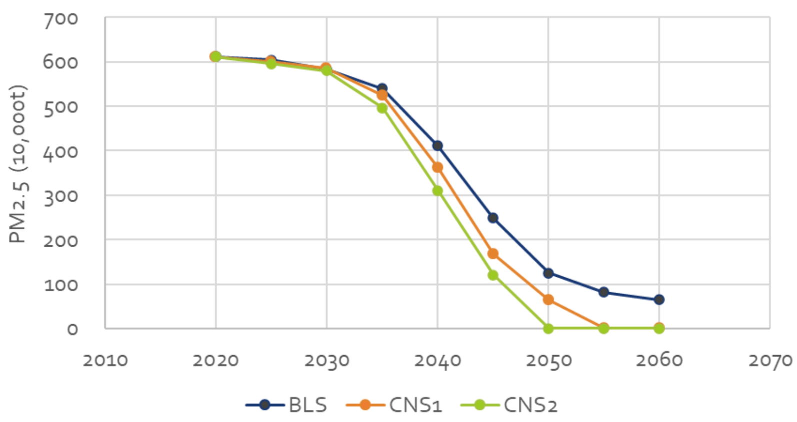


Figure 6-19 Trends in future NO_x emissions

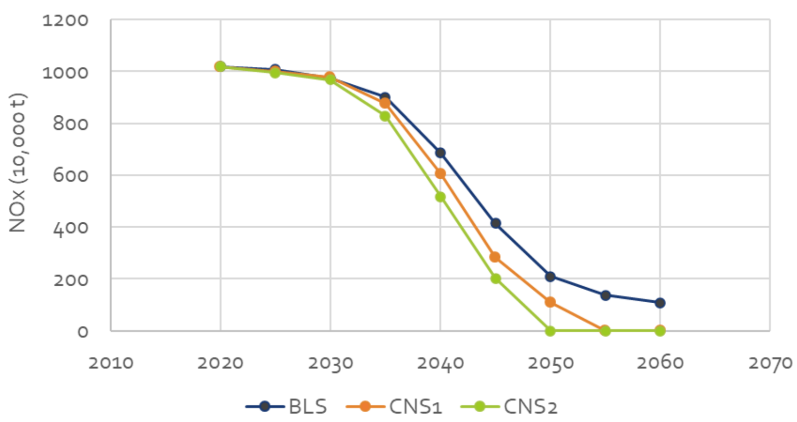
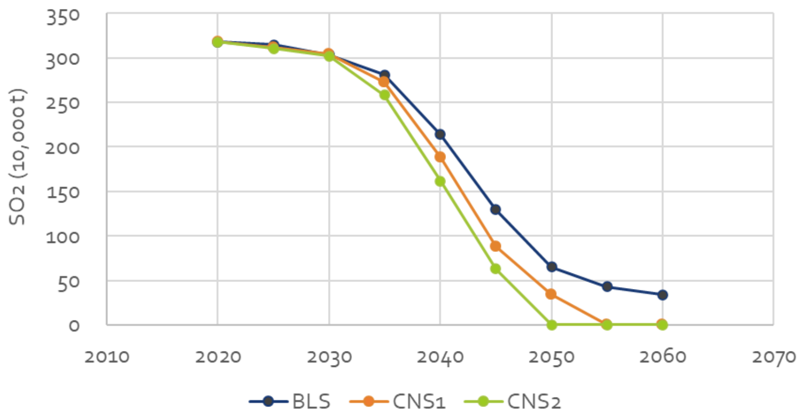


Figure 6-20 Trends in future SO_2 emissions

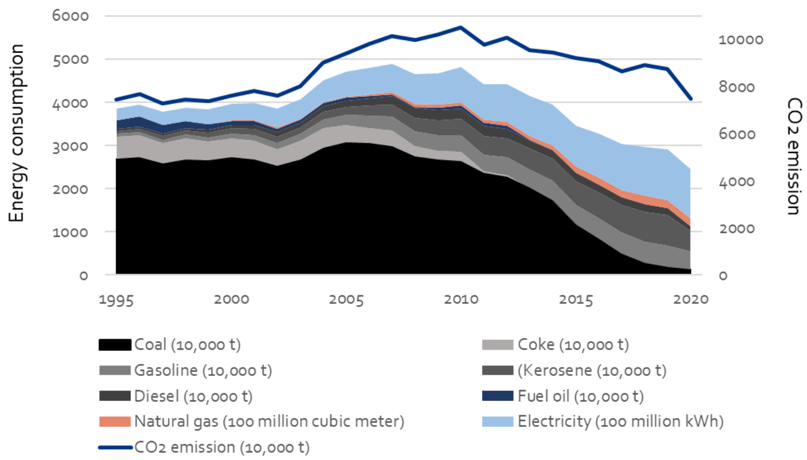


6.4 Case analysis of local energy transition – analysis of the environmental effects of Beijing's energy transition pathway

The Beijing Administrative Region encompasses a total area of 16, 410 square kilometres. The city had a permanent population of 21.9 million people as of the end of 2021, including 19.2 million urban residents and 8.3 million permanent migrants. Beijing's regional GDP in 2021 was RMB 4.03 trillion, with a ratio of 0.3:18:81.7 across three industries. Based on its permanent population, the city's regional per capita GDP was RMB 184,000. As China's capital and host city for two Olympic Games in 2008 and 2022, respectively, Beijing has been at the forefront of China's energy transition and industrial transformation. Examining the energy transition process in Beijing provides tangible insights that facilitate understanding and analysis of China's energy transition pathway and its associated socio-economic impacts.

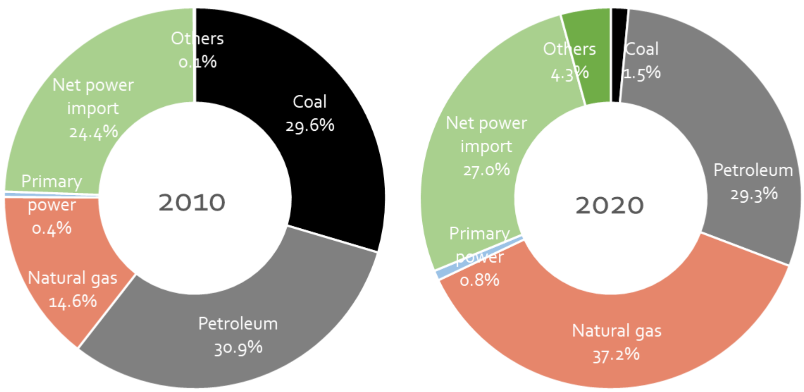
Figure 6-21 illustrates the trend of changes in energy consumption and carbon dioxide emissions in Beijing since 1995. The city's energy structure underwent significant changes from being mainly coal-based (accounting for about 80%) in 1995 to being primarily dominated by high-quality energies such as electricity (with coal accounting for only 1.5%) in 2020 (Figure 6-22). Throughout this period, the concentration of contaminants in Beijing's atmosphere fell annually, and air quality improved considerably (Figure 6-23).

Figure 6-21 Trend of changes in energy consumption and carbon dioxide emissions in Beijing



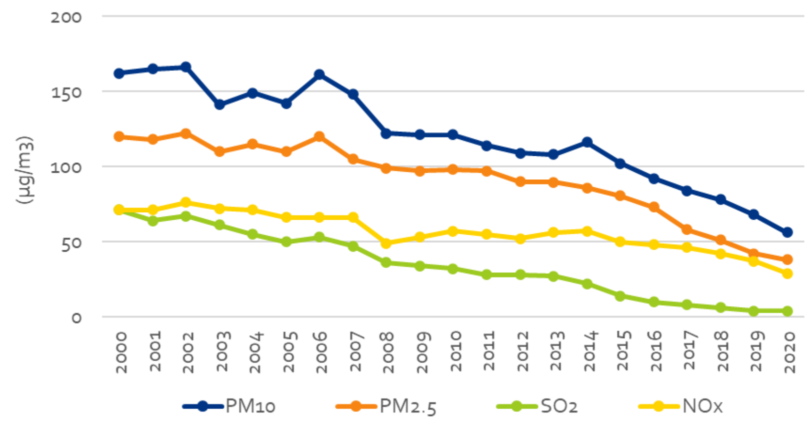
Note: The CO_2 emission does not include indirect emissions corresponding to net imported power. Data source: Energy data comes from National Bureau of Statistics while CO_2 emissions are calculated results.

Figure 6-22 Energy consumption structure in Beijing in 2010 and 2020



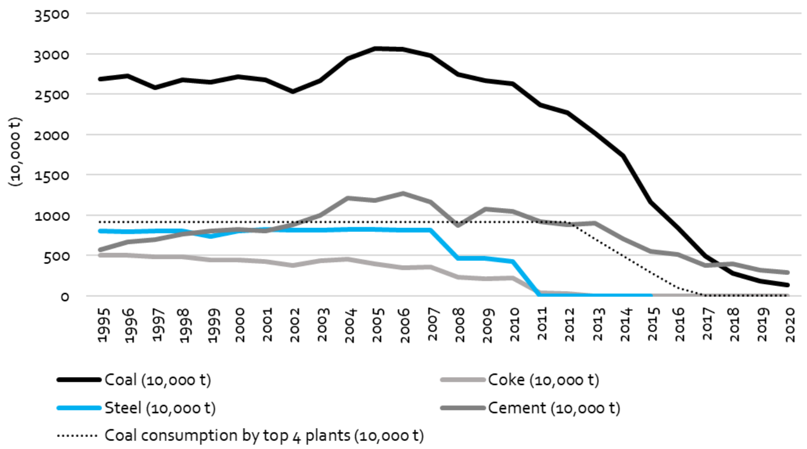
Data source: Beijing Statistical Yearbook 2021

Figure 6-23 Trend of changes in air pollutant concentration in Beijing



Data source: Beijing Municipal Ecology and Environment Bureau

Figure 6-24 The primary path for reducing coal consumption and carbon emissions in Beijing



Data source: National Bureau of Statistics, Beijing Municipal Bureau of Statistics.

Following the relocation of Shougang (Capital Steel) in 2011, both the coke consumption and crude steel production in Beijing dropped to zero in sync. In 2012, coal-fired units at Datang Gaojing Thermal Power Plant, Jingneng Shijingshan Thermal Power Plant, Guohua Beijing Thermal Power Plant, and Huaneng Beijing Thermal Power Plant were successively shut down. By 2017, all of the coal-fired thermal power units had been completely phased out. Local power and heat sources were concentrated into four major gas-fired combined heat and power centres located at Gaojing (northwest), Caoqiao (southwest), Gaobeidian (southeast), and Gao'antun (southeast). Over the past decade, the Beijing energy sector at the forefront of the campaign has launched a comprehensive battle against pollution prevention and control. The sector has implemented comprehensive measures and taken multiple steps to overcome difficulties, accelerating coal reduction and the construction of a clean and efficient energy system with unprecedented efforts. Coal consumption has been significantly reduced from 21.796 million tons in 2012 to 1.31 million tons in 2021, achieving basic "coal-free" status in plain areas. Coal reduction measures have also contributed to more than half of the direct $PM_{2.5}$ emission reductions in Beijing. With the successive completion of the four major gas-fired combined heat and power centres, Beijing has eliminated 2.7 GW of coal-fired units and added 7.2 GW of gas-fired units, truly achieving local clean electricity production. Boiler rooms of all sizes in the city have undergone renovations. Thirty-one new urban centralised heating centres and 63 large coal-fired boiler rooms in the central urban area have undergone clean energy transformation one after another, with a cumulative completion of about 40,000 tons of clean coal-fired boiler replacements, helping the city to basically realise clean replacements for urban heating and industrial coal use. The plain areas have essentially achieved the "coal-free" goal. At the same time, more than 1.3 million rural residents in the city have switched from coal to electricity or gas, ushering in a new clean heating life.

A review of Beijing's energy transition history reveals that the reduction in coal usage is a pivotal factor, largely driven by proactive transformations and enhancements in industrial and energy structures. Specifically, the 2005-initiated relocation of Shougang had a considerable impact on reducing coking coal demand at the source. Over the five-year period from 2012 to 2017, the systematic overhaul of four major coal-fired power plants, coupled with a decrease in cement production and a reduction in rural household heating coal consumption, significantly diminished the demand for coal (as shown in Figure 6-24). In addition, the strategy of compensating for local power supply deficiencies by importing electricity from external sources has been a crucial enabler for Beijing in achieving its low-carbon energy transition (as illustrated in Figure 6-21 and Figure 6-22).

Part 3: Thematic analysis

Chapter 7

Ensuring energy security in the economic development and green energy transition

7 Ensuring energy security in the economic development and green energy transition

7.1 Key messages

- China has emerged as the preeminent producer and consumer of energy globally, establishing a comprehensive energy supply system encompassing coal, electricity, petroleum, natural gas, new energy, and renewable energy. As part of its energy development initiative, China instituted a comprehensive "Five-in-One" layout to guide its energy sector towards clean, low-carbon, safe, and efficient development. By implementing the "Four Revolutions and One Cooperation" energy security strategy, the nation underscores energy development and security, leading to significant shifts in energy production and usage methods. Moreover, China has stipulated a definitive timetable to achieve carbon peaking and neutrality, aiding in the construction of a clean, low-carbon, safe, and efficient new-type energy system. The 20th National Congress of the Communist Party of China (CPC) further suggested actively and cautiously promoting carbon peaking and neutrality based on China's energy resource endowment. This approach adheres to the principle of "building the new before breaking the old," and it intends to carry out carbon peaking actions in a planned and phased manner while accelerating the planning and construction of a new-type energy system.

- China's energy development maintained a stable course throughout 2022. The nation expedited the release of high-quality coal production capacity, promoted the green and intelligent transformation of coal mines, moderately reduced coal imports, and promoted the clean and efficient utilisation of coal. Confronted with persistent supply constraints and marked price volatility in the global oil and gas market, China has expedited measures to bolster its domestic oil and gas reserves and production capabilities, while strategically optimising and diversifying the scale and origins of its oil and gas imports. New energy sources such as wind and solar power experienced rapid development, which promoted the continuous optimisation of China's power generation structure. The proportion of non-fossil fuel power generation capacity exceeded that of coal-fired power. However, due to unforeseen factors such as the COVID-19 pandemic, extreme weather, and fuel supply disruptions, uncertainties in both electricity supply and demand increased. While overall power balance was maintained in China, there were localized instances of short-term power supply shortages, which increased pressure on ensuring power security and supply.

- To ensure a stable coal supply, China seeks to optimise its coal production strategies, tailored to its unique energy resource endowment. The *14th Five-Year Plan for a Modern Energy System* proposes the construction of five major coal supply guarantee bases in Shanxi, western Inner Mongolia, eastern Inner Mongolia, northern Shaanxi, and Xinjiang. This plan prioritises the optimisation of advanced coal production capacity layout and the improvement of inter-regional transportation channels and integrated transportation systems for coal, which enhance the capability of cross-regional coal supply guarantee. China is also intensifying efforts to strengthen the coal market by improving long-term contract management and enhancing the coal and electricity price transmission mechanism. In addition, the construction of the coal storage and transportation system is intensified, with the establishment of coal reserve bases in coal consumption distribution centres, railway transportation hubs, and key ports to significantly enhance logistics and transportation capabilities. Lastly, China aims to promote a greener and smarter upgrade of the coal industry. This includes establishing a comprehensive standard system for green and intelligent coal mines and improving the development and utilisation of green and intelligent technologies for coal.

- China is proactively building a comprehensive system for ensuring energy security through the production, supply, storage, and sale of oil and gas. Firstly, China has implemented policies to increase the storage and production of oil and gas by initiating a *Seven Year Action Plan*. Additionally, the country is increasing domestic investments in oil and gas exploration and development to enhance domestic production capacities. Secondly, efforts are being made to strengthen the development of storage facilities. Clear requirements have been set for the entire natural gas industry chain, with upstream gas supply companies being required to have a gas storage capacity of no less than 10% of their annual contracted sales volume, while urban gas companies are mandated to have gas storage capacities equivalent to at least 5% of their annual gas consumption. Thirdly, China is enhancing the construction of transportation infrastructure, with the establishment of the National Petroleum and Natural Gas Pipeline Network Group Company (PipeChina) aimed at accelerating the nationwide "One Unified Grid" construction, creating a nationwide interconnected network. Lastly, China is improving the mechanism for price formation to ensure that mid to long-term contracts for gas used in people's daily lives are fully covered.

- Meanwhile, China is actively advancing the construction of a new power system that prioritises enhancing electricity supply capacity and increasing the proportion of new energy. In 2022, China's installed capacity for power generation exceeded 2500 GW, with the installed capacity of non-fossil energy exceeding 1,200 GW. The newly installed capacity of wind power and photovoltaics accounted for 66% of the national total, while the newly generated power accounted for around 69% of the national total. Efforts are underway to accelerate the construction of power system regulation capacity and comprehensively promote the clean, efficient, and flexible transformation of coal-fired power generation. By the end of 2022, the scale of flexible transformation of coal-fired power generation exceeded 100 GW, and active efforts are being made to promote pumped storage and new-type energy storage construction. By 2025, the total capacity of pumped storage exceeds 62 GW, and the installed capacity of new-type energy storage reaches 30 GW. The interconnectivity capacity of the power grid is being effectively enhanced, with the capacity for transmitting electricity from west to east reaching 300 GW in 2022. Efforts are also being increased to alleviate power shortages across regions and provinces. Lastly, China is improving the power supply security and supply system mechanism, including accelerating the construction of the power market and improving demand-side management of electricity.

7.2 The strategic approach towards energy development in China over the past decade

Energy is the cornerstone and driving force of economic and social advancement. Energy security is a comprehensive and strategic issue that is crucial to the country's prosperity, the improvement of people's lives, and the long-term stability of society. Through sustained development, China has become the world's largest producer and consumer of energy, establishing a comprehensive energy supply system for coal, electricity, oil, natural gas, new energy, and renewable energy. However, China also faces pressing challenges, including surging energy demand, constraints on energy supply, severe ecological degradation from energy production and use, an overall lag in energy technology, and high external reliance for certain energy types. To tackle these challenges, China has outlined a comprehensive "Five-in-One" layout to steer various industries, including energy. China has also tabled a comprehensive national security outlook that underscores energy as an integral component of combined development and security. It has also instigated a fresh strategy for energy security, referred to as the "Four Revolutions and One Cooperation," to navigate the country's energy evolution in this new era. Remarkably, in 2020, China delineated the goals of carbon peaking and carbon neutrality, thereby providing a lucid timeline for the formation of a clean, low-carbon, secure, and efficient new-type energy system.

Establishing the comprehensive "Five-in-one" layout to steer green energy development

The goal of energy development is to bolster and safeguard national advancement, enveloping economic construction and welfare services, as well as catalysing ecological civilization and fostering green development. While energy security is partly tied to resource security, it principally constitutes a vital element of economic security, intricately linked with social and ecological security. Aligning energy development with security is pivotal to the country's holistic development and security, necessitating superior coordination with economic development, social progression, and the construction of an ecological civilization.

Ecological prosperity paves the way for cultural prosperity, and energy production and consumption significantly impact the ecological environment. Hence, the development of green energy is an essential aspect of constructing an ecological civilization. Historically, a substantial discrepancy existed between China's energy development and the demands of building an ecological civilization. Although rapid economic and societal development has been achieved, it has concurrently exerted certain impacts on the ecological environment. Since the 18th CPC National Congress, the country has embarked on a new era of development, including within the energy sector. The report of the 18th National Congress proposed the comprehensive implementation of economic, political, cultural, social, and ecological civilization construction as an overarching "Five-In-One" layout, integrating ecological civilization construction into the holistic cause of socialism with Chinese characteristics. It unambiguously advocated for the vigorous promotion of ecological civilization construction and efforts towards building a beautiful China, thereby accomplishing the sustainable development of the Chinese nation.

For years, China has steadfastly embraced a new development philosophy centred on innovation, coordination, greenness, openness, and shared prosperity. Prioritizing high-quality development, the country regards the advancement of sustainable energy as fundamental to fostering an ecological civilization. China has earnestly embarked on a crusade against pollution, successfully safeguarding the clarity of its skies and intensifying the harnessing and application of new and renewable energy sources. In particular, China strives to promote clean coal mining and enhance efficient utilisation. It also establishes rational parameters for prohibiting open burning areas. Through a multifaceted and proactive approach, China actively and methodically promotes the substitution of scattered coal with alternative energy sources. This has yielded significant outcomes, exemplifying the country's balanced pursuit of energy development and ecological civilization.

Establishing a comprehensive national security outlook underscoring energy development and security

In 2014, General Secretary Xi Jinping introduced the concept of a comprehensive national security outlook, integrating it into the foundational strategies for cultivating and advancing socialism with Chinese characteristics in the new era. This outlook remains firmly rooted in China's distinctive national security pathway, with the security of its populace as the foremost objective. It underscores the equilibrium between development and security, designating the assurance of energy and vital resource security as a cardinal facet of protecting economic stability. By championing a revolution in energy production and consumption, this outlook seeks to align with major shifts in the energy sector, securing a sustainable, reliable, and efficient supply of resources and energy to bolster socio-economic development.

Security serves as the bedrock for development, while development reciprocates as the assurance for security. For China's energy progression, it is crucial to implement an overarching national security perspective, informed by the nation's energy resource endowment and grounded in an unwavering commitment to "building the new before breaking the old" and meticulous planning. This commitment encompasses holistic considerations, harmonizing the positioning and development of various types of energy sources, and fortifying the reciprocal support among different energy categories. Characterised by abundant coal, scarce oil and gas, and copious renewable energy resources, China's energy profile is distinctive. As the scale of renewable energy sources such as wind and solar progressively expands, the green and low-carbon transformation of the energy and power system is decidedly accelerating. Nonetheless, this progression invites increasing risks of volatility and instability, particularly in coordinating the relationship between traditional and new energy sources and optimising the integration of coal and new energy sources. The transition away from traditional energy sources must be underpinned by a reliable and secure foundation of new energy alternatives. To build a modern energy system with safety as its priority, it is imperative to harmonize the promotion of low-carbon transformation with supply assurance, with a focused effort on erecting a national energy security barrier.

Implementing the new energy security strategy of "Four revolutions and one cooperation" to guide high-quality development of energy in the new era

Since 2014, China has proposed the new energy security strategy of "four revolutions and one cooperation," which has provided guidance for high-quality energy development in the new era. This strategy focuses on promoting revolutions in energy consumption, energy supply, energy technology, and energy systems, while also strengthening international cooperation in all aspects. The implementation of this strategy has led to significant changes in China's energy production and utilisation, continuously enhancing the country's capability to ensure energy security.

In terms of energy consumption revolution, China remains committed to its fundamental national policy of resource conservation and environmental protection, while ramping up efforts to phase out outdated coal mining capacity and coal-fired power generation units, as well as enhance efficiency levels in critical sectors. China's energy consumption structure has undergone a positive transformation, with the proportion of coal consumption dropping from 68.5% in 2012 to 56.2% in 2022, while that of clean energy consumption surged from 15.5% in 2013 to 25.9% as of year-end 2022. Since 2016, China has sustained the economy's high-speed growth with an annual average energy consumption growth rate of approximately 3%. By advancing a revolution in energy consumption and curbing excessive energy use, the nation has effectively guaranteed energy security.

In terms of energy supply revolution, China has established a strategic focus on ecological priorities and green development, considering national conditions and development stage. Emphasis has been placed on deepening the structural reform of energy supply, giving priority to non-fossil energy development, promoting clean and efficient utilisation of fossil energy, enhancing energy storage and transportation systems, and incentivizing the coordinated development of multiple energy sources across different regions. Through years of development, China has built the world's largest power grid system, the largest clean coal power supply system, and maintains world-leading indicators for non-fossil energy generation in installed capacity of hydropower, wind power, photovoltaic power, and biomass power, as well as nuclear power under construction. This is furthered by championing a revolution in energy supply, forging a diversified supply system, and perpetually enhancing the quality and security of energy supply.

In terms of energy technology revolution, China has leveraged the opportunity of the new global technological revolution and industrial transformation to drive innovation in the energy sector through the implementation of innovation-driven development strategies. Major scientific and technological projects have been undertaken, resulting in significant breakthroughs in key energy technologies. For instance, China has achieved remarkable progress in developing third-generation nuclear reactors, with the Hualong One reactor now operational. Additionally, there have been significant advancements in deep natural gas reservoir theory and supporting technologies, as well as key technologies for shale oil and gas, deep-sea exploration and development. Major strides have also been made in hydrogen energy, energy storage, renewable energy, and coal-to-oil and gas technology. Through advocating a revolution in energy technology, fuelling industrial upgrades, and building a green energy technology innovation system, China accelerates the development of green and low-carbon energy.

In terms of energy system revolution, China capitalises fully on the decisive role of the market in energy resource allocation, amplifies the government's role, deepens market-oriented reforms in crucial areas such as electricity, and oil and gas. It also works to dismantle institutional barriers impeding development, with a concentrated focus on rectifying issues in an imperfect market system. These efforts provide institutional assurances for protecting national energy security and fostering high-quality energy development, thereby paving the way for rapid energy development.

In the realm of all-round strengthening of international cooperation on energy, China adheres to green development concepts and follows the principles of mutual benefit and win-win cooperation. In its international cooperation activities aimed at securing access to open markets for its energy needs and ensuring energy security, China promotes the concept of expanding openness in the energy sector. Furthermore, China actively participates in global energy governance and provides guidance for international cooperation in tackling climate change. China also promotes the building of a global community with a shared future for humanity by actively engaging in the "Belt-and-Road" initiative based on high-quality standards. By enhancing comprehensive international cooperation, China has joined efforts to forge a new paradigm in energy international collaboration, safeguarding stability and common security in the global energy market.

Advancing the energy revolution through the carbon peaking and carbon neutrality strategy

At the 75th United Nations General Assembly in September 2020, President Xi Jinping made a solemn declaration that China would increase its nationally determined contributions and adopt more powerful policies and measures to strive to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. This commitment opened up a great journey for China's carbon peak and carbon neutrality, injecting strong impetus into global efforts to address climate change and promote energy transformation.

Following the proposal of the carbon peak and carbon neutrality goal, in 2021, the CPC Central Committee and the State Council issued the *Opinions on Implementing the New Development Concept and Achieving Peak Carbon Emissions and Carbon Neutrality*, followed by the *Action Plan for Achieving Peak Carbon Emissions before 2030*. Pertinent departments have composed sector-specific implementation plans and supportive policies, while each province, autonomous region, and municipality have also crafted local implementation blueprints for peak carbon emissions. A "1+N" policy system for carbon peaking and carbon neutrality has been established.

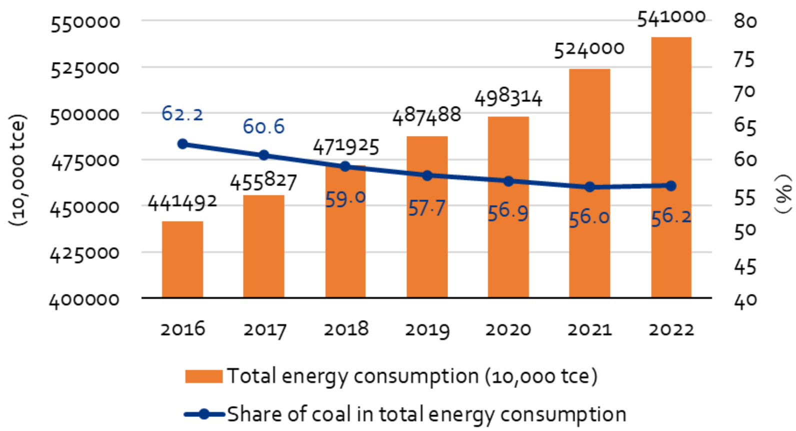
Achieving peak carbon emissions and carbon neutrality necessitates a holistic transformation of the economic and social framework under multiple objectives and restrictions. It's essential to equilibrate development and emission reduction, carbon reduction and safety, collective and local interests, immediate and long-term considerations, government and market functions, as well as domestic and international relations. Against this backdrop, Chapter 10 of the 20th CPC National Congress underscores the advancement of green development and the cultivation of a harmonious coexistence between humans and nature. It underscores the necessity to progressively and steadily pursue peak carbon emissions and carbon neutrality goals, grounded in China's energy resource endowment, and to adhere to a structured and phased approach. It emphasises the importance of intensifying the energy revolution, enhancing the clean and efficient usage of coal, bolstering efforts in oil and gas exploration, development, and reserves, expediting the planning and establishment of a new-type energy system, aligning hydropower development with ecological protection, actively and securely developing nuclear power, fortifying the construction of the energy production, supply, storage, and marketing system, and ensuring energy security.

7.3 Basic situation of China's energy security and supply in 2022

Accelerating the release of high-quality coal production capacity and promoting green and ontelligent transformation of coal mines

The proportion of coal consumption in China's primary energy consumption has continued to decline over the past few years. Since the *13th Five-Year Plan* period, China has accelerated its green and low-carbon transformation of energy, with clean and low-carbon energy developing rapidly, while the proportion of coal consumption continues to decrease. According to data from the National Bureau of Statistics, in 2022, the total national energy consumption reached 5.41 billion tons standard coal equivalent (TCE); the proportion of coal consumption in primary energy consumption decreased from 62.2% in 2016 to 56.2% by the end of 2021 (Figure 7-1).

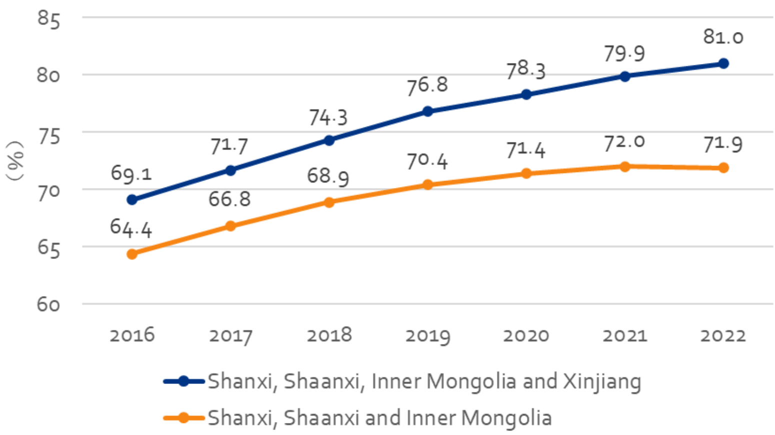
Figure 7-1 2016-2021 Total energy consumption and proportion of coal consumption in China



Data source: National Bureau of Statistics

Accelerate the structural reform on the supply side of the coal industry. The history of coal resource development in eastern and central China is long and intense, with resources gradually depleting and overall entering the mid-to-late stages of development. There are challenges such as deviations in overall occurrence, deep burial depth, complex structures, high difficulty in safe mining, and high costs of development. Since the *13th Five-Year Plan* period (2016-2020), China has been accelerating the promotion of green and digital transformation in the coal industry by integrating new technologies such as big data, artificial intelligence (AI), 5G, and blockchain with coal industry development to boost production efficiency. During the *14th Five-Year Plan* period (2021-2025), China focuses on developing advanced coal production capacity by developing large, modernized mines with good resource conditions, strong competitiveness, and high safety standards, while also strengthening the construction of intelligent and safe mines. The coal production structure and layout are optimised to concentrate on resource-rich areas in the west for coal development. According to a survey conducted by CCTDCoal.com, the total output of four provinces, including Shanxi, Shaanxi, Inner Mongolia, and Xinjiang, in 2022, accounted for 81% of the national total output, representing an increase of nearly 12 percentage points compared to the early stage of the *13th Five-Year Plan* period (Figure 7-2). However, as Chinese coal production shifts westward while major consumption areas remain concentrated in developed eastern regions, this exacerbates the separation between production and sales, putting higher demands on efficient transportation.

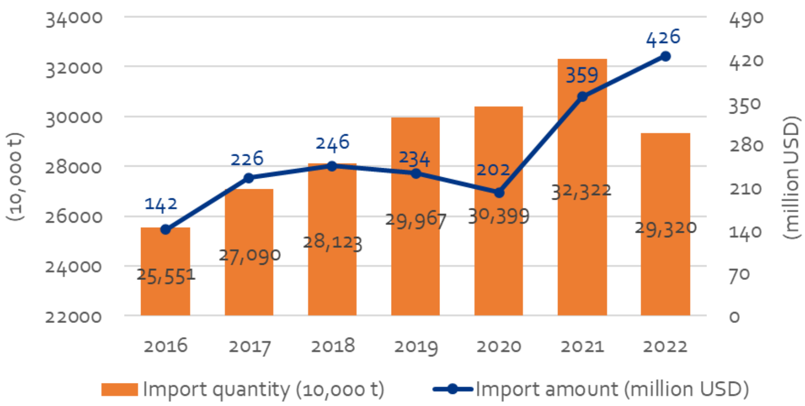
Figure 7-2 2016-2022 Changes in the proportion of Shanxi, Shaanxi, Inner Mongolia, and Xinjiang Coal production in the national total



Data source: CCTDCoal.com

In 2022, China experienced a decrease in coal import volume but an increase in prices. During the peak summer rush of 2021, China faced a surge in electricity demand, leading to a rapid increase in coal consumption. This, coupled with the global energy prices hike, resulted in a sharp climb in China's coal prices. In 2022, influenced by a combination of factors such as international geopolitics and climate change, global coal market prices remained high, far exceeding domestic prices. Amid the inverted coal prices between national and international markets, the volume of coal imports into China has notably contracted. As per customs data, China's year-on-year coal imports in 2022 plummeted by 9.2%, hitting the lowest point in nearly four years. Conversely, the aggregate quantity of coal imports into China in 2022 marked an 18.7% surge compared to the preceding year (Figure 7-3).

Figure 7-3 Volume and value of coal imports to China in recent years



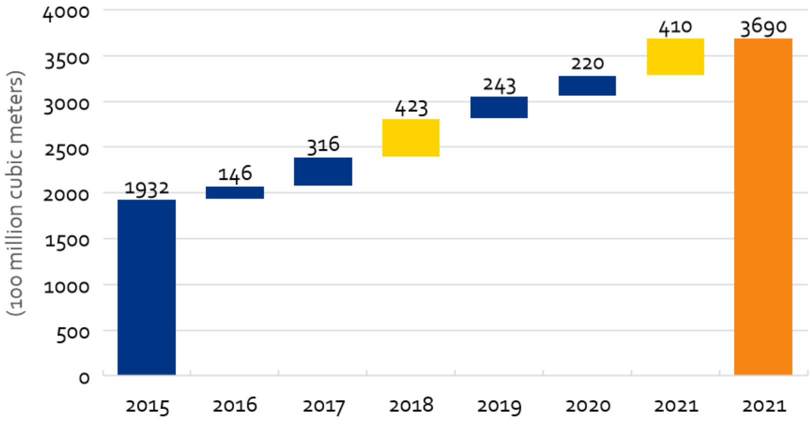
Data Source: General Administration of Customs

Ensuring stable oil-gas supply and demand to effectively cope with peak pressure

Over the past few years, the global energy supply and demand situation has become more intricate and demanding, with the oil and gas supply remaining tight and prices fluctuating significantly. Changes in international energy supply and demand, as well as price fluctuations, significantly impact domestic oil and gas supply, presenting considerable challenges in maintaining a secure and stable energy supply.

Since the *13th Five-Year Plan* period, China experienced a transition from an oversupplied to a constrained natural gas market. Nonetheless, during the *13th Five-Year Plan* period (2016-2020), China has made significant strides in achieving its air pollution prevention goals, accomplishing various tasks to enhance air quality. One notable achievement was the full implementation of clean heating in "2+26" cities in northern regions and the Fenwei Plain, covering all households that previously used coal stoves, which accounted for around 25 million households. The large-scale "coal-to-gas" conversion projects also helped increase natural gas consumption, which grew at an average annual rate of about 27 bcm, much higher than the *12th Five-Year Plan* period's average annual growth rate of 17 bcm. During the central phase of the *13th Five-Year Plan* period, the pressures on natural gas supply became increasingly apparent, exerting far-reaching effects and critically affecting the people's well-being, most notably in the heating sector. As the plan drew towards its conclusion, the surge in natural gas consumption began to moderate, registering an average annual increment of around 23 bcm for both 2019 and 2020. Concurrently, domestic output witnessed an average annual augmentation of 16.2 bcm, culminating in a taut equilibrium between supply and demand.

Figure 7-4 2015-2021 Natural gas consumption growth trend in China

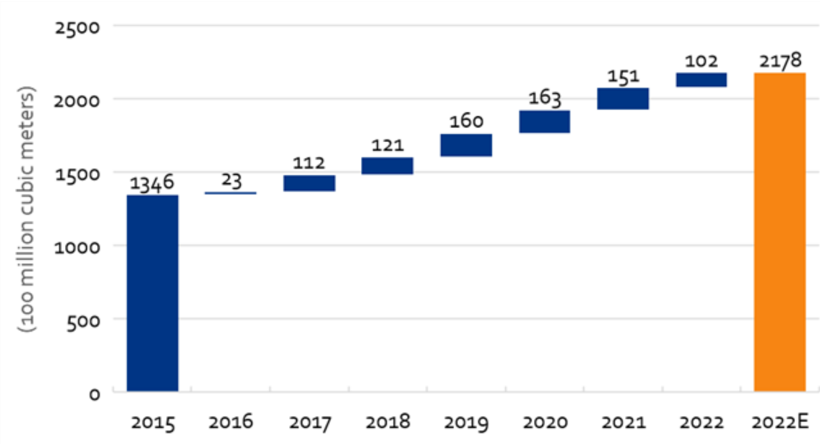


Data source: National Bureau of Statistics and National Energy Administration

From 2021 to 2022, China's natural gas market underwent a transition towards overall balance. As China embarked on the *14th Five-Year Plan* period, the demand for natural gas underwent marked fluctuations, initially rising before experiencing a downturn. This shift was precipitated by a confluence of factors, including the COVID-19 pandemic, shifting international geopolitics, and macroeconomic variances. Consequently, the natural gas market's supply and demand dynamics encountered considerable alterations during 2021-2022. In 2020, China's natural gas market achieved a breakthrough, with a market size exceeding 320 bcm. Rapid growth continued, with consumption surpassing 360 bcm in 2021, representing an annual growth rate of approximately 41 bcm - second only to the increase of approximately 42.3 bcm seen in 2018. Unlike previous years when consumption was strong during Q1 and Q4 but relatively weak during Q2 and Q3 due to seasonal characteristics, each quarter of 2021 showed clear highs followed by lows.

During the first half of 2021, demand was overly high, leading to a year-on-year growth rate close to 20%, adding about 310 bcm, which accounted for 75.6% of the annual increment and exceeded most historical annual increments. However, in the latter months of the year, the surge in consumption conspicuously tapered off, with the year-on-year growth plummeting to around 5% — a rise of roughly 10 bcm. As 2022 unfolded, the deceleration in natural gas consumption, first noted in the second half of the previous year, continued unabated. Both the second and third quarters were marked by a hitherto unprecedented and consecutive decline in year-on-year growth, spanning several months. In contrast, domestic natural gas production maintained a steady increase, surpassing an augmentation of 15.1 bcm in 2021, followed by an additional increment exceeding 10 bcm in 2022. Meanwhile, the international natural gas market prices remained at historically high levels amid fluctuations. But China's import volume was secured by long-term contracts, ensuring the country's overall supply of natural gas.

Figure 7-5 2015-2022E Growth of natural gas production in China



Data source: National Bureau of Statistics

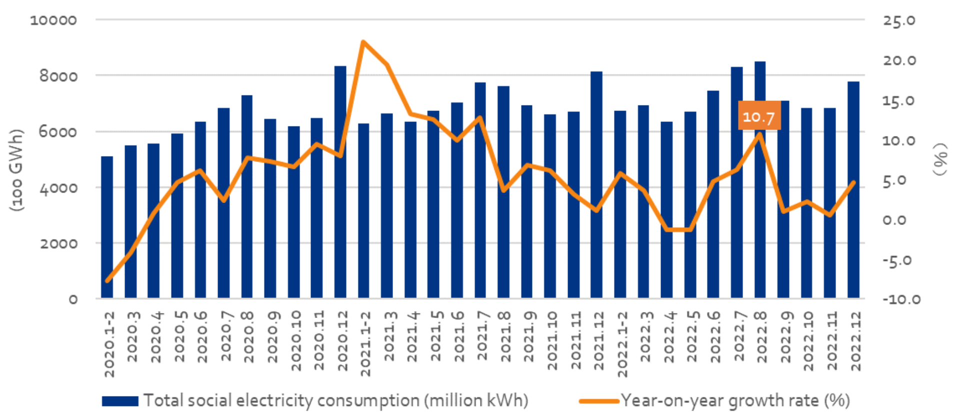
Short-term power supply tension seen in local areas despite overall balance of power supply and demand

In recent years, China has witnessed a consistent rise in total electricity consumption, with an average annual growth rate of 5.7% throughout the *13th Five-Year Plan* period. However, the year-on-year growth rate of electricity consumption has been fluctuating significantly. The rapid development of renewable energy sources, such as wind and solar power, has helped optimise China's installed capacity structure. In 2021, the installed capacity of non-fossil energy surpassed that of coal-fired energy for the first time in history, reaching 1,120 GW, accounting for 47.0% of the total installed capacity. Despite the growth in electricity demand and the development of renewable energy sources, China's power supply-demand situation has gradually shifted from being generally loose to generally tight since the onset of the *13th Five-Year Plan* period due to multiple factors. Between 2015 and 2017, the national power supply-demand situation was relatively loose, with excess electricity in some regions. However, starting in 2018, the power supply-demand situation in China became generally balanced, with temporary shortages occurring in some regions at certain times. Unexpected factors such as the COVID-19 pandemic outbreaks, extreme weather conditions, and fuel supply constraints have increased uncertainty between power supply and demand during the *14th Five-Year Plan* period, leading to a tightening trend on China's electric power security pressure.

In 2021, China saw positive signs of economic recovery at a national level as the overall pandemic situation improved. Foreign trade exports experienced significant growth, and total electricity consumption in the country increased by double digits, reaching 8,331 TWh with a year-on-year increase of 10.4%. However, challenges like limited power fuel supplies and low water levels for hydroelectricity hindered the peak generating capacity of traditional power sources such as thermal and hydroelectric power, resulting in a tight national power supply-demand situation. Regarding timeframes, there were instances of insufficient electricity supply at the onset of the year, during the peak summer demand, and in September-October in select areas. In terms of regional allocation, with the exception of the Northwest region which maintained a stable balance between power supply and demand, other regions such as East China, Central China, North China, and Southern China encountered varying levels of electricity shortage.

In 2022, the total electricity consumption continued to exhibit a growth trajectory, albeit with a significant decline in the year-on-year growth rate compared to 2021. In 2022, the overall electricity consumption reached a staggering 8,630 TWh, reflecting a year-on-year growth of a modest 3.6% (Figure 7-6). However, the months of July and August saw the longest-lasting extreme high temperature weather in decades with a wide range of impact. This weather, combined with a rapid economic recovery driving up electric load demands, resulted in 21 provincial grids reaching new highs for their electric loads. On July 15th, the national electricity load reached 1,260 GW, a 5.7% increase from the previous year. Overall, throughout this year, national power supply-demand remained balanced, but there were challenges in maintaining adequate levels of electrical security, particularly during the summer in East China and Central China. As an illustration, during August, Sichuan Province, known as one of the largest hydropower regions in China, encountered severe heat and drought conditions that resulted in a 25% increase in maximum loads compared to the previous year. Meanwhile, the output of hydropower plummeted by 50%, which caused a severe lack of both electric-power capacity (with a maximum daily shortfall exceeding 17 GW) and energy shortage (exceeding 370 GWh).

Figure 7-6 Monthly electricity consumption and growth rate nationwide since 2020



Note: Monthly average electricity consumption for January-February. Data source: China Electricity Council (CEC)

7.4 China's policies and achievements in ensuring energy supply

Ensuring coal supply and stable prices

In light of its energy resource endowment, China has adopted a coordinated approach to development and security by adhering to the principle of prioritizing construction over destruction in order to maintain a stable coal supply. Firstly, the State has devised an energy strategic plan for optimising the layout of advanced coal production capacity. In 2022, China unveiled the *14th Five-Year Plan for Modern Energy System*, detailing plans for optimising coal production capacity layout, and calling for the construction of five major coal supply bases in Shanxi, western Inner Mongolia, eastern Inner Mongolia, northern Shaanxi Province, and Xinjiang. It also includes plans to enhance cross-regional supply capabilities by improving cross-regional transportation channels and integrated coal transportation systems. Secondly, the State has intensified its efforts in annual security and supply assurance, aiming to dynamically adjust and guarantee coal supply. *The Guiding Opinions on Energy Work in 2022* were introduced with the aim of strategically managing the energy sector and enhancing the resilience of the coal supply network. The document proposes a robust approach to comprehensively address the following key aspects: coordinating resource continuity and ensuring the sustainable development of mining areas; systematically approving a batch of high-quality and technologically advanced coal mines to optimise production capacity; promoting the conversion of emergency production capacity into normalized production capacity, subject to meeting specific criteria; and establishing coal reserve bases in major consumption centres, railway transportation hubs, and key ports to ensure adequate supply during critical periods. Thirdly, the State has been actively promoting the green and intelligent upgrading of the coal industry to solidify the foundation of a secure energy supply. In 2022, two significant documents, namely *Opinions on Improving the Institutional Mechanism and Policy Measures for Green Low-Carbon Energy Transformation* and *the 14th Five-Year Plan for Technological Innovation in the Energy Sector*, were introduced, emphasizing the need for the establishment of supportive policies to advance mine optimisation systems. Additionally, these documents called for the enhancement of the standards system for constructing green and intelligent coal mines, with a particular focus on addressing crucial aspects such as environmentally friendly practices and intelligent mining techniques. Fourthly, the State has made significant strides in enhancing logistics transportation capabilities to ensure seamless coal transport. In 2022, there was a substantial improvement in cross-regional dispatching capabilities, particularly in bolstering the "North-to-South Coal Transport" and "West-to-East Coal Transport" systems. For example, the freight capacity of the "Wari" railway, which connects Shanxi to Shandong in eastern China, witnessed an impressive increase of 39.4% and 11.7% respectively, compared to 2020 and 2021. Similarly, the volume of coal transported on the "Haoji" railway, linking Inner Mongolia to Jiangxi in central China, experienced a remarkable year-on-year surge of 55.6%. Thanks to the implementation of these comprehensive supply guarantee policies, China has achieved significant progress in national coal production, supply, storage, and sales. As a result, the tight supply-demand situation has been effectively alleviated, demonstrating significant progress in ensuring a stable and reliable coal supply.

In 2022, amid a challenging and volatile international energy landscape, China bolstered its management of coal market expectations, thereby achieving a sustained and steady operation of domestic coal prices. The first step was to establish a price range for long-term coal contracts. In 2022, the *Notice on Further Improving the Coal Market Price Formation Mechanism* was released, proposing to steer the price of coal, particularly thermal coal, to fluctuate within an acceptable margin and to fortify the link between coal and electricity pricing mechanisms. Next, the State bolstered the management of long-term contracts. The *Notice on Strengthening Medium- and Long-Term Contract Management to Ensure Stable Quality of Thermal coal,* issued in 2022, mandated that, in line with market-oriented principles, a "quality grading management system" should be introduced for thermal coal, reflecting the principle of "high price for high quality, and low price for low quality". This would guide market participants to uphold contracts as negotiated, thereby ensuring stable thermal coal quality at a reasonable level. The issuance of the *Work Plan for Signing and Fulfilling Medium- and Long-Term Contracts for Thermal coal in 2023*, which was released in the same year, advocating for the rigorous application of the "benchmark price + floating price" doctrine in the execution of contract agreements. The concerted enforcement of an array of protocols designed to regulate and monitor coal prices contributed to the stability of the Chinese coal market throughout the year, ensuring that prices generally remained within a rational spectrum.

Ensuring the security of oil and gas supply

Steadily enhance the top-level design to ensure a reliable oil and gas supply, with efforts being made to build a comprehensive production-supply-storage-sales system. To address the difficulties arising from the constrained availability of natural gas in 2017, the State Council released *Several Opinions on Promoting Coordinated and Stable Development of Natural Gas in 2018*, providing vital direction for fostering the sustainable growth of the natural gas sector and ensuring a steady supply. At the operational level, several government departments, namely the National Development and Reform Commission (NDRC), Ministry of Industry and Information Technology (MIIT), Ministry of Finance (MOF), Ministry of Transport (MOT), Ministry of Water Resources (MWR), Ministry of Agriculture and Rural Affairs (MARA), and the National Energy Administration (NEA), have collaborated to establish an inter-ministerial coordination mechanism for guaranteeing the transportation of coal, electricity, oil, and gas. In recent years, the NEA, for example, issued annual guidance on the energy work, which helps further clarify the policies for promoting increased storage capacity for oil and gas, while enhancing production capacity, advancing the construction of primary natural gas pipelines, improving their inter-connectivity, and strengthening storage capacity development.

Introduce policies for increasing storage and production to enhance oil and gas production capabilities. In 2019, a *Seven-year Action Plan* was initiated, dedicated to bolstering oil and gas storage and production. Throughout the *13th Five-Year Plan* period (2016-2020), the total capital allocation to oil and gas exploration and development amounted to RMB 1.36 trillion, registering an average annual growth rate of 7.0%. The proven geological reserves of natural gas saw an addition of 5.6 trillion cubic meters, exceeding the established target; the production of natural gas rose by more than 10 bcm annually, demonstrating an average yearly growth rate of 7.4%. The *Outline of the 14th Five-Year Plan for the Modern Energy System* advocates for the enhancement of oil and gas supply capacities, an escalation in domestic oil and gas exploration and development, and a swift rise in natural gas production, with an ambitious target to exceed 230 bcm by 2025.

Clarify policies pertaining to storage and adjustment, with a specific focus on "filling the gaps". In 2018, two critical documents, namely, *Opinions on Accelerating the Construction of Gas Storage Facilities and Improving the Market Mechanism for Peak Shaving Auxiliary Services*, and *Notice on Coordinated Planning for the Construction and Operation of Gas Storage Facilities*, were issued, which, for the first time, set precise and ambitious gas storage targets at the policy level for upstream and downstream enterprises, as well as local governments. Specifically, upstream gas supply companies are required to maintain a gas storage capacity of no less than 10% of their annual contracted sales volume; local governments at or above the county level should establish a gas storage capacity equivalent to at least three days' demand in their administrative regions; urban gas companies should ensure a gas storage capacity of no less than 5% of their annual consumption. Furthermore, the *Measures for the Administration of Central Budgetary Investment (Subsidy) Special Funds for Emergency Gas Storage Facility Construction in Key Areas* was promulgated, allocating special funds from central budgets between 2018 and 2020 for gas storage facility projects, thereby catalysing the realisation of gas storage targets. Under the guidance of these national policies, the construction of gas storage facilities by relevant entities has markedly accelerated.

Stabilize natural gas prices and ensure the demand for household gas consumption. Stable energy price plays a pivotal role in both safeguarding people's livelihoods and ensuring economic stability. In China, the pricing of natural gas for residential use is stringently regulated by the government. The provision and pricing of residential gas are effectively managed, with the timely allocation of gas supply resources, and comprehensive coverage of medium- and long-term contracts for household gas. The performance of contracts and the guarantee of transportation capacity are continually improving. The pricing policy at the gas station is implemented for household consumers within the coverage of natural gas pipelines, thereby ensuring sufficient and stable energy supply for people's livelihoods.

Enhance the inter-connectivity of gas pipelines and advocate for equitable, open access for third-party entities. In 2018, corporations spearheaded the construction of over ten pipeline connection projects, thereby linking critical nodes and establishing effective joint supply between oil companies as well as between northern and southern regions. In 2019, the establishment of China Oil & Gas Pipeline Network Corporation (PipeChina) marked a significant stride towards accelerating the creation of a "national network", incorporating provinces such as Guangdong and Zhejiang and notably enhancing its supply capacity. In 2021, the NEA issued the *Special Regulatory Work Plan for Fair Access to Natural Gas Pipeline Networks and LNG Receiving Stations*, which strengthens regulatory standards for open services provided by pipeline facility operators and promotes efficient utilisation of pipeline facilities.

Expedite the development of local gas storage facilities and enhance emergency supply strategies. National departments are urging local governments to hasten the establishment of gas storage infrastructures, requiring that administrative regions at or above the county level to follow relevant national requirements to construct gas storage facilities capable of sustaining the daily gas requirements of their jurisdiction for a minimum of three days. Under national directives, various regions shall incorporate natural gas-powered buses, taxis, and other vehicles into their livelihood support systems, while honing emergency supply strategies for potential extreme scenarios. Local governments and businesses shall augment lists of non-residential users with interruptible peak-shaving loads totalling 300 million cubic meters per day, a resource that can be systematically mobilized when necessary to meet essential requirements, such as those related to people's livelihoods.

The combination of policy initiatives has proved instrumental in maintaining a balanced equilibrium in the supply and demand of oil and gas. Firstly, domestic production has surged while international supplies remain consistent. The objectives delineated in the *Seven-Year Action Plan* for oil and gas production have been surpassed, with crude oil output reaching 200 million tons and domestic production has surged while international supplies remain consistent. natural gas output exceeding 220 bcm for six consecutive years, thus leading to an approximate 3% increase in self-sufficiency. In accordance with international conventions and market rules, the majority of imported natural gas is secured via long-term contracts to effectively mitigate risks related to supply deficits or considerable price volatility. **Secondly**, the initiatives to ensure price and supply stability for domestic energy requirements have proven effective. Long-term contracts now encompass all domestic usage of natural gas; resources are procured in advance of the heating season; residents within the pipeline coverage zones benefit from station-centric pricing policies; and the rates of contract fulfilment and transportation capacity assurances continue to improve. **Thirdly**, energy demands associated with economic and social development are well catered for. During the winter heating season of 2022 alone, national consumption averaged 1.15 bcm daily, with peak usage at 1.3 bcm per day, offering robust support for economic expansion as well as societal development initiatives. **Fourthly**, peak period pressures have been proficiently managed, owing to advancements in the construction of nationwide storage facilities, which now boast over 32 bcm of storage capacity. Governments at all levels, along with various energy suppliers, have also established emergency response mechanisms.

Continuous improvement of power supply capacity

At National level

In 2022, the State coordinated efforts to meet targets for economic and social development, for clean and low-carbon energy transformation, as well as for carbon peaking and carbon neutrality by diligently ensuring power supply security during peak summer and winter periods, and by providing robust support for the stable functioning of the economy and society.

(1) Consistently Improve Power Supply Capacity

The national electricity installed capacity has witnessed substantial growth, with new energy sources playing an increasingly important role in ensuring power supply. By the end of 2022, China's installed power generation capacity amounted to 2,560 GW, representing a year-on-year growth rate of 7.8%. Among them, the installed capacity for wind power reached 370 GW, reflecting a year-on-year increase of 11.2%; the installed capacity for solar power reached 390 GW, reflecting a year-on-year increase of 28.1%. Throughout 2022, substantial efforts were directed towards promoting the construction of large-scale wind and solar bases, particularly in desert and Gobi regions. All initial batch of projects, cumulatively producing over 97 GW, have commenced construction, and the subsequent second and third batches are being sequentially implemented. In 2022, wind and PV power accounted for 66% of newly added installations nationwide and their generated electricity represented around 69% of the newly added generation nationwide, thus forming the primary source of installation and generation growth in China. Throughout most of China in the same year, the average output from wind farms and PV power plants was around 15% of the average load demand, but could surge up to 40%; during the peak summer season, provinces with a large installed capacity of PV power generation, such as Jiangsu, Shandong, and Zhejiang, achieved an average output coefficient of 0.5 during the high electricity consumption period at midday, thereby effectively supporting energy security supply.

The construction of a collection of hydropower and nuclear power projects was expedited. In 2022, all the 16 giga-watt units at the Baihetan Hydropower Station became fully operational; the hydropower base situated in the lower reaches of the Jinsha River Basin was fully completed. Additionally, the high-temperature gas-cooled reactor demonstration project accomplished a significant milestone by successfully achieving grid connection and initiating power generation for the first time. Construction projects for both the Fujian Fuqing Nuclear Power Plant and the Liaoning Hongyanhe Nuclear

Power Plant were brought to fruition, with operations commencing in earnest. Furthermore, ten nuclear power units were approved for construction nationwide.

(2) Accelerate the construction of power system regulation capacity

Promote a comprehensive, clean, efficient, and flexible transformation of coal-fired power plants, and actively leverage their supportive and regulatory roles. The renovation and upgrading of coal-fired generating units are vital means to enhance the efficiency of coal utilisation in electricity generation, diminish coal consumption, and foster clean energy consumption. In October 2021, the NDRC, in collaboration with the NEA, issued the *Implementation Plan for Nationwide Renovation and Upgrading of Coal-Fired Generating Units*, proposing that during the *14th Five-Year Plan* period, the scale of energy-saving, carbon-reducing renovations reach no less than 350 GW; the heating renovation scale reach 50 GW; and flexibility upgrades accomplish the 200 GW target. Local governments should proactively implement related work on "linking the three reforms", particularly for coal-fired plants. By the end of 2022, China's cumulative ultra-low emission coal power capacity reached 1050 GW, while its flexibility upgrades surpassed 100 GW.

Accelerate the construction of diversified energy storage. To bolster the development of new energy sources such as wind and PV power, China has been proactively advancing the construction of pumped storage and new-type energy storage. The *Medium- and Long-Term Development Plan for Pumped Storage (2021-2035)*, released in 2021, set an ambitious target of reaching a total pumped storage capacity exceeding 62 GW by 2025, and approximately 120 GW by 2030. Similarly, the *Guiding Opinions on Accelerating the Development of New-type Energy Storage*, issued in the same year, established a development goal of attaining over 30 GW of installed capacity for new-type energy storage by 2025. Two additional strategic documents were introduced in 2022: the *14th Five-Year Plan for New-type Energy Storage Development and Implementation*, and *the Notice on Further Promoting New-type Energy Storage Participation in Power Market and Dispatching Application.* These documents both aim to guide the large-scale, industrialized, and market-oriented development of new-type energy storage, thereby enhancing its utilisation efficiency.

(3) Effectively enhance power grid mutual assistance capacity

Proactively advance the planning and construction of transmission channels to augment the export capacity of clean energy. In 2022, the completion and operation of the ultra-high voltage direct current (UHVDC) channels from Baihetan to Jiangsu and Baihetan to Zhejiang—second in scale only to the Three Gorges Dam among Chinese hydroelectric power stations—marked the full completion of the Baihetan Hydropower Station's external electricity transmission project. This development supplies substantial green power to China's Yangtze River Delta region. The construction of ultra-high voltage (UHV) electricity transmission channels from clean energy bases, primarily composed of large-scale hydropower, wind, and photovoltaic (PV) power plants in Sichuan Province, Gansu Province, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, and Shaanxi Province, is being expedited. The concurrent development of key transmission channels, alongside supportive power grid and power source projects, significantly boosts the cross-provincial renewable electricity transmission capacity, thus increasing the share of green energy consumption in central and eastern China. By the close of 2022, the west-to-east power transmission capacity had risen to 300 GW.

Constantly optimise grid operation and dispatching. The related measures include fully leveraging the role of the large-scale resource optimisation platform for power grids, implementing a priority generation system across provinces or regions, intensifying efforts on inter-regional surplus exchange, and effectively boosting national overall supply guarantee capability; establishing robust provincial-level, market-oriented mechanisms for optimised scheduling, and promoting overall supply-demand balance. In 2022, the inter-regional electricity transmission across the nation reached a total of 696 TWh, depicting a year-on-year growth of 4.9%. Furthermore, the cumulative electricity dispatched by all provinces in the country amounted to 1,615 TWh, exhibiting a year-on-year growth of 2.9%. Additional measures encompass optimising grid scheduling, reducing coal consumption through increased hydropower generation, maintaining nuclear safety at full capacity, and promoting wind and solar power generation at maximum capacity whenever feasible.

(4) Enhance mechanisms for power supply security systems

Accelerate the development of electricity markets. In 2022, the *Guiding Opinions on Accelerating the Construction of a National Unified Electricity Market System* was released, outlining an initiative to expedite the creation of multi-tiered electricity markets at national, provincial (regional), and city levels. This initiative aims to enhance seamless integration between mid- to long-term transactions, spot transactions, and auxiliary service transactions within these markets. In 2022, the total volume of market transactions nationwide reached 5,250 TWh, marking a year-on-year growth rate of 39.0% and accounting for 60.8% of total societal electricity consumption—an increase of 15.4 percentage points year-on-year. The market-oriented reform for diverse types of power generation on-grid tariffs is progressing steadily. Since 2021, the *Opinions on Further Improving the Pricing Mechanism for Pumped Storage* and *the Notice on Further Deepening Market-Oriented Reform of On-Grid Tariffs for Coal-Fired Power Generation* were successively released to refine mechanisms in which prices are primarily market-determined.

Boost power demand-side management. The relevant measures include improving time-of-use pricing and peak-to-valley pricing systems, fully harnessing the potential on the demand side, motivating users to shift their power usage away from peak hours through market-based demand response measures, and curbing unreasonable power demands to alleviate peak-hour power shortages. Further measures involve optimising power orderly use management, bolstering the construction of interruptible load resources, and steadfastly safeguarding the baseline that ensures the people's livelihoods.

At local level

In 2022, local governments shouldered the primary responsibility for ensuring power supply. They enhanced monitoring and forecasting of regional power supply and demand, devised contingency plans, and guaranteed safe and stable power supply throughout the year. Significant progress was made in managing power demand-side resources, spot markets, capacity prices, and other aspects.

The power market development is accelerating. Regarding regional markets, the Southern Regional Power Market, encompassing five provinces and regions, i.e., Guangdong, Guangxi Zhuang Autonomous Region, Yunnan Province, Guizhou Province, and Hainan Province, was initiated for trial operation in July 2022, indicating the acceleration of a unified national power market system. Regarding spot markets, the first batch of eight pilot regions (beginning with Guangdong in Southern China, Western Inner Mongolia, Zhejiang Province, Shanxi Province, Shandong Province, Fujian Province, Sichuan Province, and Gansu Province) initiated long-term settlement trials by late June 2022. The second batch, comprising six pilot regions (Shanghai, Jiangsu Province, Ahui Province, Liaoning Province, Henan Province, and Hubei Province), commenced simulation trials before the end of July 2022.

Demand-side management is being continuously standardized in the power sector. In 2022, various provinces and regions including Anhui, Guanzhou, Hebei, Chongqing, Fujian, and Ningxia, successively introduced power demand response management measures, implementation rules, or detailed guidelines, further specifying the participating entities, compensation standards, and sharing mechanisms. Simultaneously, given their local power supply-demand dynamics and power consumption characteristics, these provinces and cities crafted improved demand response plans for orderly power use in 2022. These initiatives are designed to further augment their adaptability to shifts in power demand and foster refined management for orderly power utilisation.

Capacity-based electricity pricing policies are being introduced one after another. In December 2022, the Yunnan Provincial Development and Reform Commission unveiled the *Implementation Plan for Market-oriented Reform of Coal-fired Power Generation in Yunnan Province (For Trial Implementation)*. This marked the creation of the first coal-fired power generation regulation capacity market in the country. The price range flexibly varies within 30% above and below 220 RMB/kW·year, with terms independently negotiated by both buyers and sellers. Since 2022, provinces and cities such as Shandong, Sichuan, and Chongqing have successively introduced capacity pricing mechanisms for gas-fired power. These initiatives are designed to guide the healthy evolution of the gas-electricity industry and amplify its role in peak shaving. In November 2023, the NDRC and NEA jointly issued the *Notice on Establishing the Coal Power Capacity Tariff Mechanism*, which adjusted the coal power pricing system from a single tariff mechanism with electricity price only to a two-part tariff system with electricity price and capacity price. The policy aims to promote the transition of coal power into both a baseload source and a flexible power regulation source, to better support the needs of large-scale development of clean and low-carbon energy source development such as wind power and solar PV.

At enterprise level

In 2022, amidst the intricate challenges of ensuring power supply, major power generation groups and grid companies effectively upheld their primary responsibility for supply assurance, guaranteeing safe and reliable power supply throughout the year.

Cooperation between coal and electricity enterprises is deepening. To accelerate the restructuring of the energy sector, elevate energy security assurance levels, and foster the integrated growth of the coal and electricity industries, joint ventures between coal-electricity and coal-electricity-renewable energy have emerged as essential business models for energy corporations. In 2022, China Coal was engaged in a merge with State Power Investment Corporation's coal-fired power projects through a market-oriented transaction. The involved installed capacity surpasses 10 GW. Energy companies secure organisational robustness and guarantee consistent supply by fostering equity partnerships and embracing comprehensive growth strategies. This approach is pivotal in advancing the seamless integration of coal with renewable resources and in augmenting the efficiency with which renewable energy sources are utilised.

Grid companies are intensifying efforts in cross-regional surplus exchange. Since the end of September 2021, the State Grid Corporation and Southern Power Grid Company have harnessed their advantageous positions as large-scale grid platforms to intensify resource coordination, and capitalise on potential cross-regional channels across various provinces and regions. They have actively orchestrated surplus exchange activities and carried out long-term spot trading to optimise the balance of electric power supply and demand. Over 3,000 cross-provincial support operations have been coordinated, amassing a total volume close to 50 TWh, which helped achieve maximum control over the orderly use of electricity. Notably, in response to unusual power shortage in the Sichuan-Chongqing region during the summer season of 2022, they executed innovative measures such as the implementation of the Debo DC dispatching system and for the first time ever, reverse transmission back into the Sichuan-Chongqing area via the Jiangcheng DC lines. These measures ensured the safety of the power grid's lifeline and the fundamental needs related to people's livelihoods.

Chapter 8

The status and outlook of carbon pricing in China

8 The status and outlook of carbon pricing in China

8.1 Key messages

- China has instituted a multi-layered carbon market system, encompassing a national carbon market, regional carbon markets, and voluntary greenhouse gas emission trading markets. The carbon market is progressively assuming a central role in China's carbon reduction policies. Presently, the national carbon market covers only the electricity sector, accounting for roughly 40%-45% of the country's total emissions. As of the end of 2022, the accumulative trading volume of China's carbon market reached 230 million tons, with a trading value of RMB 10.5 billion and an average price of 45.5 RMB per ton. Preliminary effects of the carbon market in catalysing green, low-carbon transformation is evidenced by the 1.07% decrease in thermal power generation units' carbon intensity in 2020 compared to its 2018 level. This provides a carbon pricing guidance signal for the low-carbon transformation of the economic society. Going forward, China will concentrate on bolstering fundamental capacity building and institutional development, prioritizing data quality in the carbon market. The market scope will be promptly expanded, quota allocation methods continuously refined, and trading models and participation strategies will be progressively diversified to allow the carbon market to play a more substantial role in achieving carbon peaking and carbon neutrality.

- China has always emphasised comprehensive carbon reduction measures and developed a relatively complete system of implicit carbon pricing policies. Presently, China's implicit carbon pricing policies encompass energy, industry, urban and rural development, transportation, agriculture, and forestry sectors. The policy tools include financial subsidies, tax exemptions, energy-saving standards, target accountability evaluations, and more. Moving forward, China will continually augment the efficacy of implicit carbon pricing tools, emphasizing technological innovation and regularly adjusting the suitability of policies in response to changing scenarios. When appropriate, China will phase out policies to alleviate public expenditure. Additionally, China is consistently ameliorating the transmission mechanism from electricity to carbon prices to stimulate the integration and development of the electricity and carbon markets.

- In recent years, global carbon pricing has exhibited new characteristics, with breakthroughs in cross-border carbon emission trading regulations under climate conventions and the initiation of carbon border adjustment mechanisms in Europe and the US. Some international multilateral institutions actively champion global carbon pricing cooperation. These new trends and features of global carbon pricing present both challenges and opportunities for China.

8.2 Current status of international carbon pricing development

Over the past few years, there has been a significant uptick in the development of international carbon pricing mechanisms. These tools have become more varied and widespread, while the price of carbon has consistently risen. However, factors such as the COVID-19 pandemic and the energy crisis in Europe have led to greater fluctuations in carbon prices, which can be challenging for businesses and economies to navigate.

As the development of international carbon pricing progresses, there are now a growing number of diverse carbon pricing tools available. These tools can take on different forms and be classified in various ways, sometimes resulting in overlaps between different mechanisms. One way to classify carbon pricing is based on how external costs are internalized, resulting in categories such as carbon taxes, carbon markets, and carbon credits. Another way to distinguish pricing is by determining whether businesses incur emissions costs, known as external or internal corporate-level carbon pricing. When considering the overall impact of policies, carbon pricing can be further classified into explicit and implicit prices.[13] Additionally, some developed countries (regions) and international organizations have proposed transnational approaches to carbon pricing. For example, a carbon border adjustment mechanism (commonly known as a "carbon border tax") has been suggested, as well as a minimum price floor for CO_2 emissions (referred to as a "carbon floor price") and inclusive frameworks for establishing CO_2 emission prices. These approaches aim to create a more cohesive and effective global strategy for carbon pricing.

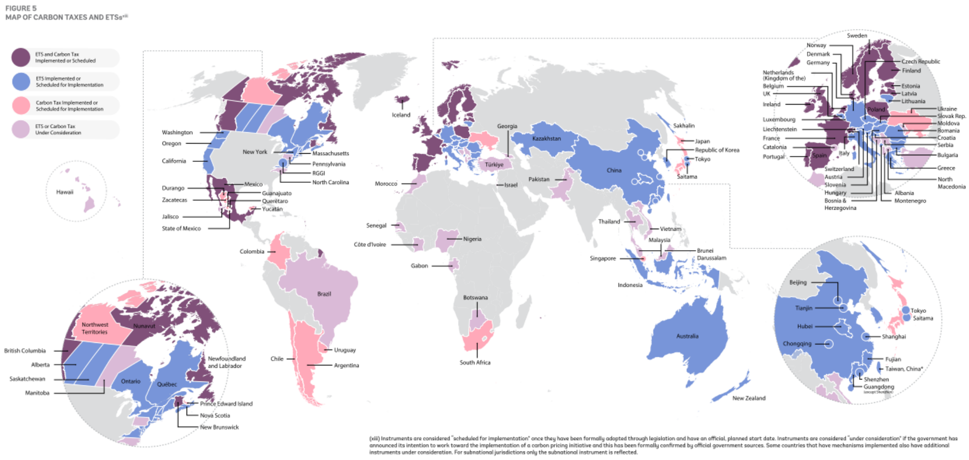
Table 8-1 Types of carbon pricing tools

Classification Method	Tool Name	Definition or Source
Based on Internalization of External Costs	Carbon Tax	Pricing carbon emissions directly by setting an explicit tax rate on GHG emissions or carbon-containing fossil fuels, with the emitter paying the tax based on approved emissions.
	Carbon Market	This refers to the mechanism for emissions entities to trade emission allowances to transfer the balance and reduce the total cost of emissions. Emitters can choose to implement emission reduction measures internally or purchase emission targets in the carbon market to achieve emission reduction targets based on the cost.
	Carbon Credit	This refers to the process of voluntary converting actions taken by enterprises, citizens, and activities into carbon emissions reductions through corresponding methodologies and processes. Carbon credits can be used by regulated companies in the carbon market to achieve their control targets, as well as help enterprises, groups, and individuals voluntarily reduce emissions.
Based on Actual Carbon Cost	Corporate-level Carbon Pricing	This refers to introducing a carbon pricing mechanism into an enterprise as a proactive management behavior that internalizes the social cost of carbon emissions. It is a new

Classification Method	Tool Name	Definition or Source
Expenditure		type of financial mitigation measure for reducing emissions.
	External Carbon Pricing	This refers to the practice of pricing carbon emissions by external factors such as policies and markets. External carbon pricing includes all carbon pricing approaches except internal carbon pricing of enterprises.
Based on Policy Effectiveness	Explicit Carbon Pricing	This refers to carbon pricing mechanisms that are used directly to reduce emissions. Explicit carbon pricing mainly refers to carbon taxes and carbon markets.
	Implicit Carbon Pricing	This refers to the unit abatement costs resulting from climate change mitigation policies other than explicit carbon pricing policies such as carbon markets and carbon taxes. It includes other related mechanisms with synergistic carbon reduction effects, such as taxes on fossil energy, subsidies or tax breaks for clean energy and energy efficiency improvements, etc.
Cross-border Carbon Pricing	Carbon Border Adjustment Mechanism	This refers to the special "tariffs" on carbon emissions that are imposed by countries or regions on high-carbon products imported.
	Carbon Floor Price	The International Monetary Fund (IMF) proposed that major emitting countries should set an "international carbon floor price", and the world should achieve a significant reduction in carbon emissions targets by 2030 through measures such as a minimum tax on carbon.[14]
	Carbon Pricing Inclusive Framework	The Organization for Economic Cooperation and Development (OECD) has proposed the establishment of an "OECD/G20 Inclusive Framework for Explicit and Implicit Carbon Pricing". This initiative aims to assess the efficacy of emission reduction efforts using explicit and implicit carbon pricing mechanisms, enhance coordination among nations in implementing climate change mitigation policies, and manage policy spillover effects.

The scope of carbon pricing continues to broaden, as an increasing number of countries worldwide adopt carbon pricing mechanisms. A growing number of developing nations are exploring and instituting domestically appropriate policies for carbon pricing. For instance, Turkey has drafted a legal framework for pilot projects within its electricity and industrial sectors' emissions trading system. Thailand intends to launch pilot projects on emissions trading systems in its Eastern Economic Corridor. In November 2020, Vietnam approved a revised Environmental Protection Law, initiating the process of creating a national carbon market. As of 2022, 68 countries and regions globally have implemented carbon market, carbon tax and other carbon pricing mechanisms, covering 32% of global GHG emissions.[15]

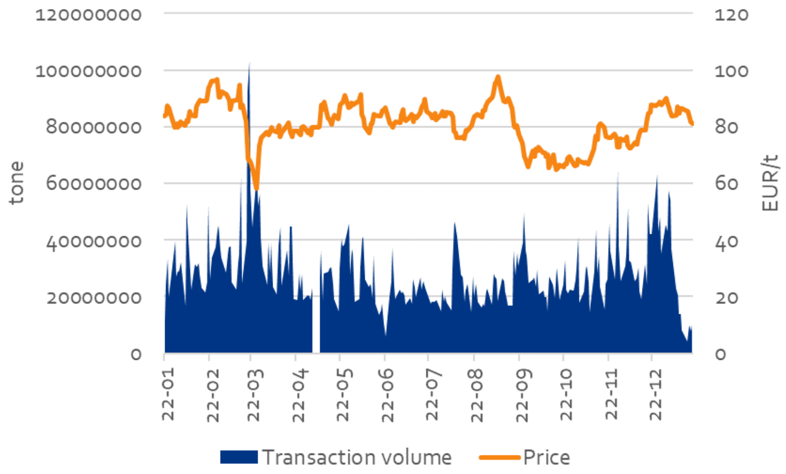
Figure 8-1 Coverage areas of global carbon taxes & markets



Source: World Bank Global Carbon Pricing Annual Report 2023

The escalating carbon prices and price volatility present significant challenges to economic operations. The European Union intends to broaden the scope of its carbon emissions trading system to encompass the shipping industry and assess the feasibility of extending carbon pricing to the transportation and construction sectors. Simultaneously, many EU member states are developing their own national carbon pricing policies for areas not encompassed by the EU Emissions Trading System (ETS). For instance, Germany has initiated a national fuel carbon emissions trading system that primarily addresses fuel emissions not regulated by the EU ETs, representing approximately 40% of the nation's GHG emissions. Luxembourg has started implementing a carbon tax system that predominantly covers emissions from transportation, shipping, and building sectors. Concurrently, through strategies such as augmenting auction quotas and instituting market stability reserves, carbon prices in Europe have exhibited an upward trend. Notably, factors like constrained natural gas supply and limited quota sales contributed to substantial fluctuations in EU carbon futures prices in mid-August 2022, with prices reaching nearly €100/tonne—compared to a range of merely €3-30/tonne between 2005 and 2020.

Figure 8-2 Significant fluctuations in EU carbon market prices in 2022



Source: WIND Database

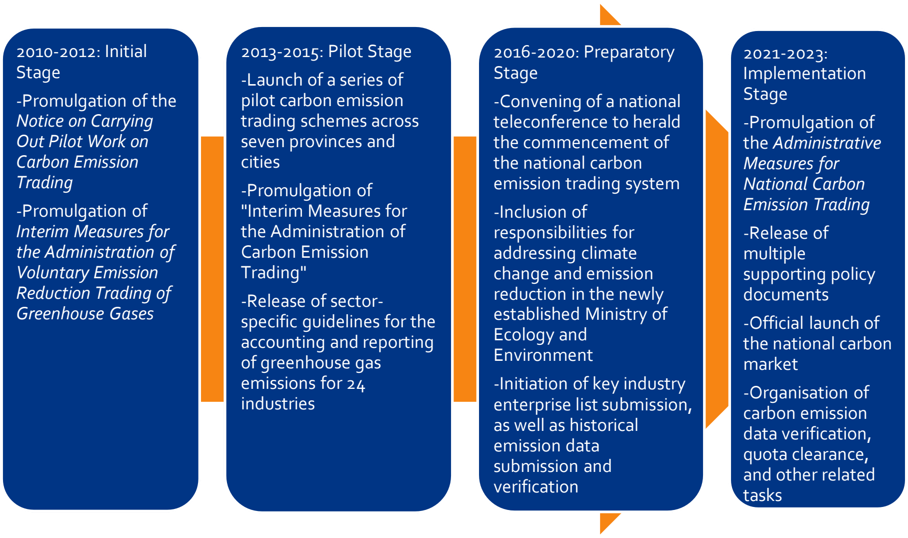
8.3 The core role of carbon markets in carbon reduction is gradually being realised

China has initially formed a multi-layered carbon market

In October 2011, China initiated pilot projects for carbon emission rights trading in seven provinces and cities, including Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, and Shenzhen. Since 2013, these seven pilot carbon markets have successively commenced online transactions, encompassing over twenty industries such as power generation, steel production, and cement manufacturing, and involving nearly three thousand key emitting units.

Moreover, on July 16th, 2021, the National Carbon Market was officially launched, building upon these pilot programs. At present, the market solely covers the power generation industry, accounting for approximately 40%-45% of the nation's emissions. To encourage widespread societal participation in voluntary carbon reduction activities, China established a GHG voluntary emission trading market in 2012. As of September 30th, 2021, the cumulative transaction volume of voluntary emission reductions has surpassed 334 Mtce, with a turnover exceeding RMB 2.9 billion.[16]

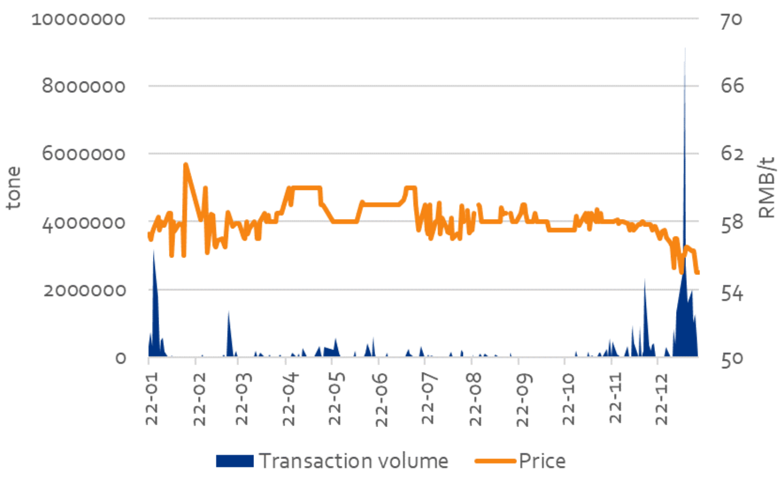
Figure 8-3 The development history of China's carbon market



Source: ERI

Since the establishment of the national carbon market, prices have typically fluctuated between 40-60 RMB/ton. As of the end of 2022, China's carbon market had amassed a trading volume of 230 million tons and a transaction value of RMB 10.5 billion, with an average price of 45.5 RMB/ton. The quota trading within China's carbon market demonstrates notable performance-driven traits, as the combined trading volumes for November and December of both 2021 and 2022 constituted 83% of the overall trading volume.

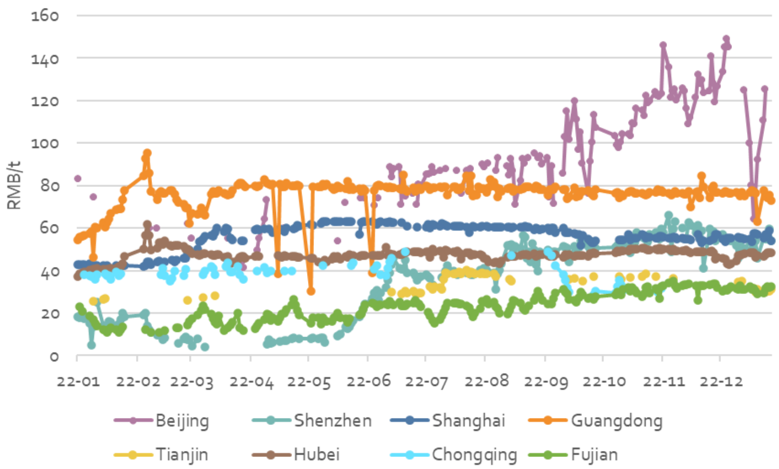
Figure 8-4 National carbon market price trend



Source: WIND Database

Regional carbon markets exhibit steady growth. In 2022, Beijing's carbon market boasted the highest price among the eight regional markets, peaking at 149 RMB/ton. Guangdong's carbon market price remained stable around 80 RMB/ton, while Fujian and Tianjin hovered around 30 RMB/ton. The other four markets were priced between 40-60 RMB/ton.

Figure 8-5 Regional carbon market price trends in 2022 (RMB/ton)

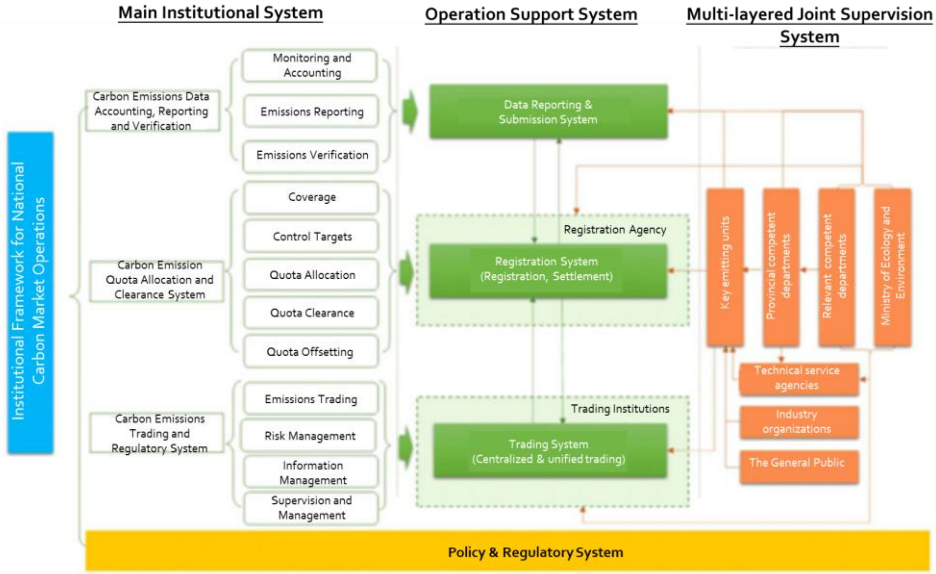


Source: WIND Database

Designing a viable carbon market tailored to China's national context

China has established a legal framework consisting of three core systems for carbon emission management, including the carbon emission data accounting, reporting, and verification system; the allocation and clearance system for carbon emission quotas; and the trade and regulation system for managing emissions, which are supported by three operational support systems, namely the data submission system, registration system, and trade platform.[17]

Figure 8-6 China's carbon market system framework

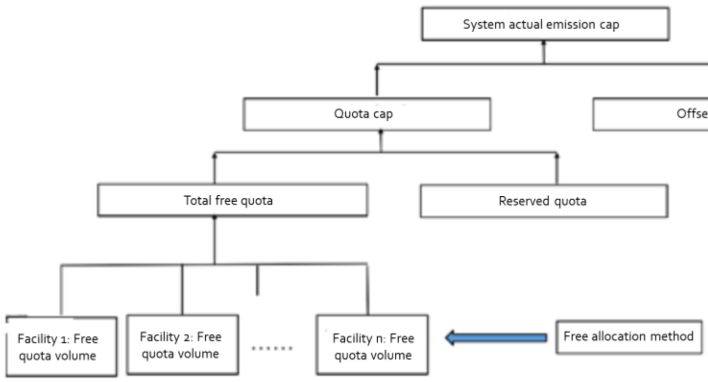


Source: The First Compliance Cycle Report on National Carbon Emission Trading Market

As per the *Measures for the Administration of Carbon Emissions Trading (for trial implementation)* released by the Ministry of Ecology and Environment, enterprises that meet the following requirements are eligible for inclusion in the national carbon emissions trading market: they must operate within industries covered by the national carbon emissions trading market, and their annual GHG emissions must amount to 26,000 tce and above, thereby categorising them as "key emitters" of GHGs. China's carbon market commences with the power generation sector (2,225 companies), which has a total allocation of approximately 4.5 billion tons in 2020, representing roughly 40% of China's total carbon emissions.

Pursuant to the *2021-2022 Implementation Plan for National Carbon Emission Trading Quota Setting and Allocation (Power Generation Industry)*[18] , quotas are determined using a "bottom-up" summation approach: first, the quota amounts of key emitting units within each administrative region are aggregated after obtaining approval; next, provincial-level administrative region quotas are established; finally, all provincial-level quotas are summed up to ascertain the national quota.

Figure 8-7 Schematic diagram of the total amount setting method for China's carbon market



China's carbon market currently adopts an industry benchmarking approach based on intensity control, which is based on the fundamental concept of intensity control. All quotas are allocated free of charge, and this method is based on actual output volume, benchmarked against advanced industry-specific carbon emission levels. Quota allocation is tied to actual output volume, which reflects the principle of rewarding advanced performance and punishing backwardness, while also considering China's current assessment system, where carbon dioxide emission intensity serves as a binding indicator. In accordance with these principles, China classifies power generation units into four distinct categories: conventional coal-fired units with a capacity of more than 300 MW, conventional coal-fired units with a capacity of less than 300 MW, unconventional coal-fired units such as coal gangue and slurry (including circulating fluidized bed combustion), and gas-fired units. Each category possesses its own electricity supply benchmark and heating supply benchmark.

Table 8-2 2021-2022 Carbon emission quota allocation method for the power generation industry

Unit Type	Unit Range	Power Supply Reference Value (tCO_2/MWh)	Heat Supply Reference Value (tCO_2/MWh)
I	Conventional coal-fired power units with a capacity of 300 MW or above	0.877	0.126
II	Conventional coal-fired power units with a capacity of 300 MW or below	0.979	0.126
III	Unconventional coal-fired power units (including coal-fired circulating fluidized bed units) that use coal gangue, coal slurry, and other non-conventional fuels	1.146	0.126
IV	Gas-fired power units	0.392	0.059
Not yet included	Biomass power units, co-firing power units, special fuel power units, power units utilising self-generated resources, and other special power units		

Regional carbon markets offer valuable insights for the design and operation of the national carbon market. Despite not yet reaching peak emissions, China exhibits significant disparities in carbon emission characteristics among regions and industries, as well as in management systems compared to European and American countries. Regional carbon markets endeavour to integrate national conditions with provincial features, drawing from experience while actively exploring practical arrangements for carbon market systems that cater to local needs. Based on their unique development stages, industrial structures, and emission reduction targets, regional carbon markets incorporate locally significant industries. For instance, Beijing includes various service industry enterprises such as hotels, schools, and government organs; Shanghai encompasses steelmaking, petrochemical, airline, and port companies; and Hubei Province integrates ceramic manufacturing and pharmaceutical industries. In addition, to investigating diverse methods like historical intensity, benchmarking against advanced levels, and auction approaches for quota allocation, regional carbon markets offer valuable reference experiences for relevant industries' inclusion in national carbon market design and quota allocation methods. Furthermore, Guangdong Province, one of the earliest pilot areas, proposed a "carbon inclusive" mechanism in 2015, which allowed public participation through subscribing to afforestation projects or donating funds towards reforestation efforts. This mechanism aims to fulfil social responsibilities and alleviate poverty in mountainous regions inhabited by ethnic minorities. In 2019, the program generated RMB 11 million in revenue, benefiting impoverished villages, nationality regions, and old revolutionary base areas in Guangdong Province. The "carbon inclusive" mechanism has not only been rapidly adopted by other pilot carbon markets but also serves as an exemplary model of how carbon markets can contribute to global poverty reduction.

Table 8-3 Coverage of regional carbon markets

Province/City	Included Industries	Inclusion Criteria (annual carbon emissions, if not otherwise specified)
Shenzhen	26 industries and construction, including energy production, processing, and conversion industries, and industrial (manufacturing) sectors	Industrial: 3000 tons of CO_2 Public buildings: 20,000 m^2 Institutional buildings: 10,000 m^2
Shanghai	Industry, power grid, heating, air port and water transport, water production, shopping malls, hotels, business offices, airports	Industrial: 20,000 tons of CO_2 Non-industrial: 10,000 tons of CO_2
Beijing	Heat production and supply, petrochemical production, cement manufacturing, transportation, other industries, services	5000 tons of CO_2
Guangdong	Cement, iron and steel, petrochemical, papermaking, and civil aviation	20,000 tons of CO_2

Tianjin	Iron and steel, chemical, petrochemical, oil and gas extraction, building materials, papermaking, aviation, heat	20,000 tons of CO_2
Hubei	16 industries such as heat, steel, cement, and chemical industries	10,000 tce in energy consumption
Chongqing	Metallurgy, chemical industry, building materials, and many other industries	20,000 tons of CO_2
Fujian	Iron and steel, chemical, petrochemical, non-ferrous, civil aviation, building materials, papermaking, ceramics	10,000 tce in energy consumption

Note: The power generation industry was initially included at the launch of each regional carbon market. However, with the introduction of the national carbon market, the power generation industry gradually withdrew from the regional carbon markets. Source: Compiled based on quota allocation plans for various regional carbon markets.

The effectiveness of China's carbon market operation is increasingly evident

The carbon market's role in fostering green and low-carbon transformation is becoming increasingly apparent. According to the Ministry of Ecology and Environment's inaugural compliance period report of the national carbon emission trading market, in 2020 the carbon emission intensity per unit of electricity produced by thermal power in the power industry decreased by 1.07% compared to the 2018 level. The national carbon market generated approximately RMB 980 million in profits for owners or relevant market participants involved in 189 voluntary emission reduction projects, e.g., wind farms and solar PV power plants. Concurrently, pilot provinces and cities have consistently met their annual targets for reducing CO_2 emissions per unit GDP for several consecutive years, outperforming non-pilot regions. For instance, during the *13th Five-Year Plan* period, Beijing's carbon intensity declined by over 23%, surpassing its planned target of a 20.5% reduction in carbon intensity[19].

The numerous advantages of the carbon market continue to unfold, as the national carbon market provides a crucial price signal that guides China's economic and social low-carbon transformation. This guidance sparks substantial interest from thermal power plants, wind and solar energy enterprises, financial institutions, and society. According to China Beijing Green Exchange (CBGEX), since the launch of the national carbon market, the volume of related businesses, such as carbon consultancy and training, has increased more than tenfold on a year-over-year basis. The national carbon market has evolved into a platform for China to demonstrate its renewed efforts and contributions to combating climate change on a global scale. It has garnered significant attention in the World Bank's annual report, which specifically highlighted the Chinese carbon market. Developed countries like the European Union and the United States, as well as developing regions such as Southeast Asia, have intensified their exchanges with China concerning the establishment of their own domestic markets. Furthermore, the carbon market has made substantial contributions to enhancing fundamental capabilities and fostering a low-carbon consciousness. Statistics indicate that 90% of the regulated enterprises in pilot areas have established functional departments or businesses dedicated to carbon asset management, a figure that notably surpasses that of other regions.

Outlook for China's carbon market development

China's national carbon market has been operating efficiently for over a year now, but it is still in its early stages. When compared to established foreign carbon markets, it is evident that China's carbon market has significant potential for development, especially considering the objectives set forth by the 20th National Congress to promote carbon peaking and carbon neutrality actively and steadily. Thus, it is crucial to prioritise the following key objectives in the near term:

- The first priority is to strengthen the basic capacity building and system building, with a focus on improving data quality. The core deficiency in the carbon market lies in the inadequacies of carbon emission data. Looking forward, it is critical to devise and implement stringent guidelines for the statistical accounting of carbon emissions. This initiative must consider the extensive volume and complex origins of coal within China, alongside the considerable obstacles presented by its statistical calculation. Additionally, the construction of the carbon market supervision system should be strengthened, utilising advanced technologies such as big data, and reinforcing supervision through the "double random, one public" mode. The next priority is to enhance information disclosure, including the disclosure of carbon market policies, allocation methods, and market operation data, as well as the disclosure of significant emission data and compliance status of enterprises. Finally, the fourth priority is to accelerate the introduction of the Interim Regulations on the Management of Carbon Emissions Trading and strive to raise the legal level.

- The second priority is to deeply integrate system design with the carbon peaking and carbon neutrality goals and based on a comprehensive impact assessment, to properly address the issue of incorporating the steel, non-ferrous, and building materials industries into the carbon market. Research indicates that technologies in aluminium electrolysis [20], steelmaking [21], and glass [22] manufacturing sectors are evenly distributed across provinces; however, their contributions to regional economies vary due to local clustering effects. Given the present economic downturn, the timing of incorporating these industries into the carbon market must be thoroughly evaluated. Regarding quota allocation methods, we should actively learn from the experience of regional carbon markets and establish allocation methods based on the actual national situation, in which the distribution of industries varies significantly. In addition, an equitable transition policy must be devised to prevent regions with a high concentration of carbon assets from being disproportionately impacted.

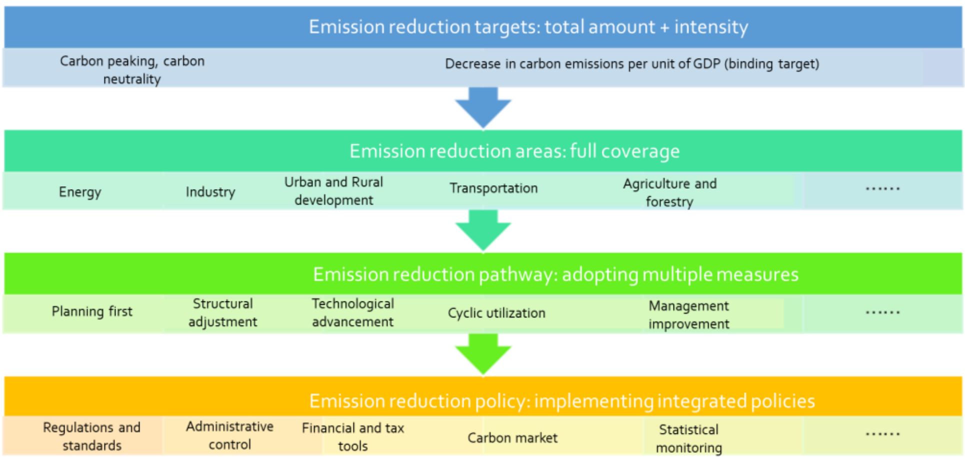
- The third priority is to progressively enrich the trading mode and participation methods for the carbon market. Currently, only emission-controlled businesses are permitted to participate in the national carbon market, which is one cause for the lack of market activity. Therefore, the extent of market participation should be broadened to include financial institutions and even individuals. In fact, financial institutions and individuals possess 23% of positions on the EU carbon market, which plays a significant role in instilling vigour and vitality into the market. Due to the inherent financial properties of carbon dioxide, carbon finance issues, such as carbon futures and carbon options, should be thoroughly studied and demonstrated, but excessive capital speculation also needs to be prevented.

8.4 Developing China's unique implicit carbon pricing policy

China has established a relatively comprehensive implicit carbon pricing policy system

China has long emphasised a holistic approach to reducing carbon emissions. In terms of emission reduction targets, binding goals for energy consumption per unit of GDP were set as early as the *11th Five-Year Plan* period. During the *12th Five-Year Plan* period, binding targets were established for carbon emissions per unit of GDP. With the proposal to reach peak carbon dioxide emissions and achieve carbon neutrality, China is expediting its shift from "dual control" over total energy consumption and intensity to "dual control" over total and intensity of carbon emissions. In terms of emission reduction sectors, China's efforts encompass all economic areas, including energy, industry, urban and rural development, transportation, agriculture, and forestry, with methane emissions also being regulated during the *14th Five-Year Plan* period. Regarding emission reduction pathways, comprehensive measures are implemented in development planning, structural adjustment, technological advancement, and cyclic utilisation. Emission reduction policies encompass regulatory standards, administrative controls, fiscal and taxation measures, carbon markets, statistical monitoring, and public guidance.

Figure 8-8 Framework for China's carbon emission reduction policies



Implicit carbon pricing plays a critical role in China's carbon pricing policy. Currently, there are two types of implicit carbon pricing within China's policy framework: negative implicit pricing (IPP) and positive IPP. Negative IPP encompasses policies that inadvertently contribute to GHG emissions (i.e., contributing to the growth of carbon emissions), such as tax exemptions or financial support for fossil fuel consumption. Positive IPP can be classified into three categories: fiscal/taxation/financial, administrative/regulatory, and synergistic efficiency enhancement. Fiscal/taxation/financial policies include clean energy development subsidies and energy conservation incentives, as well as taxes on fossil fuel usage. Administrative/regulatory policies involve energy efficiency standards and energy-saving target responsibility assessments. Synergistic efficiency enhancement policies encompass industrial structure adjustments, environmental pollution control, and circular economy initiatives, among others. The latter two policy categories have broader implications, as many of their objectives do not explicitly target carbon emission reduction. Moreover, quantifying the expenditure of certain administrative/regulatory policies is challenging. Currently, organizations such as the OECD, and some experts and scholars are actively investigating methods for quantifying the emission reduction effects and expenditures associated with these policies. They propose a concept called comprehensive carbon pricing, defined as: Comprehensive Carbon Pricing = Unit Emission Reduction Cost × Policy Emission Reduction ÷ National Total Emissions.[23]

Table 8-4 Classification of China's carbon pricing tools

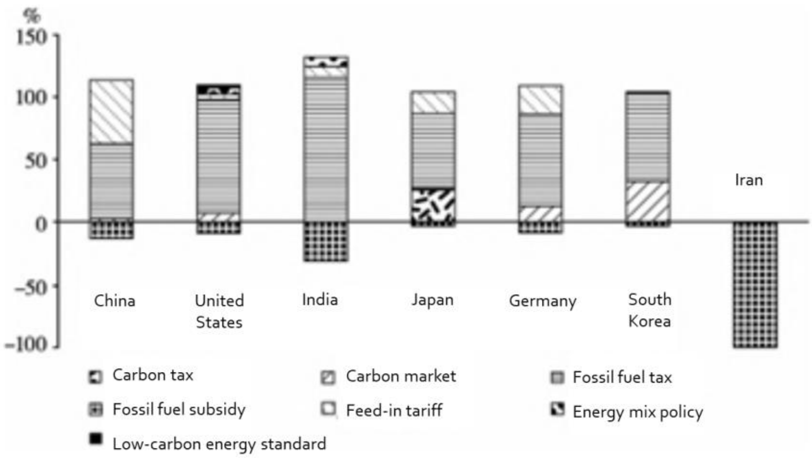
Main category	Sub-category	
Carbon market	Mandatory carbon market, voluntary emission reduction market	
Carbon tax	Carbon tax (planned), as a tax category or tax item	
Implicit carbon pricing	Positive carbon pricing	Fiscal, financial and taxation tools: financial subsidies for clean energy, financial subsidies for energy saving and efficiency improvement, fossil energy tax, etc. Administrative regulations: energy saving standards, target responsibility assessment, etc. Synergetic effects: industrial restructuring, environmental pollution control, circular economy, etc.
	Negative carbon pricing	Fossil energy tax exemptions, financial support, environmental standards, etc.

Source: Compiled by the research team

Implicit carbon pricing: a key component of China's carbon reduction policy

Implicit carbon pricing has long been an important policy tool in China, as evidenced by the prominence of fossil fuel taxes and clean energy electricity price subsidies in the country's comprehensive carbon price, according to a study from Carhart et al. (see Figure 8-9)[24]. These implicit carbon pricing policies have effectively promoted the growth of clean energy and enhanced energy efficiency in China and yielded remarkable results. For instance, since 2008, China has implemented grid-connected electricity pricing policies for photovoltaic power generation and financial subsidies for distributed power generation. In 2011, photovoltaic electricity prices were set at 1.15 RMB/kWh and 1.00 RMB /kWh, depending on the project commissioning time. This elevated pricing strategy ensured stable financial support for the nascent photovoltaic industry, establishing a solid foundation for global competitiveness and its gradual transition into the era of grid parity. According to data from the Ministry of Finance, local funds' renewable energy tariff subsidies remain as high as RMB 6.7 billion in 2022. Between 2005 and 2020, prior to the national carbon market's nationwide launch, China's CO_2 emissions per unit of GDP decreased by 48.4%, exceeding China's commitment to the international community of a 40%-45% drop by 2020. Clearly, China's implicit carbon pricing has been instrumental in fulfilling this commitment.

Figure 8-9 Proportion of comprehensive carbon prices attributable to implicit carbon pricing factors among seven major emitting countries



Source: Carhart M., Litterman B., Munnings C., et al., Measuring Comprehensive Carbon Prices of National Climate Policies [J]. Climate Policy, 2022: 1-10.

Outlook for the development of implicit carbon pricing

Implicit carbon pricing tools primarily serve to support and subsidize advanced technologies, with carbon emission reduction as a secondary benefit. Consequently, their impact on emission reduction can be uncertain. While some negative carbon pricing policies may increase carbon emissions, they are necessary to ensure energy security. Therefore, different carbon pricing tools are not simply interchangeable; they each offer unique perspectives and application scope, and are complementary on a larger scale. To enhance implicit carbon pricing policies, the following directions can be pursued:

First, is to improve the implementation efficiency of implicit carbon pricing tools. These tools should primarily focus on promoting technological innovation and continually adapt their policy application scope in response to changing circumstances, while optimising policy implementation efficiency. Concurrently, it is essential to ensure timely exits to reduce the burden on public funding. For instance, energy efficiency standards for key industry products should be updated promptly, with rewards for companies that meet these standards, and subsidies for those actively engaged in transformation efforts. Enterprises that fail to meet the standards after transformation or refuse to adapt should be closed through industrial policies or environmental policies, such as structural adjustments or environmental standards. Negative carbon pricing tools, particularly ineffective or inefficient ones, require greater emphasis on precision targeting and should be phased out as soon as possible[25].

Second, is to enhance the transmission mechanism between electricity prices and carbon prices. Electricity pricing is a critical aspect of energy market reform. As China accelerates its transition towards market-oriented electricity reforms, it is actively constructing an electricity market system. This presents an opportunity to develop diverse cost-allocation mechanisms based on corresponding compensation support systems, while preventing excessive increases in electricity prices due to high-carbon costs. Strengthening effective connections between power markets and upstream/downstream markets helps address challenges in price transmission and improve the transmission of primary energy prices into electricity generation costs, thereby rationally redistributing system costs in the new power system. By optimising the interest distribution pattern between electricity and carbon markets, effective integration of both markets can be promoted, enabling thermal power and new energy enterprises to achieve mutually beneficial outcomes and sustainable development through participation in the electricity and carbon markets.

8.5 Actively participating in global carbon pricing

New characteristics of global carbon pricing

The global climate convention has achieved a breakthrough in establishing rules for cross-border carbon emissions trading. The *Paris Agreement* introduced the Sustainable Development Mechanism (SDM) to facilitate global trade in carbon credits. In November 2021, the UN Climate Change Conference (COP26) held in Glasgow adopted the implementation rules of *Article 6 of the Paris Agreement*, adding the content of creating a regional carbon market mechanism, forming a dual-track system alongside a large international market. This development necessitated the creation of a new, UN-centred global carbon market system, with contracting parties collaboratively instituting the SDM. While cross-border carbon markets currently face challenges, the transmission of various regional carbon prices strengthens as carbon accounting and mutual recognition systems improve under global net-zero emission targets. At COP27, held in Sharm El-Sheikh, Egypt in November 2022, contracting parties further refined methods for trading carbon credit Quotas, enabling countries to engage in bilateral transactions or permit other countries or companies to utilise their credits. The SDM has developed a plan for registering and approving generated carbon credits, although it has not yet been implemented. COP27 also offered additional guidance on the rules and procedures of the SDM. Nevertheless, numerous technical differences remain concerning cross-border carbon trading mechanisms, such as each country's registration method for carbon credits, reviewing parties, carbon removal certification, and integration with existing market transaction quotas. It may take several years before countries can offset emissions using credit quotas based on emission reduction projects.

Europe and the United States have initiated research into "carbon tariffs," which may become institutionalized, normalized, and comprehensive in the future. Since 2019, the European Union has expedited its legislative process to promote the Carbon Border Adjustment Mechanism (CBAM) through various means, including legislation and diplomacy. After several rounds of intense negotiations, the European Council and European Parliament approved the final version of the CBAM Regulation on December 13th, 2022. As per the Regulation, the EU's CBAM regulatory scheme will commence on October 1st, 2023, with a three-year transition period, after which it will come into force 2026 and be fully implemented in 2034. The amended text of the CBAM Regulation proposes levies on industries such as cement, aluminium, fertiliser, power generation, and steel, encompassing both direct and indirect emissions. The United States is contemplating the introduction of carbon tariffs, too. Upon taking office, the Biden administration proposed to increase the social cost of GHG emissions to $51 per tonne of carbon dioxide, a seven-fold increase from the rate during the Trump administration. The long-term social cost of carbon may eventually reach $125 per tonne. In June 2021, the Biden administration announced its consideration of linking the *Paris Agreement* with the new *North American Free Trade Agreement (NAFTA)* and imposing carbon tariffs on nations that have not met their commitments under the *Paris Agreement* targets. Furthermore, countries such as the UK, French, and Canada are also advocating for the imposition of "carbon tariffs".

Some prominent international multilateral organizations are actively promoting global carbon pricing cooperation. In 2021, the International Monetary Fund (IMF) suggested that principal carbon-emitting countries should adopt an "International Carbon Price Floor (ICPF)." If to set benchmark carbon prices at $75, $50, and $25 per tonne for nations such as Canada, China, the European Union, India, the United Kingdom, and the United States, then it can facilitate a 23% decrease in global emissions by 2030, relative to baseline figures. Additionally, the Organization for Economic Co-operation and Development (OECD) has introduced a comprehensive carbon pricing framework. The International Energy Agency (IEA) has underscored the vital role of carbon pricing in achieving global net-zero emissions. Furthermore, the G20, APEC, G7, and UN-SDG have all pledged or aimed to phase out inefficient fossil fuel subsidies, which effectively function as negative carbon prices.

Actively participating in global carbon pricing

Overall, the current trends and characteristics of global carbon pricing present both challenges and opportunities for China. On one hand, it enables high-quality, new energy and emission reduction projects to participate in the international market. On the other hand, being the largest carbon emitter also entails a higher cost burden associated with carbon pricing.

In the face of this new situation, China should promote global green, low-carbon development within the United Nations framework, countering unilateralism and ensuring equitable distribution of developmental benefits. To leverage mechanisms such as negotiations under the UN Framework Convention on Climate Change (UNFCCC) and the World Trade Organization (WTO), and actively participate in negotiations on global climate trade governance through engagement and cooperation with organizations like the World Bank or OECD Member Countries. Comprehensive research should be conducted on compliance standards, calculation methods, data transparency, and legislative frameworks. This will enable the reasonable determination of export/import responsibilities for emission reduction and facilitate cooperation in shaping equitable, well-founded systems for global carbon pricing.

We should strengthen restrictions on energy-efficient emission reductions within export industries, aligning with a long-term strategy to advance trade transformation while enhancing our global standing and green competitiveness in the industrial division of labour. Effectively leveraging external pressure from carbon pricing mechanism adjustments is essential for optimising import/export structures, curtailing exports of low value-added, high-carbon emission products, and spurring critical industries to transition and upgrade towards a low-carbon, high value-added orientation. It is crucial to adopt international energy efficiency standards as a benchmark for promoting energy-saving upgrades in key industries and fostering the use of green electricity, hydrogen, and other resources for profound decarbonisation. We must establish and refine a green, low-carbon, circular economic development system by incorporating green design and manufacturing, constructing a green supply chain, and minimising the carbon footprint of products throughout their life cycle.

Chapter 9

Methane emissions control

9 Methane emissions control

9.1 Key messages

- Methane (CH_4) ranks as the second most significant greenhouse gas after carbon dioxide (CO_2). Anthropogenic activities have led to a near doubling of atmospheric methane concentrations since pre-industrial times. Currently, worldwide methane emissions stand at approximately 580 million tonnes annually. The agricultural sector emerges as the predominant source of human-induced emissions, with the energy sector following closely. Coal, oil, and natural gas emissions– the triad of fossil energy sources – are approximately on par with each other.
- This chapter discusses methane emissions in the following Parts. Part 9.2 provides insight into the properties of methane as a greenhouse gas; Part 9.3 delves into the current global scenario of methane emissions; Part 9.4 details methane emissions specifically within China; Part 9.5 delineate the strategies and actions China has employed for methane management and emission mitigation, as well as future directions for their action plan; Part 9.6 reviews the advances in methane emission control and reduction in European and American contexts; and Part 9.7 introduces the global methane pledge.

9.2 Characteristics of methane as a greenhouse gas

Methane and carbon dioxide are the two principal greenhouse gases. Methane exhibits a high radiative efficiency (measured by radiative efficiency), yet its emissions are relatively limited, and it can be swiftly removed from the atmosphere. On the other hand, carbon dioxide has a relatively weaker radiative efficiency, but it is emitted in vast quantities and can persist in the atmosphere for hundreds of years.

Table 9-1 Methane and Carbon Dioxide – Comparison

	Anthropogenic Methane	Fossil Carbon Dioxide
Global emissions (billion tonnes per year)	0.356* [i]	34.5** [j]
Radiative efficiency (watts per square meter per billion tonnes)	0.211 [k]	0.00175 [l]
Residence time in atmosphere	decades	centuries to millennia
Global warming potential – 20 years	81.2[m]	1

*Note: *356 Tg(CH_4)/y = 0.356 billion tons of CH_4 per year; **9.4 Pg(C)/y = 34.5 billion tons of CO_2 per year.*

Methane and carbon dioxide behave very differently in the atmosphere. Methane is a very reactive molecule readily oxidized to carbon dioxide and other compounds. Carbon dioxide is unreactive and can be removed from the atmosphere mainly by being dissolved in seawater, which is a slow process. (Carbon dioxide also cycles in and out of terrestrial plant life). As a result, carbon dioxide can remain in the atmosphere for centuries or millennia after being emitted. Even though carbon dioxide is a relatively weak greenhouse gas, its long lifetime makes it a dangerous climate change agent.

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[i] Table 5.2 - 356 Tg(CH_4)/y = 0.356 billion tons of CH_4 per year. Intergovernmental Panel on Climate Change. (2021). *Climate Change in 2021: Physical Science Basis, Sixth Assessment Report of the IPCC Working Group I Report*. https://www.ipcc.ch/assessment-report/ar6/

[j] Table 5.1 - 9.4 Pg(C)/y = 34.5 billion tons of CO_2 per year. Intergovernmental Panel on Climate Change. (2021). *Climate Change in 2021: Physical Science Basis, Sixth Assessment Report of the IPCC Working Group I Report*. https://www.ipcc.ch/assessment-report/ar6/

[k] Roy, M., Edwards, M. R., & Trancik, J. E. (2015). *Methane mitigation timelines to inform energy technology evaluation*. *10*(114024). https://iopscience.iop.org/1748-9326/10/11/114024/media/erl114024_suppdata.pdf

[l] Roy, M., Edwards, M. R., & Trancik, J. E. (2015). *Methane mitigation timelines to inform energy technology evaluation*. *10*(114024). https://iopscience.iop.org/1748-9326/10/11/114024/media/erl114024_suppdata.pdf

[m] Table 7.SM.7. Table 5.2 - 356 Tg(CH_4)/y = 0.356 billion tons of CH_4 per year. Intergovernmental Panel on Climate Change. (2021). *Climate Change in 2021: Physical Science Basis, Sixth Assessment Report of the IPCC Working Group I Report*. https://www.ipcc.ch/assessment-report/ar6/; Kleinberg, R. L. (2020). *The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers*. https://eartharxiv.org/repository/view/1686/

Figure 9-1 illustrates the persistence of the two gases in the atmosphere.

Figure 9-1 Atmospheric decays following pulses of carbon dioxide and methane[26]

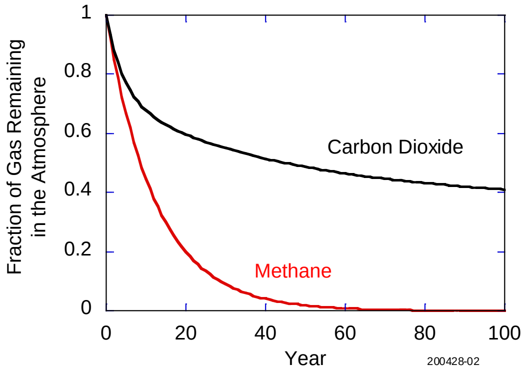


Image source: Robert L Preprint et al., EarthArXiv

The immediate warming effect of an added ton of methane in the atmosphere is significantly higher than the effect of an added ton of carbon dioxide. (See Table 9-1, radiative efficiency.) As a result of its short residence time in the atmosphere, if rates of methane emissions decrease, the Earth's temperature rise will slow relatively quickly.

Indeed, reductions in the methane emissions are a far more powerful tool for moderating temperature increases over the next 30 years than reductions in carbon dioxide emissions. Reductions in both methane and carbon dioxide emissions are essential for a long-term solution to climate change, but in the short-term reductions in methane emissions are far more powerful, as shown in Figure 9-2.

Figure 9-2 Global average temperature responds slowly to carbon dioxide emission reductions, but relatively quickly to methane emission reductions. Redrawn from Shindell [27]

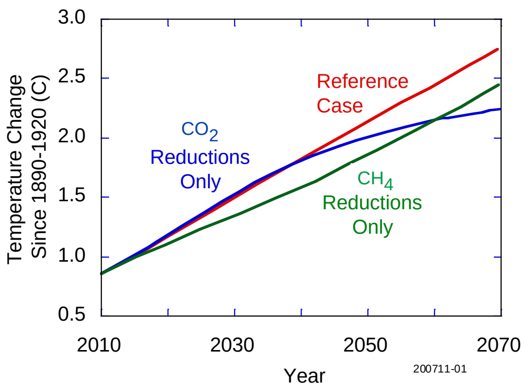


Image source: Drew Shindell et al., Science magazine

Global Warming Potential (GWP) is a measure that attempts to put the climate impacts of different greenhouse gases on a single scale. The GWP of a gas depends on the time frame being considered, because different gases stay in the atmosphere for different periods of time. For example, the 20-year GWP is 81.2 and the 100-year GWP is 27.[28]

Methane and other volatile organic compounds contribute to the formation of smog. When methane and other VOCs react with nitrogen oxides (NO_x) in the presence of sunlight, the result is often ground-level ozone and smog. This can be very harmful to human health as well as to crops and other vegetation. The significance of methane emissions in smog formation depends on conditions in each location.

9.3 Global methane emissions

The concentration of methane in the atmosphere varies by location. The lowest concentrations – roughly 1,650 parts per billion by volume (ppbv) -- are found over Antarctica, which has no exposed sources of methane. The highest concentrations -- approaching 1,950 ppbv -- are in the Middle East, South Asia, and East Asia. (See Figure 9-3).

Figure 9-3 Atmospheric methane concentration (parts per billion by volume) mapped by the Copernicus Sentinel-5P (TROPOMI) mission at 7 km x 7 km resolution [29]

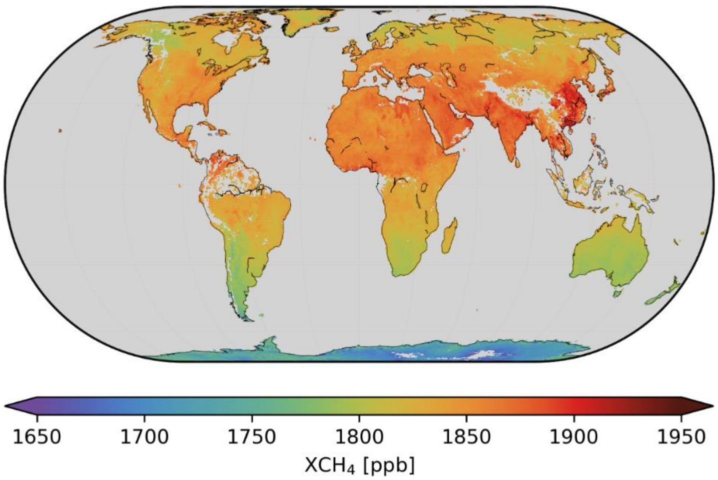


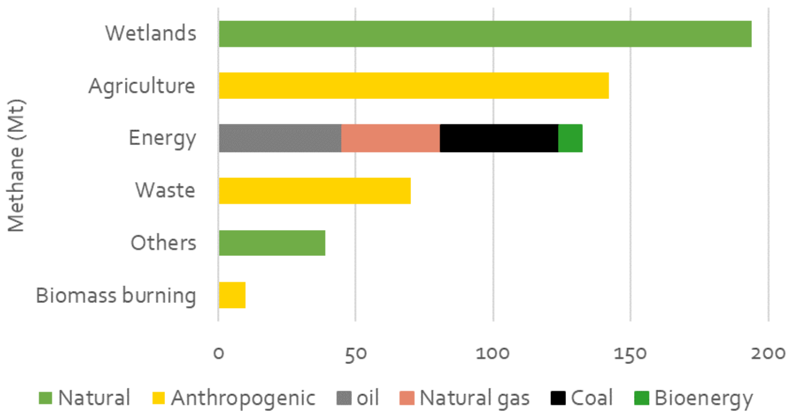
Image source: Global Carbon Budget 2020

Methane emissions can be categorised into two types: natural and anthropogenic. Natural emissions stem predominantly from environmental sources such as wetlands. Anthropogenic emissions, on the other hand, arise chiefly from agricultural practices (including livestock rearing and rice cultivation) and the energy industry (encompassing coal, oil, natural gas, and the development and biomass energy utilisation).

The estimation of global methane emissions is fraught with uncertainty, primarily due to the paucity of comparable statistical data. The *Global Methane Tracker 2023* report by the

International Energy Agency (IEA) provides the latest estimates, positing that the annual global methane emissions stand at roughly 580 million tonnes, of this total, natural sources contribute around 40%, while anthropogenic activities account for the remaining 60%, as depicted in Figure 9-4. Within the anthropogenic category, agriculture is the predominant contributor, responsible for approximately a quarter of overall emissions. The energy sector follows, with coal, oil, and natural gas—collectively the primary fossil fuel sources—contributing substantially and equally to global methane emissions.

Figure 9-4 Global methane emissions



Data source: Saunois et al. Global Methane Budget 2000-2017

9.4 Methane emissions in China

China's methane emission estimates are predominantly derived from its national greenhouse gas inventories, which are reported to the United Nations Framework Convention on Climate Change (UNFCCC) through *China's National Communications and Biennial Update Reports on Climate Change*. The *Second Biennial Update Report* indicates that, in 2014, China's methane emissions totalled 55.3 million tonnes, of these, energy activities were responsible for 24.8 million tonnes, comprising 44.8% of emissions; agricultural activities contributed 22.2 million tonnes, making up 40.2%; waste disposal was attributed 6.6 million tonnes, amounting to 11.9%; and other sources made up the remaining 3.1%. It is anticipated that China will soon present its *Fourth National Communication and Third Biennial Update Report*, which will include more recent data on methane emissions.

9.5 China's policies, measures, and actions for controlling methane emissions

Policy measure and actions already taken

The Chinese government has consistently prioritised the control of non-CO_2 greenhouse gases, including methane, and has implemented an array of effective policies and measures.

(1) Policy guidance as a driver for methane emission control

The *12th Five-Year Plan for Greenhouse Gas Emission Control*, promulgated by the State Council in 2012, emphasised the need to bolster the management of livestock farming, urban waste disposal, and utilisation to curb the increase of methane and other greenhouse gas emissions. Subsequent directives, such as the *13th Five-Year Plan for Greenhouse Gas Emission Control*, specifically targeted the mitigation of methane emissions from agricultural fields, advocated for the capture and utilisation of methane in landfills and sewage treatment plants, and called for the integrated control of methane and conventional pollutants.

In 2021, the Ministry of Ecology and Environment released the *Guiding Opinions on Coordinating and Strengthening Work Related to Climate Change and Ecological Environmental Protection*. This document proposed the establishment of pilot programmes to monitor methane emissions at significant emission sources within key industries, including oil, natural gas, and coal mining at the point-source level. It also suggested the exploration of extensive regional monitoring for methane and other non-CO_2 greenhouse gases.

Following this, in 2022, the National Development and Reform Commission alongside the National Energy Administration unveiled the *14th Five-Year Plan for Modern Energy Systems*, which called for improved methane recovery and use in oil and gas fields, and a reduction in emissions from the extraction and use of fossil fuels.

(2) Integrated control of methane emissions from coal mines for occupational safety and climate action

To rigorously manage emissions from coal mines, relevant Chinese authorities have released a succession of technical standards.

The *2008 Emission Standard for Coal Bed Methane (Coal Mine Gas) (GB21522-2008)* explicitly bans the direct discharge of surface coal bed methane and high concentration methane (volume concentration higher or equal than 30%).

Subsequent strategic documents, the *12th Five-Year Plan for Coal Bed Methane (Coal Mine Gas) Development and Utilisation (2011)* and the *13th Five-Year Plan for Coal Bed Methane (Coal Mine Gas) Development and Utilisation (2016)*, set forth directives for the enhanced development and utilisation of coal bed methane (coal mine gas) to mitigate greenhouse gas emissions.

The *Guidelines for Greenhouse Gas Emission Accounting and Reporting for China's Oil and Natural Gas Production Enterprises* released in 2014, prescribe the accounting measures for methane emissions resulting from flaring, process venting, leaks, and also cover recovery and utilisation processes within the exploration, development, processing, storage, and transport stages of oil and natural gas production.

In 2020, the document *Notice on Further Strengthening Environmental Impact Assessment Management of Coal Resource Development*, proposed that methane with a concentration $\geqslant$8% should be utilised safely; it also advocated for the comprehensive utilisation of methane with a concentration between 2-8% and low-grade vented methane, by promoting innovative development methods.

(3) Initiatives by oil and gas corporations to mitigate methane emissions

Sinopec's *2018 Green Enterprise Action Plan* mandates oil and gas companies to enhance the recovery and reduction of methane emissions from associated petroleum gas, well test gas, and during the collection and transport of crude oil.

From 2018 to 2022, companies such as Beijing Gas Group, ENN Energy, and Hong Kong China Gas successively endorsed the *Methane Guiding Principles (MGP)*.

In 2020, the *Methane Emission Control Action Plan* was issued by CNPC, outlining specific objectives for the control of methane emissions.

The Oil and Gas Methane Emission Control Alliance was founded in 2021 by six entities, including Sinopec, CNPC, CNOOC, PipeChina, Beijing Gas, China Resources Gas, and ENN Energy, demonstrating a collaborative approach to emission control.

Furthering international collaboration, China Gas joined the Oil and Gas Methane Partnership (OGMP) under the auspices of the United Nations Environment Programme in 2021, becoming its first Chinese member.

(4) Targeting ecological farming practices for agricultural methane emission reduction

In a bid to combat methane emissions from agriculture, the Ministry of Agriculture and Rural Affairs introduced the *Guiding Opinions on Promoting Ecological Farm Construction* in 2022. This document prioritises ecological farming practices, proposing exploration of low-carbon incentive policies specifically addressing significant sources of methane emissions, such as those from rice cultivation, nitrous oxide from agriculture, methane from ruminant digestion, and both methane and N_2O from the management of livestock manure.

Moreover, a joint directive from the Ministry of Agriculture and Rural Affairs and the National Development and Reform Commission culminated in the *Implementation Plan for Agricultural and Rural Emission Reductions and Carbon Sequestration*. This plan outlines essential tasks within three primary sectors: crop production, livestock breeding, and fisheries. Its initiatives include strategies to diminish methane emissions from rice fields, lower the intensity of enteric methane from ruminants, and mitigate both methane and N_2O emissions in livestock manure management. Among these, reducing rice paddy methane emissions has been highlighted as one of the ten major actions.

(5) Leveraging carbon market mechanisms to encourage methane mitigation

China's approach to managing Clean Development Mechanism (CDM) projects distinctly prioritises methane reduction initiatives. During the initial commitment period of the *Kyoto Protocol*, China developed numerous successful methane reduction CDM projects, including coal mine methane-to-energy, landfill gas recovery and power generation, and biogas projects. By the close of 2011, over 230 methane reduction CDM cooperation projects had received approval from the Chinese government, resulting in an annual CO_2 equivalent emissions reduction surpassing 60 million tonnes. These projects not only assisted partner developed nations in meeting their Kyoto commitments economically but also bolstered China's sustainable progress.

Despite the waning global demand for CDM projects, the Chinese government has continued to promote the participation of methane reduction ventures in the domestic voluntary carbon market. It has crafted a compendium of CCER (Chinese Certified Emission Reduction) methane reduction methodologies. These include, but are not limited to, CM-003-V02 for the *Recovery and Utilisation or Flaring/Oxidation of Coal Mine, Coal Bed, and Ventilation Air Methane*; CMS-017-V01 for *Methane Emission Reduction in Rice Cultivation Through Water Management Adjustments*; and CMS-026-V01 for *Methane Recovery from Small-scale Domestic and Farm Operations*. Notably, landfill gas recovery, biogas utilisation, and coal mine methane power generation CCER projects in China have achieved CO_2 equivalent methane emission reductions of approximately 2.09 million, 2.17 million, and 4.02 million tonnes respectively.

In October 2023, the MEE and the State Administration for Market Regulation (SAMR) jointly issued the *Administrative Measures for Voluntary Greenhouse Gas Emission Reduction Trading (Trial)* (CCER for short), and methane is among the greenhouse gases covered. The document specifies that the MEE is responsible for the organisation, formulation, and release of the relevant technical specifications such as CCER methodology, which will serve as the basis for the validation and implementation of CCER projects in relevant fields, as well as the accounting and verification of emission reductions.

(6) Green finance incentives for methane emission reduction initiatives

In 2007, the Ministry of Finance alongside the State Administration of Taxation promulgated the *Notice on Expedited Tax Policies for Coal Seam Gas Extraction*, specifying that the state would provisionally exempt resource tax on the extraction of coal seam gas at the surface level.

In 2020, the China Banking and Insurance Regulatory Commission inaugurated the Green Finance Statistics System, incorporating the collection of various unorganised emissions, such as methane and other greenhouse gases, during industrial production processes, as well as the construction and operation of facilities for emission reduction projects, into the scope of support for green financing.

The subsequent year, the People's Bank of China unveiled the Green Loan Statistics System, which expanded the green loan remit to include the development and operation of coal seam gas (coal mine gas) extraction and utilisation facilities.

Further advancements in 2021 were marked by the collaborative issuance of the *Green Bond Endorsed Project Catalogue* by the People's Bank of China, the National Development and Reform Commission, and the China Securities Regulatory Commission. This catalogue was broadened to incorporate support for projects that address methane emissions. Included were the detection and repair of methane leaks, the development or integrated utilisation of methane at low concentrations, and the manufacturing and commercial activities related to equipment for waste resource utilisation and non-hazardous treatment. This encompasses the generation of biogas from both catering and agricultural waste, as well as the construction and operation of facilities for biogas production from livestock manure, amongst other methane mitigation endeavours.

In 2022, the Ministry of Ecology and Environment set forth the *Reference Criteria for Registration of Local Pilot Climate Investment and Financing Projects within the Climate Investment and Financing Directory*. This initiative expanded the framework of climate investment and financial backing to include projects aimed at reducing methane emissions.

Policies, measures, and actions for the future

Within the ambit of the *14th Five-Year Plan*, China has delineated a robust strategy for intensifying its management of methane and other non-CO_2 greenhouse gases. This comprehensive plan encompasses the introduction of more stringent measures, supported by the drafting and implementation of pertinent policies, to catalyse concerted action on methane emission mitigation. One notable initiative is the National Energy Administration's endeavour to synchronise the development of coal seam gas with the integrated management of coal mine methane, prompting regions and pivotal enterprises to engage in the creation of the *Coal Seam Gas (Coal Mine Gas) Development and Utilisation Plan*. This blueprint outlines an ambitious target: the exploitation and utilisation of 10 bcm of coal seam gas nationwide by 2025, also delineating the trajectory and principal tasks for the coal seam gas industry throughout the duration of the *14th Five-Year Plan* period.

In November 2023, a coalition of eleven Chinese government departments, including the MEE, Ministry of Foreign Affairs, the NDRC, Ministry of Science and Technology (MoST), Ministry of Industry and Information Technology (MIIT), Ministry of Finance (MoF), Ministry of Natural Resources (MNR), Ministry of Housing and Urban-Rural Development (MoHURD), Ministry of Agriculture and Rural Affairs (MARA), Ministry of Emergency

Management, and the NEA, collaboratively issued the *Methane Emission Control Action Plan*. This strategic plan adheres to five foundational principles: "coordinated planning, solidifying foundations, categorized implementation, steady and orderly progress, and risk prevention". It identifies eight crucial tasks to regulate methane emissions, outlining specific measures for effective methane emission management across various sectors and levels. These crucial tasks include:

1) Enhancing the development of a comprehensive system for monitoring, accounting, reporting, and verification of methane emissions
2) Fostering methane emission reduction initiatives within the energy sector
3) Encouraging agricultural methane emission control practices
4) Improving methane emission management in waste and sewage treatment processes
5) Bolstering the integrated control of pollutants and methane
6) Advancing technological innovation and regulatory supervision for methane emission reduction
7) Hastening the formation of legal, standard, and policy frameworks for methane control
8) Amplifying efforts in global methane governance and international cooperation

The implementation of these measures is aimed at accomplishing the following anticipated goals:

During the *14th Five-Year Plan* period, the development and implementation of policies, technologies, and standard systems for methane emission control progressively advances. Core competencies such as statistical accounting, monitoring, and regulation of methane emissions see marked improvements. There are notable advancements in the utilisation of methane resources and emission reduction. The agricultural sector observes a moderate decline in methane emission intensity per unit of produce in both planting and breeding industries. Additionally, the resource utilization rate of urban domestic waste and the harmless disposal rate of urban sewage sludge steadily rise.

During the subsequent *15th Five-Year Plan* period, there are further enhancements in the policies, technologies, and standards pertaining to methane emission control. Core competencies in areas like statistical accounting, monitoring, and regulation of methane emissions are significantly strengthened. The effectiveness and management standards of methane emission control see substantial improvements. The utilization levels of coal mine gas are elevated, and the methane emission intensity per unit of agricultural product in the planting and breeding industries is further reduced. Subsequently, the oil and natural gas extraction industry aims to progressively achieve zero routine flaring in onshore oil and gas extraction.

9.6 Developments in methane emission control in Europe and the United States

United States

Recent US policies related to methane emissions include the *Inflation Reduction Act (IRA)* and the *Methane Emissions Reduction Action Plan of 2022*.

The Inflation Reduction Act was passed by the US Congress and signed by President Joe Biden in 2022. It includes three sections on methane emissions.

1) Methane Emissions Reduction Program: This program requires the Environmental Protection Agency (EPA) to implement a waste charge on methane emissions from oil and gas companies that report under the *Clean Air Act*. The charge will start at $900 per metric ton of methane reported in 2024 and will increase to $1,500 in 2026 and thereafter. Under the program, EPA has $1.55 billion for financial and technical assistance to abate methane emissions, including $700 million for methane mitigation at marginal conventional wells.[30]

2) Royalties for Produced Methane on Federal Lands and Waters: This provision expands the scope of royalty collection for natural gas produced on federal lands or the outer continental shelf by including gas that is consumed or lost by venting, flaring or negligent releases during upstream operations. Exceptions include gas vented or flared for no longer than 48 hours in emergencies, gas used within the area of a lease, and gas that is unavoidably lost.[31]

3) Monitoring Methane Emissions: The IRA authorizes EPA to provide $20 million for grants and activities to monitor methane emissions.[32]

The *Methane Emissions Reduction Action Plan* was initially released by the U.S. government in November 2021. It was updated in 2022 in connection with COP 27, where President Biden announced $20 billion in new investments targeting methane emissions reduction. The Plan outlines more than 50 actions to abate methane emissions across various sectors, including oil & gas, landfills & food waste, abandoned coal mines, agriculture, building & industrial, and manufacturing. The Plan outlines steps including the following.

1) For the oil and gas sector: stronger standards to cut methane emissions, a "Super-Emitter Response Program" that requires operators to respond to credible third-party reports of high-volume methane leaks, and requirements to plug methane leaks from orphaned oil and gas wells.[33]

2) For landfills and food waste: conducting outreach and developing new resources to capture 70% of methane for all landfills nationwide, in addition to launching new efforts to cut national food waste and loss by 50% by 2030.[34]

3) For abandoned coal mines: $11 billion for eligible states and tribes to reclaim abandoned coal mines over 15 years to help eliminate methane pollution, while creating job opportunities for coal workers.[35]

European Union

The *EU Methane Strategy*, published in October 2020, outlines both cross-sector and sector-specific actions to significantly reduce methane emissions. The document focuses on actions in the energy sector, the agricultural sector, the waste sector, as well as international cooperation. Some of the cross-sector and energy-related proposed measures include:

1) Improving measurement and reporting on methane emissions by companies across all relevant sectors

2) Strengthening satellite-based detection and monitoring of methane emissions through the EU's Copernicus programme

3) Accelerating the development of the market for biogas from sustainable sources

4) Delivering legislative proposals on compulsory monitoring, reporting, and verification (MRV) of all energy-related methane emissions and obligations to improve leak detection and repair on all fossil gas infrastructure

5) Considering legislation on eliminating routine venting and flaring in the energy sector

6) Extending the OGMP framework to more oil and gas companies, the coal sector, as well as the closed/abandoned sites

7) Promoting remedial work under the initiative for Coal Regions in Transitio.[36]

In December 2021, in accordance with the *EU Methane Strategy*, the European Commission proposed a *Regulation Aimed at Reducing Methane Emissions in the Energy Sector*. The proposal was endorsed by the EU Council of Energy Ministers in December 2022. This is the first-ever EU legislative proposal for a regulation on methane emissions reduction in the energy sector. The legislation provides a stricter legal framework for the MRV of energy sector methane emissions as well as mandates on leak detection/repair and ban on venting and routine flaring. Under the legislation, operators must submit direct source-level methane emissions measurements instead of estimates based on emission factors. Oil and gas companies are required to carry out quarterly surveys to detect leaks and to repair any leaks immediately. For coal, the regulation prohibits venting and flaring of methane above certain threshold. It also requires Member States to report the inventory of inactive wells and mines and to develop mitigation plans for the inactive sites. Lastly, the legislation requires importers to submit information about the fuel source and ways to measure and mitigate emissions[37].

9.7 Global Methane Pledge

The Global Methane Pledge (GMP) was launched at COP26 in November 2021. Roughly 150 countries have joined the GMP, representing nearly 50% of the global anthropogenic methane emissions and two-thirds of global GDP.[38]

Under the GMP, participating countries agree to a collective goal of cutting anthropogenic methane emissions by at least 30 percent by 2030 from the 2020 levels. Countries commit to take comprehensive domestic actions to reduce methane emissions and to move towards using the highest tier IPCC good practice inventory methodologies to quantify methane emissions.

The International Methane Emissions Observatory (IMEO) is an initiative of the United Nations Environment Program to help prioritise actions and monitor commitments under the GMP. IMEO collects and integrates methane emissions data. At COP27 in November 2022, IMEO launched the *Methane Alert and Response System*, which will focus on data collection from very large point sources from the energy sector.[39]

Chapter 10
Achievements and trends of energy transformation in major regions of China

10 Achievements and trends of energy transformation in major regions of China

Regions are important spaces for economic and social development and ecological protection, as well as key carriers for the production and supply and consumption, and circulation of energy. Since the 18th National Congress of the CPC, the CPC puts forward the major regional strategies such as the coordinated development of Beijing-Tianjin-Hebei region, the integrated development of the Yangtze River Delta, the Yangtze River Economic Belt, the Guangdong-Hong Kong-Macao Greater Bay Area, and the ecological protection and high-quality development of the Yellow River Basin, which have made corresponding regional deployment and spatial guidelines for energy transformation and green and low-carbon development and have witnessed a series of representative achievements and landmark projects.

10.1 Key messages

- The *Development Plan Outline for the Yangtze River Economic Belt* issued in September 2016 has been instrumental in endorsing eco-friendly and green development strategies across provinces and cities along the Yangtze River. Post-implementation of the *Yangtze River Economic Belt* strategy, there has been noticeable improvement in the policy system, fostering both protection and development of the basin. Provinces and cities along the river have actively pursued industrial transformation, evidenced by a significant decrease in energy consumption intensity from 1.33 tce per ten thousand RMB in 2000 to 0.38 tce in 2019. This reveals the effective implementation of a green and low-carbon transformation in the region. The construction of numerous mega hydropower stations such as Three Gorges, Wudongde, Xiluodu, Xiangjiaba, and Baihetan, leveraging the advantageous resources of the Yangtze River, has garnered global attention.

- The Greater Bay Area, encompassing Guangdong, Hong Kong, and Macau, stands as one of China's pre-eminent metropolitan regions, boasting both a formidable economic magnitude and an exceptional dynamism in innovation. The *West-to-East Electricity Transmission (WEET)* initiative has rendered substantial reinforcement for the sustainable progression of the Greater Bay Area. In recent years, the energy consumption structure in the Greater Bay Area has undergone a shift towards cleaner and lower carbon energy. This area has pioneered the city-level "carbon peak" target. The low-carbon pilot cities within the region, namely Guangzhou, Shenzhen, and Zhongshan, have set ambitious carbon emission peak targets for 2020, 2020-2022, and 2023-2025, surpassing the national goal of achieving carbon peak by 2030. In 2020, clean energy accounted for over 60% of the Greater Bay Area's energy supply, with 206 TWh of electricity transmitted via the WEET Project, contributing 37.1% to total social electricity consumption.

- The Yangtze River Delta region has become a prime destination for major interprovincial and interregional energy infrastructure projects such as "Coal from the North to the South," "Gas from the West to the East," and "Electricity from the West to the East." The region has experienced a rapid rise in new energy generation over the past few years, with the average annual growth rates for wind, solar, and nuclear power generation reported to be as high as 21%, 51%, and 12.9% respectively between 2016 and 2020. The region, despite its limitations in land and space resources for large-scale centralised wind farms and solar power plants, has emerged as a major hub for distributed photovoltaic power generation in China, and among the country's top five offshore wind power bases. Provinces such as Zhejiang have addressed the stability of new energy supplies by leveraging pumped-storage hydropower. The Yangtze River Delta region, capitalizing on an integrated development layout, is facilitating interconnection among regional energy infrastructures such as ultra-high voltage, distribution networks, and hydrogen energy. The new energy industry has thereby become a "green engine" propelling economic development of the region.
- A decade ago, the Beijing-Tianjin-Hebei region grappled with severe "haze crises," and stark conflicts existed between economic development and resource environment. Over the past decade, the region has expedited clean energy substitution, steadily transitioning from coal-dominance to a cleaner, more diversified energy mix. In 2020, the proportion of coal in Beijing's energy consumption fell to a mere 1.5%, and coal usage in the plains of Beijing has almost been eliminated. Similarly, in Tianjin and Hebei Province, coal for heating has been practically eliminated in all areas except mountainous regions (Tianjin) and rural plains (Hebei) respectively. The three regions are collectively striving for an integrated energy system and promoting green, low-carbon development in a coordinated manner.
- The Yellow River Basin, a traditionally resource-rich region, faces the most significant challenges in China's energy transformation. Provinces such as Shanxi, Inner Mongolia, and Shaanxi have been instrumental in maintaining the stability of coal prices and supplies, albeit at the expense of ecological and environmental damage. Hence, it is essential to redirect the focus of the Yellow River Basin from a traditional energy base to a comprehensive energy base, transitioning from fossil fuel reliance to a balanced mix of fossil and non-fossil energy sources. Integrating subsidence area management with photovoltaic power generation presents a vital pathway for transitioning traditional energy areas, particularly in regions affected by subsidence from coal mining, with idle land and fragile vegetation. Further, large-scale wind and solar power projects in desert, Gobi, and wasteland areas are being expedited, with the construction of the Kubuqi Desert photovoltaic project in Inner Mongolia marking a new phase in the holistic treatment of "photovoltaics + desert control." Additionally, the Yellow River basin boasts notable achievements such as

the establishment of the Qinghai "hydro-wind-solar" multi-energy complementary base, clean heating projects in the "Three Rivers Source" region, and Shandong Province's forefront position in national photovoltaic development.

10.2 The region of the Yangtze River Economic Belt

The Yangtze River Economic Belt is a river basin economic belt spanning three regions of the east, central, and west of China, with a geographical scope covering 11 provinces and cities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan, accounting for about 1/5 of the national territory. The Yangtze River Economic Belt was developed from the concept of Yangtze River Industrial Intensive Belt in the 1980s, which was initially proposed as an economic zone centred on an array of supercities or megacities in the Yangtze River basin, connecting small-, medium- and large-sized cities in their respective hinterlands through their radiation and absorption effects. Today, the Yangtze River Economic Belt capitalises on the golden waterway provided by the Yangtze River, with a total population and economy of more than 40% of the country, and with the typical characteristics of important ecological status, robust comprehensive strength, and immense development potential.

Advancing the *Yangtze River Economic Belt* strategy is crucial for directing provinces and cities along the river to prioritise ecological concerns and adopt sustainable development practices. In September 2016, the release of the *Yangtze River Economic Belt Development Plan Outline* signified that the growth of the Yangtze River Economic Belt had been formally elevated to a national strategy. Subsequently, in July 2017, the *Yangtze River Economic Belt Ecological Protection Plan* established guidelines for optimising the energy infrastructure and managing the overall coal consumption within the Yangtze River Economic Belt. The plan specified that "by 2020, total coal consumption should be limited to below 1.2 Btce ...with Shanghai, Jiangsu, and Zhejiang experiencing a decrease in overall coal consumption… Meanwhile, Hubei and Hunan should maintain their total coal consumption at or below their 2015 levels … and Chongqing and Sichuan should similarly not surpass their 2015 levels of total coal consumption."

The policy system for the overall protection and development of the basin has been gradually improved

The progression of the Yangtze River Economic Belt is a vital strategic matter that impacts China's comprehensive development. General Secretary Xi Jinping has actively engaged in inspections related to the belt's growth and presided over symposiums in Chongqing (upstream) in 2016, Wuhan (midstream) in 2018, and Nanjing (downstream) in 2020. In these gatherings, he presented significant propositions for "transforming the belt into a golden economic region distinguished by improved ecology, integrated transportation systems, a more balanced economy, a consolidated market, and well-established mechanisms, and exploring a new path for ecological priority and green development." Moreover, he stressed that "we must leave a clean and beautiful Yangtze River to future generations." He further clarified the direction and laid down rules for the green and low-carbon development of the Yangtze River Economic Belt of "together with great protection, but not with great exploiting."

The policy structure supporting green development in the Yangtze River Economic Belt has been increasingly improving. During the *14th Five-Year Plan* period, the Office of the Leading Group of the Yangtze River Economic Belt organized and compiled the *14th Five-Year Plan for the Development of the Yangtze River Economic Belt*. It includes special plans and implementation plans for key areas and key industries, forming a "1+N" planning policy system, such as the comprehensive transportation system planning and environmental pollution control "4+1" project, wetland protection, plastic pollution control, protection, and restoration of important tributary systems, etc. Embedded within this structure, the *14th Five-Year Plan for the Development of the Yangtze River Economic Belt* explicitly highlights the necessity to nurture environmentally friendly, low-carbon economic growth in the Yangtze River Economic Belt. Principal goals involve adjusting and optimising the energy infrastructure, facilitating green transitions in key industries, and stringently enforcing dual-control measures concerning energy consumption intensity. Additionally, the plan accentuates the significance of resolutely restraining the uncontrolled expansion of energy-intensive projects with high emissions.

The industrial transformation has been successful and the energy consumption intensity has continued to decline

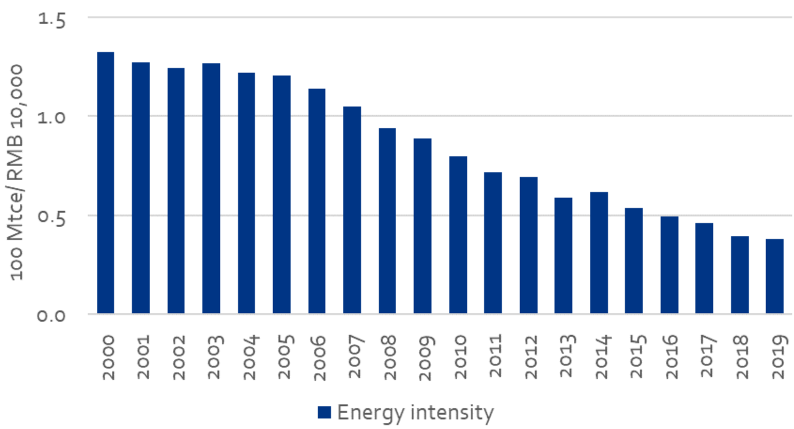
Since the implementation of the *Yangtze River Economic Belt* strategy, the provinces and cities along the river have actively promoted industrial transformation. First, is to advance the upgrading of industries such as steelmaking, petrochemicals, non-ferrous metals, building materials, and shipbuilding, to reduce overcapacity, and excess inventory. Second, is to facilitate the orderly and targeted relocation of industries, with downstream regions actively directing the movement of resource-processing, labour-intensive sectors, and domestically driven capital and technologically advanced industries to the midstream and upstream areas. The midstream and upstream regions, in accordance with their local resources and environmental carrying capacity[n], accommodate relevant industries based on specific local conditions, while simultaneously prohibiting the transfer of polluting industries and enterprises to these regions. Third, is to form several industrial clusters by relying on key cities along the belt, integrating various types of development zones and industrial parks, and guiding production factors to concentrate in more competitive areas. Finally, fourth is to actively develop service industries such as R&D design, financial insurance, energy conservation and environmental protection, education and training, culture and sports, and health care for the elderly, among others. Data shows that from 2016 to 2020, more than 8,000 industrial enterprises along the Yangtze River Economic Belt have been relocated and transformed; the scale of

[n] Based on a specific stage of development, economic and technological level, production and living style and ecological protection objectives, the maximum reasonable goal that resource and environmental elements within a certain geographical area can support human activities such as agricultural production and urban construction.

industries such as electronic information and equipment manufacturing accounts for more than 50% of the national proportion, and the provinces and cities along the belt have a prominent position in the country in terms of basic research and key technology research, leading in the digital economy, electronic information, biomedicine, aerospace, and other industries of the country.

The transformation of the industrial structure has carry to a reduction in energy consumption intensity. Under a series of measures, the industrial structure of the Yangtze River Economic Belt has been continuously optimised. The average value of the three industrial structures of the 11 provinces and cities along the belt has been adjusted from 15.7%, 46.5%, 37.8% in 2000 to 7.2%, 38.8%, 54% in 2020. The proportion of the primary and secondary industries has dropped significantly, and the proportion of the tertiary industry has increased by 16.2%. Driven by the upgrading of the industrial structure, since 2000, the economic aggregate of the 11 provinces and cities along the Yangtze River Economic Belt has increased from RMB 4.1 trillion to RMB 47.2 trillion in 2020, an increase of about 11.6 times, and the nominal growth rate is as high as 13%. At the same time, the energy consumption intensity dropped from 1.33 tce/10,000 RMB in 2000 to 0.38 tce/10,000 RMB in 2019, which fully reflects the effectiveness of the green and low-carbon transformation and development path of the Yangtze River Economic Belt.

Figure 10-1 2000-2019 Changes in energy consumption intensity of the Yangtze River Economic Belt



Leveraging the resource advantages of the Yangtze River, the construction of super hydropower stations has garnered global attention

The Yangtze River Economic Belt relies on the Yangtze River, with the most prominent resource advantage being abundant hydropower resources. Thanks to this, several super hydropower stations constructed on its course gained world-renowned achievements. Among them, the Three Gorges Dam was completed in 2009 with a total installed capacity of 22.5 GW. It is the largest hydropower station in the world and the largest engineering project ever built in China. Since its completion, China has successively built four super hydropower stations on the Yangtze River, namely Wudongde Hydropower Station (10.2 GW), Xiluodu Hydropower Station (13.9 GW), Xiangjiaba Hydropower Station (6.4 GW) and Baihetan Hydropower Station Hydropower Station (16 GW), whose installed capacity all ranks among the top in the world. They do not only provide a steady stream of clean electricity for the provinces and cities along the Yangtze River but also make positive contributions to the ecological environment on both sides of the river.

Box 10-1 Construction of super hydropower stations along the Yangtze River

Downstream the Yangtze River, there are five super hydropower stations including the Three Gorges Dam, Wudongde Dam, Baihetan Dam, Xiluodu Dam, and Xiangjiaba Dam. Among them, the Three Gorges Dam was approved for construction by the National People's Congress of China in 1992 and officially commenced construction in 1994. It began storing water and generating electricity on June 1st, 2003, and was completed in 2009. With a total installed capacity of 22.5 GW, the Three Gorges Dam is the largest hydropower station in the world and the largest engineering project ever built in China.

The Wudongde Hydropower Station holds the distinction of being the fourth largest in China and the seventh largest globally. It surpasses the construction challenges posed by the Xiangjiaba and Xiluodu Dams. The dam's structure is remarkably slender, with a base thickness of just 51 meters and a mere 0.19 meters at its thinnest point on top. The arch-like design, coupled with innovative building materials and methods, enables Wudongde to endure water pressure despite its deceptively delicate yet robust composition. The multitude of sensors embedded in the station to track real-time status fluctuations have earned it the moniker "smart dam."

Baihetan Hydropower Station claims the position of China's second-largest hydroelectric facility, following the Three Gorges Dam. It is renowned for its vast single-machine capacity, extensive scale, and the highest technical complexity among all dams built to date along the downstream section of the Jinsha River's mainstream cascade development projects. This station yields multiple advantages, with a primary emphasis on power generation and secondary benefits including flood management, sediment capture, downstream navigation enhancements, and reservoir area water transportation development. Baihetan boasts an average annual power generation of 62.4 TWh, conserving 19.7 Mtce per year and decreasing carbon dioxide emissions by 51.6 million tons annually.

Xiangjiaba and Xiluodu hydropower stations, constructed in 2014 and 2015 respectively collectively manage 85% of the Jinsha River basin. The Xiluodu station functions as an upstream regulatory reservoir for the Xiangjiaba station, while the Xiangjiaba station serves as a downstream counter-regulating reservoir. Although the Xiluodu station has a larger construction scale, the installed capacity of the Xiangjiaba station is greater. Among the four hydroelectric power plants, Xiangjiaba is the only one with irrigation capabilities and is equipped with the world's largest ship lift.

Figure 10-2 Photos of four super hydropower stations along the Yangtze River

The Three Gorges Dam

Wudongde Dam

Baihetan Dam

Xiluodu Dam

Xiangjiaba Dam

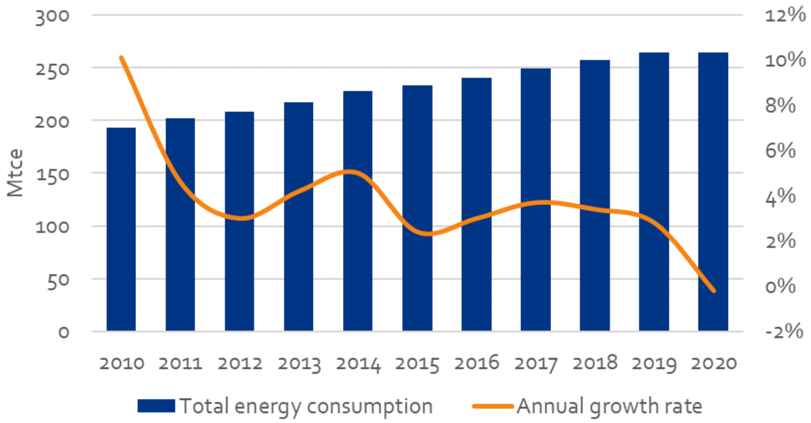
Source: Photos from the Internet

10.3 The region of Guangdong-Hong Kong-Macao Greater Bay Area

The geographical scope of the Guangdong-Hong Kong-Macao Greater Bay Area covers nine cities in Guangdong Province including Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Zhongshan, Huizhou, Jiangmen, Zhaoqing, and Hong Kong SAR and Macao SAR. With a total area of 56,500 square kilometres. In 2021, the total economic volume of the Guangdong-Hong Kong-Macao Greater Bay Area has reached RMB 12.6 trillion, creating about 11% of the country's total economic volume with less than 1% of the national territorial area; there are 24 Fortune 500 companies and 57,000 high-tech companies., being one of the world-class urban agglomerations with the largest economic volume and the most innovative vitality in the country.

In recent years, the Guangdong-Hong Kong-Macao Greater Bay Area has experienced steady growth in total energy consumption, while the energy consumption structure has increasingly shifted towards cleaner and more low-carbon sources. Historically, due to the region's scarcity of traditional energy resources and its burgeoning economy characterised by heightened energy requirements, fossil fuels have primarily been sourced both from within the province and externally. The region’s overall dependence on external electricity supply is approximately 60%. In 2019, the Central Committee of the CPC and the State Council officially issued the *Development Plan of Guangdong-Hong Kong-Macao Greater Bay Area*, marking the entry of a new stage in the construction of the country's Greater Bay Area. With the deepening of the construction of the Guangdong-Hong Kong-Macao Greater Bay Area, the energy consumption structure in the region has been continuously optimised. In 2020, the total energy consumption of the Greater Bay Area was 264 Mtce. In terms of the growth rate of energy consumption, except for the growth rate of over 10% in 2010, the overall growth rate in the Guangdong-Hong Kong-Macao Greater Bay Area has shown a downward trend. From the perspective of energy consumption structure, in 2010, the comprehensive energy consumption structure of the Greater Bay Area was dominated by fossil energy, of which coal, oil, and natural gas accounted for 39.5%, 35.1%, and 5.7% of the total energy consumption, accounting for 80.3% of the total energy consumption, while electricity and other non-fossil energy accounted for only 19.7%. In 2020, the proportion of coal and oil consumption in the Guangdong-Hong Kong-Macao Greater Bay Area both dropped to 30.6%, the proportion of natural gas consumption increased to 12.6%, and the proportion of electricity and other non-fossil energy increased to 26.3%. Energy consumption continues to be cleaner.

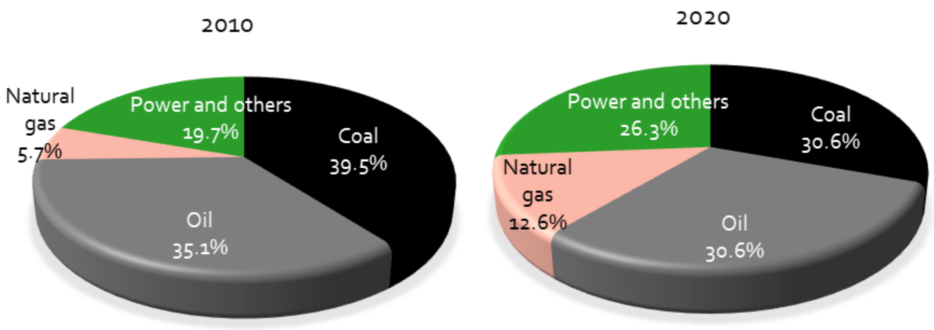
Figure 10-3 Total energy consumption and growth rate of Guangdong-Hong Kong-Macao Greater Bay Area from 2010 to 2020



The optimisation of the energy structure in the Guangdong-Hong Kong-Macao Greater Bay Area can be attributed to several factors. First, the region benefits from Guangdong Province's geographical location and resource advantages, particularly its abundant coastal wind and solar resources. Second, the nine cities of Guangdong Province, along with Hong Kong and Macao, possess a robust economic foundation and the capacity to drive energy structure upgrades through continuous industrial advancements. Third, regional cooperation has facilitated the reduction of traditional energy consumption in the Greater Bay Area, with clean electricity transmitted from Yunnan and other southwestern regions through the West-East Power Transmission Project, contributing to carbon reduction and pollution control in the area.

The *Outline Development Plan for Guangdong-Hong Kong-Macao Greater Bay Area* proposed the construction of an energy security guarantee system, the optimisation of the energy structure and layout, and the development of a clean, low-carbon, safe, and efficient energy supply system during the *14th Five-Year Plan* period. To promote coordinated energy development in the Guangdong-Hong Kong-Macao Greater Bay Area, the *Guangdong Provincial 14th Five-Year Plan for Energy Development* emphasises actively fostering energy coordination in the region, guided by the concept of "complying with the development orientation of the Greater Bay Area, meeting the needs of Hong Kong and Macau, and leveraging the strengths of Guangdong." This approach will establish an overall planning coordination pattern among Guangdong, Hong Kong, and Macao, with interconnected infrastructure and complementary advantages, ultimately leading to mutually beneficial cooperation.

Figure 10-4 2010-2020 Energy consumption structure of Guangdong-Hong Kong-Macao Greater Bay Area in 2010 and 2020



Take the lead in proposing carbon peaking at the city level

The energy consumption of the Guangdong-Hong Kong-Macao Greater Bay Area is primarily concentrated in Guangzhou and Shenzhen. In 2020, the total energy consumption of nine cities in Guangdong Province was 244 Mtce, accounting for 92.7% of the energy consumption of the whole Greater Bay Area. From the perspective of major cities, the total comprehensive energy consumption in Guangzhou and Shenzhen is 63 Mtce and 46 Mtce respectively, accounting for 24% and 17.4% of the total comprehensive energy consumption in the Guangdong-Hong Kong-Macao Greater Bay Area, adding up to 41.4%. The total comprehensive energy consumption of Dongguan, Foshan, and Huizhou is 31 Mtce, 30 Mtce, and 28 Mtce respectively, and the total comprehensive energy consumption of the remaining six cities is less than 20 Mtce.

Major cities in the Guangdong-Hong Kong-Macao Greater Bay Area took the lead in proposing carbon peaking targets that precede China's overall target. In recent years, the carbon emissions of Hong Kong and Macau have been relatively stable and have entered the peak fluctuation range of carbon emissions. Many cities in Guangdong Province put forward the development goal of carbon peaking during the *14th Five-Year Plan* period, playing a leading demonstration role in the field of carbon neutrality. Specifically, low-carbon pilot cities such as Guangzhou, Shenzhen, and Zhongshan have set targets for carbon peaking emissions in 2020, 2020-2022, and 2023-2025, respectively, ahead of China's overall target of carbon peaking emissions by 2030.

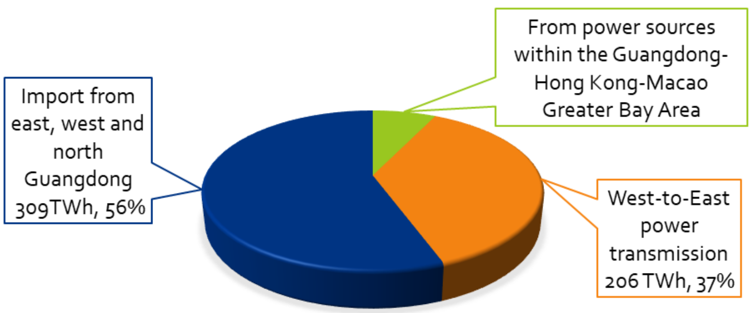
Industrial structure optimisation to guide low-carbon development of cities

Due to the relatively high proportion of tertiary industry in cities, the carbon emissions per unit of GDP in the Guangdong-Hong Kong-Macao Greater Bay Area are lower than in other regions. In 2020, the tertiary industry in Hong Kong and Macau accounted for 93.7% and 95.7% of the GDP respectively. Secondly, the tertiary industry in Guangdong and Shenzhen accounts for more than 60%, and the development of the service-oriented economy has already reached a certain scale. Based on this, the proportion of energy used by the tertiary industry in cities such as Guangzhou, Shenzhen, and Macau in 2020 was all higher than 40%, and the corresponding carbon emissions per unit of GDP in these cities were relatively low. According to the *Annual Research Report on Carbon Neutrality in Guangdong-Hong Kong-Macao Greater Bay Area*, among the cities in the Guangdong-Hong Kong-Macao Greater Bay Area, Macao has the lowest carbon emissions per unit of GDP, followed by Shenzhen, Hong Kong, and Guangzhou, the carbon emissions per unit of GDP in these three cities are comparable to those of countries such as the United Kingdom and Norway, and slightly lower than the United States. The industrial structure of cities such as Jiangmen and Huizhou is still dominated by manufacturing. In 2020, the proportion of energy used by the secondary industry in these cities exceeded 50%, so their carbon emissions per unit of GDP are 30% to 50% higher than the average level of China.

Regional collaboration to help clean energy use in the Greater Bay Area

The insufficient local power supply in the Guangdong-Hong Kong-Macao Greater Bay Area highlights the importance of "West-to-East Power Transmission" and coordinating within the province. In 2020, the Guangdong-Hong Kong-Macao Greater Bay Area recorded a total electricity consumption of 555 TWh. However, the total electricity supply from within the region accounted for only 55.7% or 309 TWh of the total consumption. According to the data provided by China Southern Power Grid, in instances where the electricity demand in the region cannot be fully met, approximately 44.3% of the total electricity consumption in the Guangdong-Hong Kong-Macao Greater Bay Area is derived from regional collaborative supply, with the WEET contributing 206 TWh or 37.1% of the total consumption. To support the demand, eastern, western, and northern Guangdong also supplied approximately 40 TWh of electricity to the Greater Bay Area in 2020, which accounted for 7.2% of the total electricity consumption.

Figure 10-5 The proportion of electricity supply in the Guangdong-Hong Kong-Macao Greater Bay Area in 2020



Clean energy sources were the dominant power supply in the Guangdong-Hong Kong-Macao Greater Bay Area, accounting for over 60% of the total. Specifically, in 2020, clean electricity made up approximately 58.7% of the regional power supply, with a total generation of around 181 TWh. The proportion of clean electricity transmitted from western China to eastern regions was about 74%, amounting to roughly 153 TWh. Even after excluding the transmission of clean energy from Guangdong Province's eastern, western, and northeastern regions to the Greater Bay Area, the proportion of clean energy in the region was still 60% in 2020.

Achievements in new energy development

In 2020, the new energy power generation in the Guangdong-Hong Kong-Macao Greater Bay Area was 16.4 TWh, an increase of 18% year-on-year, accounting for 5.4% of the total power generation, an increase of 4 percentage points over 2010. At the same time, the Greater Bay Area has made full use of its geographical advantages and resource endowments in coastal areas, and the scale of installed offshore wind power has achieved rapid growth. In 2020, the installed capacity of wind power in Guangdong Province reached 5.7 GW, an increase of more than 8 times compared with 620 MW in 2010. Among them, offshore wind power is showing rapid growth. By the end of 2020, the installed capacity of offshore wind power grid-connected in Guangdong Province reached 1.01 GW, a year-on-year increase of 257%.

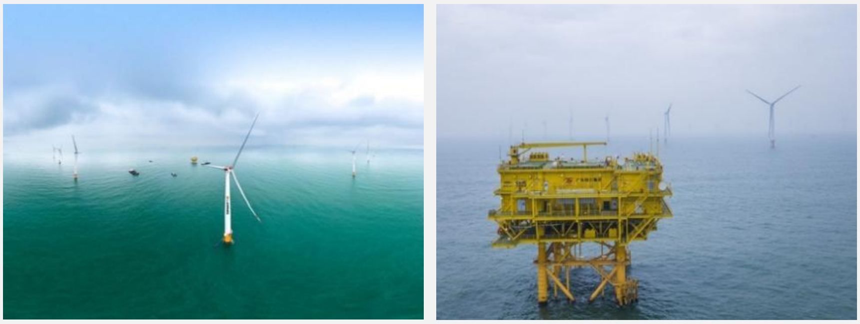
Box 10-2 Introduction to Offshore Wind Power Development in Guangdong-Hong Kong-Macao Greater Bay Area

In 2020, Guangdong Province saw the addition of four newly commissioned offshore wind farm projects: Guangdong Zhanjiang Wailuo (0.2 GW), CGN Yangjiang Nanpeng Island (0.4 GW), Guangdong Yangjiang Shaba (Three Gorges) (0.3 GW), and Zhuhai Jinwan (0.3 GW). Furthermore, an under-construction offshore wind farm is set to have an installed capacity of up to 8.1 GW, positioning Guangdong as one of the leading provinces in the country in terms of offshore wind energy capacity. As the development of offshore wind power gradually moves from offshore to the open sea, the Guangdong-Hong Kong-Macao Greater Bay Area has broken through the technical bottleneck of offshore wind power transmission in offshore deep-water areas and open sea areas. Further, it mastered the key technologies of open sea wind power transmission and has possessed the research and development and integrated supply capabilities of related wind power equipment. Moreover, this knowledge has been used to provide technical and experience reference for offshore wind power in other regions of the country.

At 11:18 on April 2, 2021, all 55 wind turbines of the Zhuhai Jinwan Offshore Wind Farm Project, a subsidiary of Guangdong Energy Group, were connected to the grid for power generation. As the second batch of key offshore wind power projects in Guangdong Province, since the first wind turbine was connected to the grid and put into operation on November 18, 2020, it took less than five months to achieve full capacity connection to the grid and operation. It is currently the largest offshore wind farm under construction in the Guangdong-Hong Kong-Macao Greater Bay Area.

Calculated based on standard coal for thermal power generation, it can save 229,600 tce and reduce carbon dioxide emissions by 456,300 tons every year.

Figure 10-6 A glimpse of the Zhuhai Jinwan offshore wind farm project



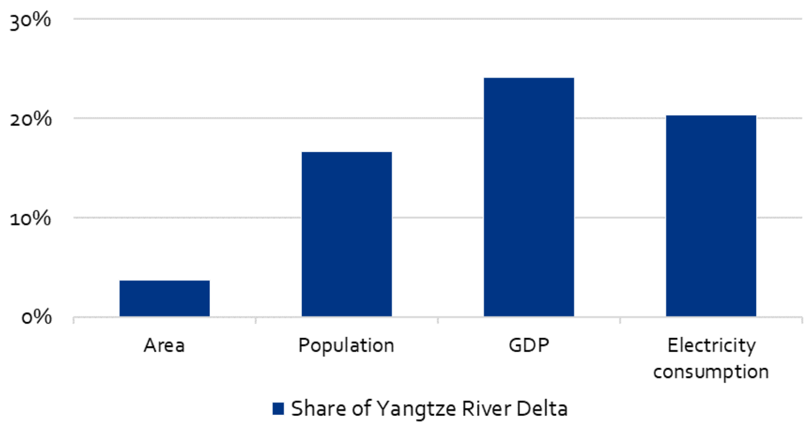
Source: Photo from the State-owned Assets Supervision and Administration Commission of the Government of Guangdong Province

10.4 The region of the Yangtze River Delta

The Yangtze River Delta region is one of the regions with the most active economic development, the highest degree of openness, and the strongest innovation capability in China. The Yangtze River Delta region includes three provinces and one city, that is Shanghai, Jiangsu Province, Zhejiang Province, and Anhui Province, with an area of 358,000 square kilometres, a total population of 235 million, a total GDP of RMB 24.5 trillion in 2020. It brings together 16.7% of the country's population and creates 24.2% of the total economic output within 3.7% of the country's land area, and overall labour productivity ranks at the forefront of the country. The *Outline of the Integrated Development Plan of Yangtze River Delta Region* issued in December 2019 proposed the strategic positioning of the Yangtze River Delta region's development before 2035, that is, to become "a strong and active growth pole of national development, a national model area for high-quality development, the first to basically realise the modernization, leading the regional integrated development demonstration area and the new highland of reform and opening up in the new era".

The Yangtze River Delta region is not only one of the regions with the most concentrated energy consumption in China but also one of the regions with the least energy resources. Energy development in the Yangtze River Delta exhibits traits such as high overall demand, a significant proportion of fossil fuel consumption, and a substantial reliance on external resources. In 2018, Jiangsu, Zhejiang, and Shanghai together consumed 650 Mtce in energy, constituting roughly 15% of the nation's total consumption. Per capita energy consumption surpasses the national mean (3.3 tce per person), with Jiangsu, Zhejiang, and Shanghai registering 3.9, 3.7, and 4.9 tce, respectively, per person. In 2020, the Yangtze River Delta's electricity consumption constituted 20.3% of China's total electricity usage; the annual per capita electricity usage was 5,551 kWh, which is 1.2 times higher than the national average. Owing to the scarcity of conventional energy resources in the region, the Yangtze River Delta depends heavily on input from other provinces, facilitated by key inter-provincial/inter-regional initiatives such as "North-to-South Coal Transportation," "West-to-East Gas Transmission," and "West-to-East Power Transmission." The percentage of imported power remains relatively high. The composition of energy consumption continues to lean towards carbon-intensive sources: over half (50%) of the total primary energy consumed is coal, and the installed capacity from coal-fired power plants remains high. The proportion of renewable energies nationwide reached an average rate of approximately 27.5% in 2019. Shanghai achieved a renewable energy consumption ratio of up to 34.5%, primarily due to its dependence on imported green power. Nevertheless, Jiangsu and Zhejiang only attained 15% and 20%, respectively, falling below the national average. Among these, the proportion of non-hydro renewable energy consumption in Shanghai, Jiangsu, and Zhejiang was 4.2%, 7.4%, and 6.7%, respectively, all under the national average of 10.2%. With the continuing expansion of the region's economic scale, there is mounting pressure on both total energy consumption and energy intensity management. The Yangtze River Delta leverages its local industrial strengths and integrated planning to speed up energy transformation, prioritizing the development of renewable energy, improvement of energy efficiency, and advancement of cleaner energy sources to satisfy its ever-increasing energy demands in a more ecologically sustainable fashion.

Figure 10-7 2020 Major energy and economic indicators in the Yangtze River Delta region as a share of the national total

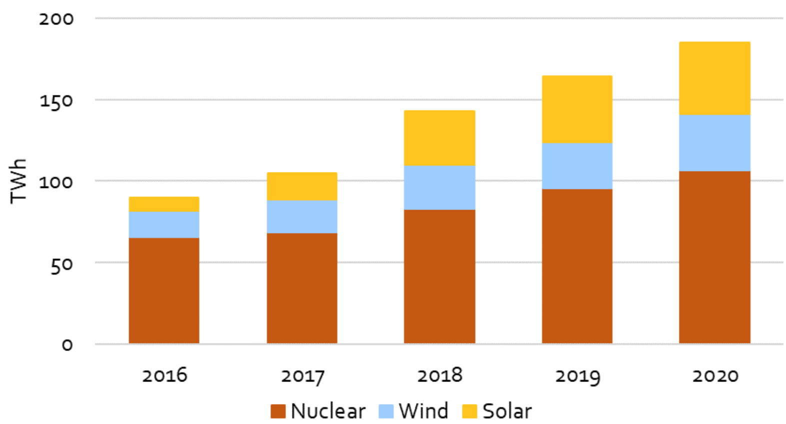


Source: National Bureau of Statistics, Energy Research Institute of the National Development and Reform Commission

Clean low-carbon energy development and utilisation maintain high-speed growth

New energy power generation in the Yangtze River Delta region has maintained rapid growth in recent years. In 2020, wind, solar, and nuclear power generation in the region's three provinces and one city reached 34 TWh, 44 TWh, and 107 TWh respectively. From 2016 to 2020, the average annual growth rates of wind, solar, and nuclear power generation were as high as 21%, 51%, and 12.9%, respectively.

Figure 10-8 2016-2020 Low-carbon energy generation in the Yangtze River Delta region



Source: China Energy Statistical Yearbook; Energy Research Institute of the National Development and Reform Commission

Distributed renewable energy is advancing rapidly, exhibiting immense potential. The Yangtze River Delta region, encompassing Jiangsu, Zhejiang, and Shanghai, ranks among China's premier areas for distributed energy development, particularly in distributed photovoltaics. These regions grapple with the challenge of meeting burgeoning energy demands for economic growth, while simultaneously contending with scarce land and space resources that hinder large-scale development of centralised wind farms and photovoltaic power stations. Consequently, increasing the share of renewable energy consumption poses significant challenges. Nevertheless, the region benefits from well-established industries, dense industrial parks, ample rooftop space in factories, and a wealth of fishery breeding waters and agricultural greenhouses, all of which present excellent opportunities for distributed photovoltaic development. As of the end of 2019, Jiangsu, Zhejiang, and Shanghai had achieved a total installed capacity of 17 GW for distributed photovoltaics, representing 27% of the national total installed capacity and solidifying the region's status as a key area for distributed photovoltaics. Based on relevant research evaluation [40], the potential installed capacity for distributed photovoltaics in Jiangsu, Zhejiang and Shanghai is estimated to range between 180 GW and 200 GW, while decentralised wind power development potential falls between 32.6 GW and 82.7 GW. Their combined potential of both sources could satisfy 48% to 69% of the additional electricity demand until 2035. However, due to prevailing distribution network structures and operating modes, the grid's capacity to accommodate distributed power sources remains significantly below their development potential.

Making significant strides in the large-scale development of offshore wind power. China's five major offshore wind power bases include the Yangtze River Delta, Shandong Peninsula, southern Fujian, eastern Guangdong, and the Beibu Gulf. In 2021, the Jiaxing No.2 offshore wind power transmission project was officially put into operation in Pinghu, Zhejiang. The Jiaxing No.1 and Shengsi No.2 wind power projects connecting to the Jiaxing grid have also entered their final commissioning phases. Collectively, these projects form the largest cluster of offshore wind farms under construction in the Yangtze River Delta, boasting a total installed capacity of 1,000 MW from 188 turbines. Upon grid connection, it is anticipated that the renewable energy output reaches 2.5 TWh per year, sufficient to meet the annual electricity demand of over a million households with 5 family members each. Additionally, these projects save 798,000 tce per year and reduce carbon dioxide emissions by 1.7 million tons, marking a significant milestone in China's offshore wind industry.

Relying on pumped-hydro storage to improve the stability of new energy supply. Acting as a high-quality and flexible resource, pumped storage plays a crucial role in enhancing the stability of new energy supply. Pumped storage power stations in Zhejiang and Anhui provinces perform essential tasks such as peak regulation, valley filling, and energy storage for the East China Power Grid. Zhejiang Province currently leads the nation in pumped storage projects under construction, with five operational facilities, seven projects underway, and over 20 projects in planning, site selection, or pending construction stages. Alongside large-scale power station constructions exceeding 1.2 GW in capacity, numerous small- and medium-sized pumped storage power stations are planned or under construction throughout Zhejiang Province. These projects are primarily concentrated in mountainous areas such as Lishui City, Quzhou City, and Jinhua City, directly stimulating regional investment and supporting mountainous area development. As Zhejiang experiences large-scale development of volatile new energies like wind and solar power and increasing air conditioning loads, the latter of which account for approximately one third of the social peak load, the demand for pumped storage power stations grows, particularly during peak summer periods when electricity system peaks and valleys differ significantly. To address this demand, Zhejiang Province has accelerated its construction of pumped storage projects. In December 2021, the Tiantai Pumped Storage Power Station Project, with an investment of RMB 10.7 billion, was fully launched. Boasting a rated head of 724 meters, the world's highest-head pump-storage plant has a total installed capacity of 1,700 MW, with the largest single-unit capacity in China. In March 2022, the Wenzhou Taishun Pumped Storage Project commenced construction with an investment of RMB 7.1 billion and an installed capacity of 1,200 MW. In September, the Jiande Pumped Storage Power Station in Zhejiang initiated preparatory work, investing RMB 14 billion and achieving an installed capacity of 2,400 MW, ranking second in China and first in East China. This project also marks China's first privately funded pumped storage power station. Anhui Province has completed four pumped storage power stations with a combined installed capacity of 3,480 MW, ranking third nationwide. Two additional pumped storage power stations are under construction, with a total installed capacity of 2,480 MW. During the *14th Five-Year Plan* period, Anhui Province will approve nine pumped storage projects with an installed capacity of 10,800 MW. By 2025, 2030, and 2035, the province's cumulative installed capacity of pumped storage power stations reaches 4.7 GW, over 10 GW, and 16 GW, respectively.

Creating a sample of cross-regional integrated low-carbon development. The Yangtze River Delta ecological green integrated development demonstration zone, located at the intersection of Shanghai, Jiangsu, and Zhejiang, released the *Implementation Plan for Carbon Peaking and Carbon Neutrality in the Yangtze River Delta Ecological Green Integrated Development Demonstration Zone* and the *Special Plan for Near-Zero Carbon Emissions in Water Town Guesthouse* in October 2022, which aims to reduce the demonstration zone's energy consumption intensity by approximately 15% compared to 2020 and lower carbon emission intensity by over 20% compared to 2020 by 2025. By 2030, the zone will achieve high-quality peak emissions reduction, hence laying a solid foundation for realising carbon neutrality goals. The document advocates for actively promoting advanced green low-carbon technologies through pilot projects and vigorously supporting distributed photovoltaics, ground (water) source heat pumps, hydrogen energy, biomass energy, near-zero carbon buildings, and other technological facilities. These initiatives should be designed in conjunction with key projects in their vicinity, enabling simultaneous construction and operation. The construction of the "Three Parklands" (i.e., Jiangnan low-lying paddy field, mulberry fish pond, and water town wetland) emphasises near-zero carbon buildings and low-carbon three-dimensional agriculture methods. By implementing wetting expansion and greening enhancement measures, the parklands will continuously improve their capacity to absorb atmospheric carbon dioxide, thus establishing an exemplary area for low-carbon development in the Yangtze River Delta.

Advancing the interconnection of new power infrastructure

Relying on the integrated development layout, the Yangtze River Delta region is promoting interconnectivity among regional energy infrastructure, including ultra-high voltage, distribution networks, and hydrogen energy networks. Power integration facilitates coordinated allocation of power resources among the one municipality and three provinces in the Yangtze River Delta region, boosts collaborative development of regional energy sources, establishes a safe, stable, and efficient regional power supply system, and jointly advances clean urban energy. In terms of the regional power market, a 2019 research report of the Shanghai Yangtze River Delta Energy Research Institute indicates that the annual electricity consumption in the Yangtze River Delta region was nearly 1,720 TWh, accounting for approximately 24% of China's total electricity consumption. Market-based transactions within and between provinces in East China reached 594 TWh and 31 TWh, respectively, with year-on-year growth rates of 39% and

42%. The integration of electric power markets in the Yangtze River Delta region and East China continues to progress, optimising the allocation of electric power resources and operational resources. In terms of regional backbone grids, the Yangtze River Delta leads the nation in the development of an ultra-high voltage backbone grid structure. In terms of the regional distribution grid, the 10 kV power tie-line project extending from Jiashan to Qingpu was completed and commenced operations in September 2020. Concurrently, the 10 kV interconnection project from Qingpu to Wujiang was officially completed and connected, achieving distribution grid interconnectivity between Shanghai, Zhejiang, and Jiangsu, and marking a new phase of cross-regional power integration in the Yangtze River Delta region. Regarding hydrogen energy and low-carbon transportation, four energy enterprises from the three provinces and one city within the Yangtze River Delta region signed the *Framework Agreement on the Integration of Energy Infrastructure in the Yangtze River Delta* in June 2020. This agreement proposes the establishment of a cooperative mechanism among energy enterprises in the Yangtze River Delta, fostering interconnectivity and interoperability of energy infrastructure across regions, and the creation of a hydrogen logistics demonstration line within the region. Shanghai is progressively promoting full adoption of new energy vehicles in the public sector, advancing the construction of charging stations, battery swapping stations, and hydrogen refuelling stations. The city also champions low-carbon green travel and is expediting the development of a green transportation system compatible with the mega-city.

Building digitalised, intelligent, and low-carbon infrastructure. In recent years, the Yangtze River Delta region has witnessed the emergence of many new energy technologies, models, and business formats, such as "Internet +" smart energy, energy storage, blockchain, and comprehensive energy services. Leveraging its advantages in integrated development, the Yangtze River Delta region has put in place an integrated and optimised energy system with regional linkage and intelligent control to promote innovation and development in the region. Unlike traditional power infrastructure, new power infrastructures like 5G base stations and big data centres are planned and constructed synchronously with information infrastructure through the combination of information technology (IT) to facilitate the open sharing of relevant infrastructure resources. This approach helps create a clean, low-carbon, safe, and efficient modern energy system.

The new energy industry as a "green engine" for economic development

Leveraging its industrial strengths, the Yangtze River Delta region has experienced significant growth in the new energy sector in recent years. The three provinces and one city in the region have collaboratively established an integrated new energy industry ecosystem that integrates technology and industry based on their unique resource endowments and industrial foundations to address the vast market demand for energy transformation. According to data from Xinhua Daily [41], large-scale electric power equipment in the Yangtze River Delta constitutes approximately one-third of the nation's total output, solar cell production accounts for half, and offshore wind turbine production represents 60%. Jiangsu Province boasts a comprehensive photovoltaic industry chain and wind power equipment manufacturing capabilities. Its distributed photovoltaic installed capacity ranks second in China, and it has developed an internationally competitive photovoltaic full-industry chain, with over 40% of the country's silicon wafer, crystalline silicon cell and component production. The province's products are evolving towards differentiation and branding, earning a reputation as "the world relies on China for solar PV products while China relies on Jiangsu for them." Shanghai takes the lead in new energy technology research and development, as well as international marketing, while Zhejiang Province exhibits distinct strengths in both photovoltaic and nuclear power component industries. Anhui Province, on the other hand, excels in the application of new energy electrical products and biomass power generation.

During the *14th Five-Year Plan* period, the Yangtze River Delta region will persist in its robust development of strategic emerging industries, including new energy. Zhejiang Province aims to optimise and reinforce strategic emerging industries and future industries, fostering numerous strategic emerging industry clusters such as for next-generation information technology, biotechnology, new materials, high-end equipment, new energy, intelligent automobiles, green environmental protection, and aviation and aerospace equipment, as well as marine equipment. Jiangsu Province plans to actively increase investment in major scientific and technological infrastructure projects, strategic emerging industries, and exceptional industrial chains. This includes deploying new infrastructure such as 5G communication networks, big data centres, the Internet of Things (IoT), ultra-high voltage power transmission systems, smart grids, and artificial intelligence. Additionally, the province will accelerate the construction of major energy projects like natural gas storage facilities, coal transfer, storage, and transportation stations, supporting power sources, and electricity transmission. Anhui Province strongly supports various regional initiatives, such as Hefei's new display technology industry, integrated circuit industry, new energy vehicles, and intelligent connected vehicles (ICVs); Huainan's big data centre and new energy battery; Chuzhou's smart home appliances and silicon-based materials; Liuan’s high-end equipment, iron-based materials, Maanshan’s green smart manufacturing, Wuhu’s ICVs, high-end equipment manufacturing, Xuancheng’s auto parts, Tongling’s advanced materials, Chizhou’s semiconductor materials, high-performance magnesium-based light alloy, Anqing’s chemical industry transformation and upgrading, and new energy vehicles, and Huangshan’s semiconductor materials, green air-rail logistics and other major project construction. The province will also implement future industry cultivation projects by developing quantum technology, bio-manufacturing, and advanced nuclear power industries. This will promote the deep integration of the Internet of Things (IoT), big data, AI, cloud computing, and blockchain with various industries to encourage the healthy development of the platform and sharing economy. Shanghai City will vigorously promote the intelligent and green upgrading of key industries such as steel and petrochemicals, accelerate the transformation and development of key areas like Taopu, Nanda, Wusong, Gaoqiao, Wujing, and Jinshan Binhai, and actively explore intensive, connotative, green, high-quality land-use models. The city will prioritise the development of energy-saving and environmental protection industries, continuously advance the optimisation of the energy structure, promote green transformation in key industries and fields, accelerate the cultivation of new growth points that align with green development requirements, and extend the green economic industrial chain.

10.5 The region of Beijing-Tianjin-Hebei

Development situation of the Beijing-Tianjin-Hebei region

The Beijing-Tianjin-Hebei region encompasses three interconnected areas: Beijing, Tianjin, and Hebei Province. These areas are closely linked in terms of geography, economy, and ecology, forming an ecological community with a shared destiny. The region represents one of China's three most dynamic economic growth poles, with an overarching vision to establish "a world-class city cluster centred on the capital city; a leading area for regional coordinated development reform; a new engine for national innovation-driven economic growth; and a demonstration area for ecological restoration and environmental improvement."

A decade ago, the Beijing, Tianjin, and Hebei region grappled with a severe "haze crisis," highlighting the growing tensions between economic development and the balance of resources and the environment. The region's urban energy primarily depended on coal, and as total coal consumption increased, environmental pollution intensified. Beijing implemented various measures to address the haze, particularly by supporting new energy vehicle enterprises, expediting advancements in vehicle exhaust treatment technology, and enhancing fuel quality. Tianjin actively promoted "electricity replacing coal" and "electricity replacing oil" initiatives to support haze mitigation efforts. In 2015, Hebei Province focused on energy conservation and emission reduction, strictly enforcing new environmental protection laws, introducing a three-year plan for in-depth air pollution treatment, and utilising a "sword" approach to combat pollution. This involved promoting pollution control in key industries, such as iron and steel, electricity, cement, and petrochemicals, while actively advocating clean production and comprehensive resource utilisation. The Beijing-Tianjin-Hebei region pioneered the establishment of ecological and environmental monitoring systems and databases, along with joint environmental law enforcement. Strict measures were implemented to manage high-energy-consuming and high-polluting enterprises, encouraging structural transformation, accelerating research and development of energy-saving and emission-reduction technologies, and promoting their application. The region actively fostered low-carbon industries, represented by green energy, such as photovoltaic power generation, wind energy, solar energy, and power automation, and implemented a strategy for cluster development.

Action plan for the coordinated development of energy in the Beijing-Tianjin-Hebei region [42]

As energy consumption in the Beijing-Tianjin-Hebei region enters a period of rapid growth, it is essential to address shared needs, including optimising the energy structure, enhancing air quality, bolstering facility construction, and ensuring energy supply security. To achieve this, the *Beijing-Tianjin-Hebei Coordinated Development Plan for Energy (2016-2025)* has been formulated and implemented in alignment with the broader *Outline for Beijing-Tianjin-Hebei Coordinated Development Plan*.

The three localities (i.e., Beijing, Tianjin, and Hebei Province) in the region, guided by the integration of energy facilities, aim to establish a unified new-type energy system. Adhering to the principle of "moderate advancement," the planning and layout of fundamental energy infrastructure will be executed, regional energy supply coordinated, and a diversified energy security framework established. The three localities will also expedite power integration construction by developing ultra-high voltage transmission channels, enhancing 500 kV backbone networks, reinforcing supporting power source construction, optimising regional power source layout, and coordinating new-energy vehicle charging facilities. Meanwhile, the Beijing-Tianjin-Hebei region will accelerate the integration of oil and gas facilities by collaborating on the development and utilisation of oil and gas resources, strengthening crude oil storage and transportation capacity, promoting natural gas pipeline transportation, and expediting the construction of LNG pipeline transportation capacity. The level of clean heating in the region has been elevated, as exemplified by Hebei Zhuozhou Thermal Power Plant supplying heat to both Zhuozhou City in Hebei Province and Fangshan District in Beijing.

The collaboration among these three localities underscores a commitment to fostering green, low-carbon development collectively. They are dedicated to jointly implementing innovation-driven development strategies, enhancing their governance capabilities in energy management, and conducting joint research to refine unified standard systems. These efforts aim to accelerate market-oriented progress in developing renewable energy sources, such as wind and solar power, while concentrating on alleviating coal consumption pressure and promoting structural optimisation.

The three localities are committed to enhancing the synergy of green energy development. They aim to promote the development of renewable energy, efforts include establishing a renewable energy demonstration area in Zhangjiakou, constructing a low-carbon Olympic zone in Chongli. Plans are in place to create high-end energy application demonstration zones in the Xiongan New Area, Beijing Municipal Administrative Centre, Tianjin Binhai New Area, Winter Olympics competition area, and the new Beijing airport, among other emerging energy-consuming places. These initiatives support the development of renewable energy sources, primarily geothermal, wind, and solar power, and encourage the adoption of innovative, intelligently integrated energy utilisation models that complement multiple energy sources. The localities are also focused on promoting renewable energy consumption and prioritizing grid access for renewable and clean energy sources, such as those in the Zhangjiakou Renewable Energy Demonstration Zone.

Box 10-3 Zhangbei flexible DC grid test and demonstration project

Boasting abundant resources such as wind and solar energy, Zhangjiakou City, Hebei Province serves as a national renewable energy comprehensive demonstration area. Zhangbei County in Zhangjiakou City currently has a total installed renewable energy capacity of 8,090 MW, ranking among the top in the country. It generates more than 10 TWh of green electricity annually, making the new energy industry the driving force behind local economic development. In 2022, the county achieved a new energy industry tax revenue of RMB 490 million.[43] Zhangbei's new energy requires large-scale distribution for consumption, and the Zhangbei Flexible DC Power Grid Pilot Demonstration Project holds demonstrative significance for large-scale output of new energy.

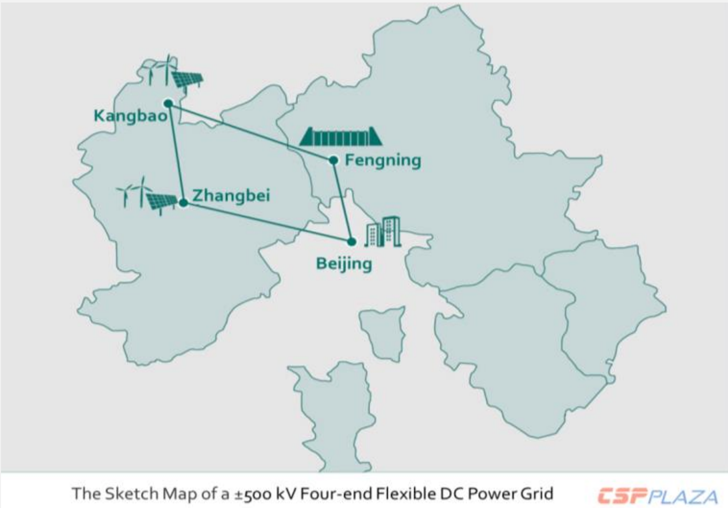
When wind, solar, and other volatile new energy sources are connected to the AC grid, their fluctuating power outputs can cause disturbances in the entire grid system. As grid scale increases, the impact on the safe and stable operation of the grid becomes more prominent. Conventional DC transmission requires strong support from the sending-end AC grid, and there are still technical limitations when transmission power follows the frequent fluctuations of new energy output. Flexible DC transmission is a controllable mode that reduces intermittent disturbances to the grid through comprehensive control of new energy generation, such as wind and solar power. It offers fast response speed, good controllability, and flexible operation, making it suitable for renewable energy grid connection, distributed generation grid connection, and isolated island power supply scenarios.

The Zhangbei Flexible DC Network Pilot Demonstration Project, constructed by the State Grid, is the world's first flexible DC network project and boasts the highest voltage level and largest transmission capacity among global flexible DC projects. The project's core technology and key equipment are internationally groundbreaking. Officially launched on February 28, 2018, and put into operation in June 2020, the project can deliver 14 TWh of clean electricity to Beijing annually, equivalent to one-tenth of Beijing's yearly electricity consumption. [44] This significantly enhances Zhangjiakou's clean energy transmission capacity and effectively addresses the challenge of accommodating 10 GW level of clean energy consumption in the Zhangbei region.

The Zhangbei Flexible DC Project is a four-terminal flexible direct current network that integrates and transmits various forms of energy, including large-scale wind power, photovoltaic, energy storage, and pumped storage. The project relies on a 666 km ±500 kV DC transmission line, with four new converter stations constructed in

Zhangbei, Kangbao, Fengning, and Beijing to achieve a maximum transmission capacity of 4.5 GW and a total converter capacity of 9 GW.[45] Among them: in the Zhangjiakou area, two new energy transmission converter stations are built in Kangbao and Zhangbei, with converter capacities of 1.5 GW and 3 GW respectively; in the Chengde area, a Fengning regulating end converter station is built with a converter capacity of 1.5 GW, and six units of the Fengning Pumped Storage Power Station will be connected to the demonstration project; in Yanqing District, Beijing, a receiving end converter station with a converter capacity of 3 GW is constructed to transform random and fluctuating wind power and photovoltaic generation into stable-output clean electricity, directly supplying power to the Yanqing competition area of the Beijing Winter Olympics (see Figure 10-9).

Figure 10-9 Zhangbei Flexible DC Grid Test and Demonstration Project



Source: Photo from Solar Thermal Power Network

The market mechanism promotes the consumption of clean energy in the Beijing-Tianjin-Hebei region. On December 30, 2020, the North China Regulatory Bureau of the National Energy Administration issued the *Beijing-Tianjin-Hebei Green Electricity Market Trading Rules* and supporting implementation details for priority dispatch. Firstly, it innovates new energy consumption mechanisms through market-oriented means. On one hand, based on policies that ensure the purchase of new energy consumption, these rules optimise resource allocation through markets; on the other hand, they stimulate active participation by new energy power plants in markets and facilitate contracting between users or electricity sales companies and new energy power plants. Secondly, the rules aim to achieve regional optimisation of green electricity resources. They fully coordinate production and consumption imbalances in new energy electricity among provincial-level grids in the Beijing-Tianjin-Hebei region, utilising market-oriented means to ensure efficient clean-energy consumption and reasonable pricing for new-energy generation, thus aiding the clean low-carbon transformation of the region's energy structure. Thirdly, the rules aim to fully meet the expectations of market entities by allowing transaction types such as bilateral negotiation and centralised pricing. New-energy power plants have pricing rights, which permit them to expand their revenue by developing reasonable trading strategies. Wholesale users can directly trade with these power plants to buy renewable electricity, while electricity sales companies can integrate agent-users with them to meet the urgent demands of electric-power consumers for renewable-electricity use. In the end, fourthly, the rules aim to promote a change in awareness among market entities. They implement development concepts such as safety, greenness, efficiency, and commercialization, which are oriented to make changes in inherent perceptions held by market entities towards forms like bilateral negotiation or competitive bidding when dealing with renewable energies.

Achievements and future challenges

Beijing-Tianjin-Hebei region has accelerated the promotion of clean energy substitution, transitioning its energy structure from coal-based to diversified and cleaner sources. In 2020, coal consumption in Beijing accounted for only 1.5% of total energy consumption, with plain areas essentially achieving "coal-free" status; in Tianjin, aside from smokeless coal used in mountainous areas, scattered coal for heating was largely eliminated in other areas; and similarly, in the rural plain areas of Hebei Province. As of the end of 2020, the total installed capacity of new energy reached 71.3 GW, of which 29.7 GW was wind power and 41.7 GW was solar PV. The utilisation rate remains at 95% above.

The Beijing-Tianjin-Hebei region has achieved its target on non-fossil fuel share under its commitment to carbon neutrality but faces challenges such as a shrinking space for continued reduction in coal use; prominent seasonal supply-demand contradictions regarding natural gas; insufficient development and utilisation of non-fossil fuel resources; increasing rigid demand for energy use, etc. Over the next decade, continuous high-speed growth in both newly installed capacities and generated electricity from renewable energies, especially those located in northern Hebei, will demand higher requirements on grid planning, construction, and regulation capability improvement within this region. To achieve goals related to improving the non-fossil fuel share ratio while ensuring the safe supply of clean energy such as natural gas and increasing the proportion of purchased green electricity, it is necessary to break through administrative restrictions and seek better solutions through regional energy cooperation in a broader perspective. In particular, the Beijing-Tianjin-Hebei region needs to intensify efforts in coordinating and addressing issues related to clean, low-carbon energy supply and security on the supply side. Based on the goal of building a new type of regional clean, low-carbon, safe, and efficient energy system, these three localities urgently need to actively promote and deeply participate in Beijing-Tianjin-Hebei's energy cooperation. They should also expand their space for coordinated development in terms of technology, infrastructure, institutional mechanisms related to clean energies, including non-fossil fuel resources' development, storage, transmission, consumption, as well as multidimensional safety guaranteeing measures with smart, flexible regulation capabilities. This will facilitate the construction of a new type of regional energy system that will help achieve carbon neutrality goals within this region.

10.6 The region of the Yellow River basin

The Yellow River Basin spans across four major landform units in China, including the Qinghai-Tibet Plateau, Inner Mongolia Plateau, Loess Plateau, and North China Plain. It also has the natural ecological corridor of the Yellow River and multiple important ecological functional areas. Additionally, it is an important traditional energy and renewable energy base in China. The *Outline of Ecological Protection and High-quality Development Plan for the Yellow River Basin* requires prioritizing ecology and green development, adjusting regional industrial layout, developing emerging industries, promoting clean production, and firmly taking the path of green and sustainable high-quality development. In recent years, the level of energy supply security and green development in the Yellow River Basin has continued to improve. Provinces such as Shanxi, Inner Mongolia, and Shaanxi have played a key role in stabilizing coal prices and focusing on large-scale wind power, photovoltaic projects' construction in desert areas, such as the Gobi Desert regions. The installed capacity of wind power and photovoltaics reached 140 GW (46.7% of the national total) and 120 GW (43.3% of the national total), respectively. The first million-ton-level carbon dioxide capture, utilisation, and storage (CCUS) project was completed at Shengli Oilfield in Shandong Province[46].

Coal mining subsidence area governance + photovoltaic development [47] [48]

The Yellow River Basin is a traditional resource-rich area and the region with the most significant task of China's energy transformation. The total area of the Yellow River Basin is 800,000 square kilometres, including over 357,000 square kilometres of coal-bearing areas. Both the economically recoverable coal reserves and coal production are currently ranked first in the country. Nine out of fourteen large-scale coal production bases planned by the state are distributed along this river. In Shanxi, Shaanxi, Inner Mongolia, Ningxia, and Gansu provinces along the Yellow River, two-thirds of China's remaining coal resources have been discovered. Currently, traditional energy bases are shifting towards comprehensive energy bases, where fossil fuels will gradually be replaced by a more balanced focus on both fossil and non-fossil fuels.

The integration of land reclamation in subsidence areas caused by coal mining activities and PV power generation provides a crucial pathway for transforming traditional energy regions. Given that after residents move away from subsidence areas due to mining activities, there may be idle land and fragile ecological vegetation conditions left behind; various PV power station development models, such as agri-PV complementary systems or forest-PV complementary systems, can drive ecological governance in mining areas while alleviating conflicts between PV power stations and their land use through comprehensive utilisation of abandoned mines. The main projects involved in treating subsidence areas include slope greening engineering and land consolidation engineering.

During construction processes for PV power stations, local terrain levelling is equivalent to carrying out environmental treatment on mined lands; the installation of PV components indirectly contributes to vegetation greening, which not only reduces evaporation within site boundaries but also increases soil moisture content through regular cleaning cycles for these components. For perennial water accumulation zones formed by surface sinking, it may be considered using floating-type solar PV plants instead. During construction processes for PV power stations, existing vegetation should be preserved as much as possible; after project completion, suitable shrub forests or shrub economic forests that are suitable for local growth can be planted between solar arrays to achieve synchronous development of ecological and economic benefits.

In 2015, Shanxi began exploring the use of PV to mitigate subsidence caused by coal mining. In 2016, the national plan aimed to build PV leader bases with a capacity of 5.5 GW, including 4.5 GW dedicated to coal mining subsidence management. The first batch of the PV leader bases were implemented in the coal mining subsidence area spanning 1687.8 square kilometres in Nanjiao District, Xinrong District, and Zuoyun County of Datong City. In recent years, leveraging its abundant solar energy resources, Datong has constructed PV power stations in the coal mining subsidence areas while carrying out ecological management, such as planting in the PV fields and backfilling areas. At present, a 150 MW PV facility for coal mining subsidence management has been completed. The Datong Municipal Government has introduced supporting measures, such as the *Management Measures for National Advanced Technology PV Demonstration Base Projects in Datong Coal Mining Subsidence Areas* and *the Ecological Protection Management Measures for National Advanced Technology PV Demonstration Bases in Datong Coal Mining Subsidence Areas*, providing excellent examples for the coordinated development of green low-carbon transformation, ecological protection compensation, and the revitalization of beautiful rural areas.

As ecological civilization construction and energy revolution progress, the *Revitalization Development Plan for Special Type Regions during the 14th Five-Year Plan* proposes to "deeply promote comprehensive management of coal-mining subsided areas, coordinate the promotion of comprehensive land improvement and utilisation, activate land resources, and adaptively promote the use of damaged land from subsidence areas for solar and wind power generation." The *Implementation Plan for High-Quality Development Demonstrative Zones Supporting Industrial Transformation and Upgrading of Old Industrial Cities and Resource-Based Cities during the 14th Five-Year Plan Period* emphasises the innovation of the "PV +" model, encourages a diversified layout of PV power generation, and supports cities such as Baotou, Ordos, Shizuishan, as well as regions like Ningdong Energy Chemical Base, in harnessing deserts, Gobi deserts, wastelands, coal mining subsidence areas, open-pit mine waste dumps, and closed mines for wind and solar power generation based on local conditions.

PV and wind power bases in desert, Gobi and arid areas

Constructing large-scale wind power and PV bases in desert, gobi, and arid areas is conducive to fully utilising the advantages of abundant wind energy and solar resources in these regions with good construction conditions. One of the latest achievements in recent years is PV sand control, which not only blocks wind but also absorbs light, reduces land temperature, reduces soil water evaporation, and increases soil water accumulation to achieve dual benefits of efficient utilisation of solar energy resources in desert areas and greening deserts. The first batch of large-scale wind and solar power base projects with approximately 100 GW in capacity, focusing on desert, gobi, and arid areas, are mainly distributed in six provinces (regions) including Inner Mongolia, Qinghai, Gansu, Ningxia, Shaanxi, and Xinjiang Production and Construction Corps. All these projects have commenced construction. Subsequent projects will focus on Kubuqi, Ulanbuh, Tenggeri, Badain Jaran Desert, and other desert and gobi areas, as well as coal mining subsidence areas, to eventually finalize the implementation of planning layout schemes for a total scale of approximately 455 GW of large-scale wind and solar power base projects. In light of the overall layout of large-scale wind and solar power bases focusing on desert and arid areas and following the principle of "exploiting all possible and necessary resources," efforts will be made to ensure the successful construction of the subsequent second batch of large-scale wind and solar power base projects.

The initiation of Inner Mongolia's Kubuqi Desert PV Project signifies a groundbreaking phase in China's integrated ecological management, using a holistic approach that combines together PV power generation and sand control.[49] Prior to the project's inception, the ecological environment was exceedingly delicate, rendering it one of Inner Mongolia's most severely desertified and erosion-prone areas. Furthermore, it serves as a primary source of wind-blown sand in the Beijing-Tianjin-Hebei region and a crucial flow sand contributor to the Yellow River's multiple bends. Nonetheless, the region boasts over 3,180 hours of consistent annual sunshine and plentiful solar thermal resources. The Kubuqi 2 GW PV+sand control base stands as the largest of its kind in China and one of the first extensive wind and solar power base projects to commence construction nationwide. Through technological innovation and cross-party collaboration, the project can attain triple land utilisation: electricity generation atop solar panels, crop cultivation beneath the panels, and animal husbandry between them. Upon completion, it will be capable of restoring and managing 100 thousand mu (approximately 6,667 hectares) of desert land annually, supplying green electricity with an average yearly output of four TWh, conserving 1.3 Mtce per annum, and reducing carbon dioxide emissions by 3.4 million tons each year. It will effectively establish vital ecological security barriers in northern China and the Yellow River Basin.

Hydro-wind-solar multi-energy complementary bases in Qinghai

The upper reaches of the Yellow River represent a vital hydropower and solar energy base in China. With a theoretical reserve of hydroelectric resources totalling 21.9 GW, it ranks fifth in the nation. This area is also one of China's thirteen major hydropower bases, exhibiting exceptional hydroelectric regulation performance. Furthermore, the theoretical development potential of PV resources amounts to 3,500 GW, securing the second place in the country, with the lowest PV power generation costs nationwide. Wind energy technology surpasses 75 GW, ranking among the top in China. It holds immense development potential for low wind-speed wind power. The vast desert land, spanning over 100,000 square kilometres, offers significant advantages for new energy development.

In recent years, Qinghai Province has prioritised promoting clean energy development, constructing a modern power system, and fostering diversified storage capacities to establish national-level PV power generation and wind power bases. During his 2016 visit to Qinghai Province, President Xi Jinping suggested that "Qinghai should become an important new energy industry base," and in his 2021 visit, he further emphasised the need "to build a national highland for clean energy industries." By the end of 2021, Qinghai Province's installed electricity capacity reached 42.9 GW, with clean energy constituting 90.8% of the total installed capacity and new-energy sources representing 61.4%. Both indicators rank first in the nation. In the first half of 2022, clean energy represented 84.8% of Qinghai's total electricity output, while new-energy-generated electricity from wind and solar power accounted for 42.3%, surpassing hydro-power generated electricity by 96 days[50].

The *Action Plan for Building Qinghai into a National Clean Energy Industry High Ground* advocates for the harmonious development of clean energy and ecological environments, and the steady advancement of the upstream Yellow River clean energy base. It aims to deeply explore the hydropower development potential in the upper reaches of the Yellow River, expedite the expansion and transformation of existing hydropower stations in the area, and construct large-scale energy storage projects for cascade power stations. This will enable long-term energy storage regulation within power systems. Additionally, the plan seeks to establish national-level PV and wind power bases. By 2030, the grid-connected wind and PV power installations to reach approximately 100 GW. It also aims to demonstrate and promote the friendly integration of solar thermal and PV power plants, with Qinghai's installed capacity for solar thermal power plants exceeds 3 GW by 2030. The plan encourages steady progress in other clean energy developments, such as geothermal energy, and outlines the construction of a gas-fired power station on a certain scale to drive integrated development between gas-fired electricity generation and new energies. By leveraging Qinghai's advantages in resource complementarity with neighbouring provinces and regions, as well as its complementary adjustment capabilities and system characteristics, the plan emphasises strengthening inter-provincial grid connections and accelerating cross-regional electric transmission channel construction. This will establish Qinghai as a Northwest regional centre for electricity regulation and storage, as well as a green electricity export base.

Clean heating in the Three River Source region (sanjiangyuan)

The Three River Source region in Qinghai Province is the world's highest and largest plateau wetland, as well as a vital water source conservation area in China. This area has a cold climate. Data from the Qinghai Provincial Climate Centre reveals that the heating period typically spans 7-8 months, extending up to 10-11 months in Qumalai County, Zhiduo County, Gande County, and Madoi County. Historically, locals have relied on burning coal and cow dung for heating, resulting in low energy efficiency, poor heating quality, and pollution emissions.

The *Action Plan for Qinghai to Build a National Clean Energy Industry High Ground* calls for the full implementation of the "Clean Sanjiangyuan" project and the establishment of demonstration counties for clean heating. Adhering to the principles of supply-demand balance and electricity-based transformation, pilot reforms will be gradually expanded in scope. A clean heating system, primarily utilising renewable energy sources, geothermal energy, or electric power, will be developed, with efforts directed toward phasing out coal-fired heating systems. Clean centralised heating systems will be prioritised in urban areas, while centralised or distributed clean heating systems are actively promoted in rural areas. This will enable the gradual elimination of scattered coal-burning stoves and cow dung heaters, leading to province-wide cleanliness during the winter heating season.

Launched in May 2020, the Sanjiangyuan Smart Energy Clean Heating Construction and Renovation Project follows the principles of pilot testing, step-by-step implementation, and classification.[51] Traditional coal-fired stoves are being progressively replaced with efficient and clean electric stoves. Drawing from the experience of clean energy pilots, Qinghai has developed a feasible plan for clean heating renovation, prioritizing public places such as schools and health services, followed by towns and rural pastoral areas. Simultaneously, Qinghai's abundant clean electricity resources and rapid growth in new energy power generation, primarily from photovoltaics, support the promotion of "electricity substituting coal" while providing a means to consume clean energy.

Shandong Province leads the nation in PV installations

Located downstream of the Yellow River, Shandong is one of the "five poles" driving development in the Yellow River Basin. Its major economic indicators, such as regional GDP, industrial output value, and import/export volume, all rank first among provinces along the Yellow River, making it a vital industrial base and strategic support for economic development in northern China. Shandong boasts both land-based and marine resources, with interconnected rivers, lakes, and seas creating the most complete warm-temperate wetland ecosystems in China. These ecosystems play a crucial role in maintaining ecological security downstream along the Yellow River basin and the Bohai Sea.

The *Ecological Protection and High-Quality Development Plan of the Yellow River Basin in Shandong Province* emphasises vigorously developing clean energy, promoting optimisation and adjustment of the energy structure, and comprehensively building a modern energy system that is clean, low-carbon, safe, and efficient. The plan includes implementing the "External Power Supply to Shandong" project, deepening strategic cooperation on energy with provinces such as Gansu and Inner Mongolia, planning and constructing a new channel for external power supply to Shandong, and completing the Longdong-Shandong UHVDC project. It also promotes projects like the expansion of China Petrochemical's Shandong LNG receiving station and the Sino-Russian Eastern Line Shandong section natural gas pipeline construction. Safe nuclear power development and steady advancement of major nuclear power projects are encouraged. The plan supports project construction in coal mining subsidence areas in southwestern Shandong Province and salt-alkali wasteland PV power generation in northern Shandong Province. It advocates scientifically arranging public hydrogen refuelling stations to create a hydrogen corridor on highways. The implementation of new energy microgrids, energy IoTs (Internet of Things), and "Internet + Smart Energy" will promote green energy transformation. By 2025, the plan aims to absorb approximately 150 TWh of electricity from outside the province annually, achieve an LNG unloading capacity of around 25 million tons per year, add about 4,000 kilometres of long-distance oil and gas pipelines under operation or construction, reach an installed capacity for nuclear power plants under operation or construction at around 13 GW, and achieve an installed capacity for renewable energy generation at over 80 GW.

The *State Council's Opinions on Supporting Shandong Province to Deepen the Conversion of New and Old Kinetic Energy, Promote Green, Low-Carbon, and High-Quality Development (Guo Fa [2022] No. 18)* emphasises the need to establish a green, low-carbon production and lifestyle. The transformation and upgrading of traditional kinetic energy should occur alongside the cultivation of new kinetic energy. By leading in promoting ecological protection and high-quality development in the Yellow River Basin, significant optimisation of energy and industrial structures is envisioned by 2027, with non-fossil fuels becoming the primary source for incremental energy consumption. Among major initiatives, efforts will focus on promoting large-scale and high-proportion development of non-fossil fuels, vigorously developing renewable energy sources, and utilising land such as salt-alkali wasteland in northern Shandong Province or coal-mining subsidence areas in the southwestern part of the province to build large-scale wind and solar power bases. Exploring distributed PV integrated development models and creating deep-sea offshore wind power bases with 1 GW capacity will also be prioritised. The promotion of advanced, independently developed nuclear reactor types for scaled-up deployment will be encouraged, along with the expansion of comprehensive utilisation such as heating supply and seawater desalination. The plan supports "Shandong green electricity import," with Shandong Province and sending provinces cooperating in the construction of large-scale wind and solar power bases. The acceleration of ultra-high-voltage transmission channel construction from Longdong to Shandong Province will be prioritised, ensuring that renewable energy accounts for no less than 50% of newly built ultra-high-voltage transmission channels, in principle. The development of a smart energy system featuring coordinated interaction between generation, network, load, and storage will be pursued, along with the promotion of pumped-storage power station construction and the improvement of new-type energy storage application levels.

As a leading pilot zone for the conversion of new and old kinetic energy in China, Shandong Province has become one of the major provinces for household PV installation, thanks to supportive policies. Boasting long sunshine hours, abundant rooftop resources, high per capita GDP levels, and well-established sales channels, Shandong's household PV installation has maintained a leading position in China for many years, aided by the active implementation of the "PV promotion at the county level" policy.[52] In 2021, Shandong Province added a grid-connected capacity of 10.7 GW, making it the only province to exceed 10 GW and accounting for 19.5% of the national total. Its cumulative installed capacity reached 33.4 GW, ranking first among all provinces in terms of both newly added and cumulative installed capacity, according to data from the National Energy Administration (NEA). Shandong Province's newly added scale under the management index for household PV projects was 21.6 GW, ranking first across China, based on NEA data released this year. In the first half of 2022, Shandong Province added a grid-connected capacity of 3.7 GW, with distributed PV accounting for 3.4 GW, ranking top nationwide again. Among these additions, newly installed distributed PV on households amounted to 1.9 GW, ranking third nationally. As of the end of June 2022, the cumulative installed solar power generation capacity reached 37.1 GW, maintaining Shandong's leading position across China.

Chapter 11
Climate policy and best case practice in Denmark

11 Climate policy and best case practice in Denmark

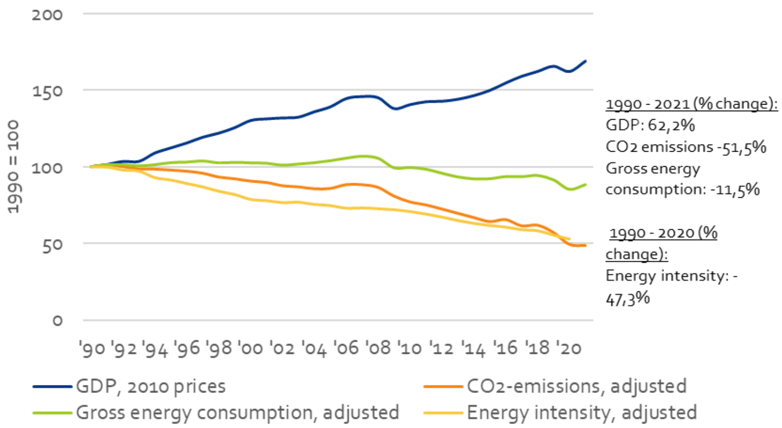
11.1 Key messages

- Denmark's green transition has been driven by considerable legislative efforts and is founded upon many years of experience in energy planning, policy implementation, and clean energy technology development. Today, more than 50% of electricity generation comes from wind and solar energy, while ensuring a security of power supply of 99.996%. Going forward, the Climate Act mandates a 70% reduction in CO_2 emissions by 2030 relative to 1990 levels, and further political agreement has been reached to reach 100% green power by 2030 and carbon neutrality by 2045. Continuous analysis of the development of the energy sector is conducted to inform policy implementation and to tracking progress towards political goals, through an annual climate policy cycle, instructed by the Climate Act.
- In conjunction with high VRE penetration, high security of electricity supply in Denmark has been achieved through grid planning, monitoring, and analysis. Denmark's participation in the international electricity market, Nordpool, introduces flexible operation to the regional power system through interconnectors, which enable the cross-border trade and thus further integration of complementary renewable energy sources, like hydro, wind, and solar. As the Nordpool price zones become further interconnected, electricity supply security will become ever-increasingly a regional concern. In Denmark, the national transmission system operator closely monitors and analyses the development of electricity supply security and aims for no more than 38 outage minutes per year by 2032, by carrying out a grid planning process that considers the risks and costs associated with potential special incidents, such as extreme weather conditions.
- Denmark's path to further decarbonisation involves sector coupling through direct and indirect electrification, alongside large-scale interconnection of the power system across countries. Denmark is among the global leaders in energy efficiency in industry and buildings and has one of the highest penetration rates of district heating. Energy storage and heat pumps are vital to the future of further sector integration in Denmark, through coupling the Danish building sector with the power and heat sectors, which not only decarbonises the sector but also adds flexibility to the power system. Denmark's advocacy for P2X solutions will reduce GHG emissions in the sectors that are most challenging to decarbonise, i.e., transport and industry. Additionally, the development of CCUS technologies will provide contingency for achieving future GHG emission reductions and fulfilling climate targets.

11.2 Current status and development prospects of climate work in Denmark

Over the course of four decades, Denmark has transitioned from almost complete fossil fuel dependency to a high level of overall renewable energy usage (43.1% of observed energy consumption as of 2021). Growing economic activity has coincided with decreasing energy intensity, increasing energy efficiency and declining CO_2 emissions, shown in Figure 11-1.

Figure 11-1 Denmark's GDP, CO_2 emissions and gross energy consumption, 1990-2020. Source: Danish Energy Agency's Yearly Energy Statistics



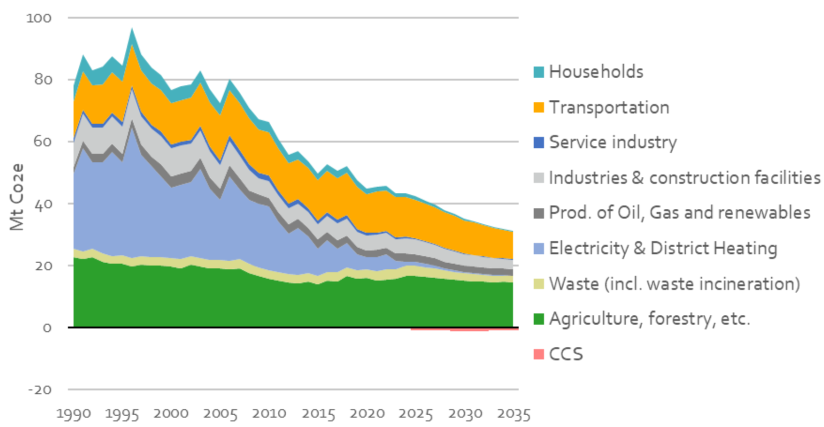
Underlying this transformation is a long history of energy and climate policy agreements, which in most cases, have been backed by a broad political base in the Danish parliament. This broad political support for energy and climate transformation has facilitated the establishment of institutional setups, policies and regulations that secure Denmark's energy and climate goals and commitments in both the mid and long term.

Status and projections on Denmark's climate effort

The Danish Energy Agency (DEA) prepares an annual *Denmark's Climate Status and Outlook* report that provides an account of historical greenhouse gas (GHG) emissions in Denmark and a projection for emission and energy trends. The latest report, *Denmark's Climate Status and Outlook 2022* (CSO22) collects emissions data from 1990 to 2020, showing that Denmark had reduced its GHG emissions by 43% with respect to 1990 by the end of 2020. The projections are made towards 2035, through a Frozen Policy scenario, i.e., considering all enacted policies, in the absence of any further policy development. In the Frozen Policy scenario, the GHG emissions fall by 47% and 57% relative to 1990 levels by 2025 and 2030, respectively. The CSO22 indicates the need for further policies, for Denmark to fulfil its climate ambitions.

When announced policies are considered in addition to existing policies, as presented by the Danish government in its *Climate Programme 2022* – which includes all relevant policies adopted so far – the reduction effort reaches 49.5% by 2025 and 63.6% by 2030. This leaves a reduction deficit of 0.5 – 4.5 percentage points relative to Denmark's goal of a 50-54% reduction by 2025 and 6.4 percentage points relative to Denmark's 70% reduction goal by 2030. Figure 11-2 presents an overview of Denmark's historical and projected emissions by sector.

Figure 11-2 1990-2035 Denmark's total emissions by sector



Note: the latest statistical year in the figure is 2020, while the remaining years are projections.
Source: Danish Energy Agency

One notable characteristic of the present status of Denmark's climate efforts is that emissions from electricity generation and district heating have fallen to 9% of total emissions in 2020, leaving agriculture and transportation as the sectors that require the most effort to decarbonise. Jointly, these two sectors accounted for 63% of all GHG emissions in 2020.

Agriculture, which is projected to emit 15.1 Mt CO_2e (and account for 45% of emissions) in 2030 without additional policies, is expected to reduce its emissions by 55-65% by 2030, in accordance with the parliamentary agreement on the matter. However, the largest share of the estimated reduction effort depends on the achievement of technological progress in areas such as brown bio-refining (biochar), as it is currently challenging to adequately limit agricultural emissions without limiting production.

Another important area of effort for the success of Danish climate goals is road transportation, accounting for approximately 26% of all emissions. From which passenger car transport accounts for the largest share, 58%. Here, the success of the reduction effort is placed primarily on electrification with an ambition of 1 million low-emission vehicles by 2030. According to recent figures from Statistics Denmark, electric vehicles (EVs), Plug-in Hybrid Electric Vehicles (PHEVs) and other low-emission vehicles are making strides, as 39.1% of new vehicles sold in the period October 2021-September 2022 were of this type. A ban on the sale of new gasoline- and diesel-fuelled vehicles is still not yet within reach, as this is currently outside the limits of EU legislation. An agreement was reached in October by the European Parliament and Council that all new cars and vans registered in Europe will be zero-emission by 2035.

Another aspect of the Danish reduction effort is the likely contribution of CCS, which is estimated to capture up to 4% of emissions by 2030 and begin activity by 2025. This technology is particularly relevant for some industrial, agricultural, and other processes such as waste-to-heat and waste-to-electricity, which may otherwise be difficult to decarbonise.

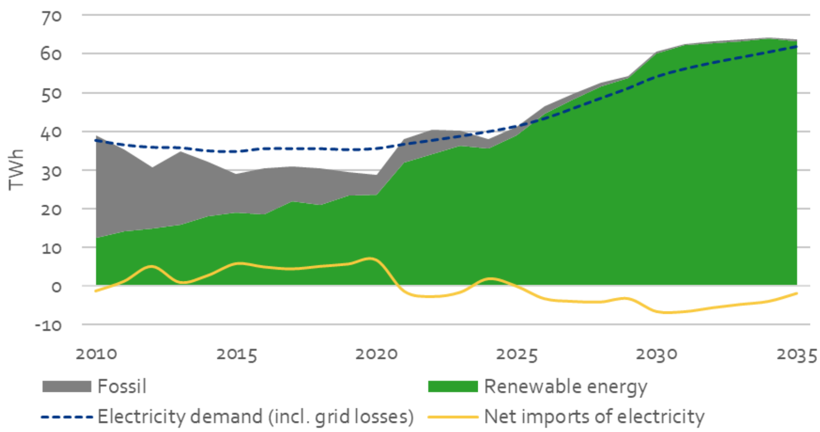
Denmark's way forward in the Green transition is electrification

One of the most important aspects of Denmark's green transition is electrification. As shown in Figure 11-2, electricity and heat generation will have been almost entirely decarbonised by 2030. Emissions from these sectors reduced by 77 % and 60% during the period from 1990 to 2021, respectively[53]. This presents a solid starting point for the direct electrification of transportation, heating, and potentially other industrial processes. Indirect electrification, through the production of synthetic fuels in Power-to-X processes such as electrolysis, is also expected to play an important role.

As Figure 11-3 shows, both variable renewable electricity generation and consumption are set to increase in a Frozen Policy scenario, which projects Denmark as a net exporter of electricity to neighbouring countries through the cross-border Interconnectors.

In addition, the demand structure is expected to change substantially as EVs, and heat pumps enter the system with a flexible consumption pattern. Classic consumption from households and businesses is expected to represent approximately one-half of the total by 2030, down from the 90% share it represented in 2019. The commissioning of new large-scale data centres is also expected to increase electricity demand, but their relatively constant consumption pattern will add less flexibility. Furthermore, the electricity system could become even more interconnected than it is at present, as offshore wind generation could facilitate the creation of international offshore wind hubs with other European countries, such as Germany, Belgium, and the Netherlands.

Figure 11-3 2010-2035 Electricity production, demand, and imports



Source: Danish Energy Agency

11.3 Danish climate policy and energy transition policy

As early as 1990, the Danish Parliament approved *Energy 2000*, which contained a CO_2 reduction target (the first in the world) towards 2005. The plan was followed by several new energy and climate agreements in the 2000s and 2010s. In 2020, the Danish Parliament passed the *Climate Act*, which entails a commitment to reducing greenhouse gas emissions (GHG) by 70 % by 2030 (relative to 1990) and to achieving climate neutrality by 2050 at the latest. These climate objectives align with the *Paris Agreement*. Denmark is also subject to several climate targets set out by the EU.

Table 11-1 shows an overview of current climate and energy targets and commitments in Denmark. It should be noted that the parties comprising the recently formed Danish government have agreed expedite its national decarbonisation targets by pledging climate neutrality in 2045 and net negative emissions in 2050, corresponding to a reduction in greenhouse gas emissions of 110% relative to 1990 levels.

Table 11-1 Overview of Denmark's national climate objectives, agreements, and international commitments about climate change

Denmark's *Climate Act*	
Area of relevance	**Description**
10-year greenhouse gases (GHG) reduction goal	By 2030, Denmark's GHG emissions shall be 70% lower than in 1990.
5-year indicative GHG reduction goal	By 2025, Denmark's GHG shall be 50-54% lower than in 1990.
Net zero emissions	By 2050, Denmark must be climate neutral by 2050 at the latest.
Selected sectoral agreements by members of the Danish parliament:	
Area of relevance	**Description**
Energy	By 2030, Denmark's energy sector shall not rely anymore on coal, oil, and natural gas. Denmark has an ambition to quadruple its onshore renewable energy output from solar and onshore wind (production from these sources was 11.8 TWh in 2020). It has also been agreed to quintuple offshore wind capacity to 12.9 GW by 2030.
Agriculture and forestry	By 2030, the sectors will have reduced GHG emissions by 55-65% relative to 1990.
Road transportation	By 2030, road transportation will have reduced its emissions by 2.1 Mt CO_2e (1 Mt CO_2e by 2025). Ambition to have 1 million zero and low-emission vehicles (30% of the fleet).
EU "Fit for 55"	
Area of relevance	**Description**
Sectors within the EU ETS	Concerned sectors will jointly reduce GHG emissions by 61% in 2030, relative to 2005.
Renewable energy	EU countries will jointly achieve 40% of renewable energy in the overall energy mix.
Energy efficiency	EU countries will jointly reduce final energy consumption by 36% in 2030 (relative to the 2007 EU Reference Scenario), which is equivalent to a 9% reduction relative to the EU Reference Scenario 2020.

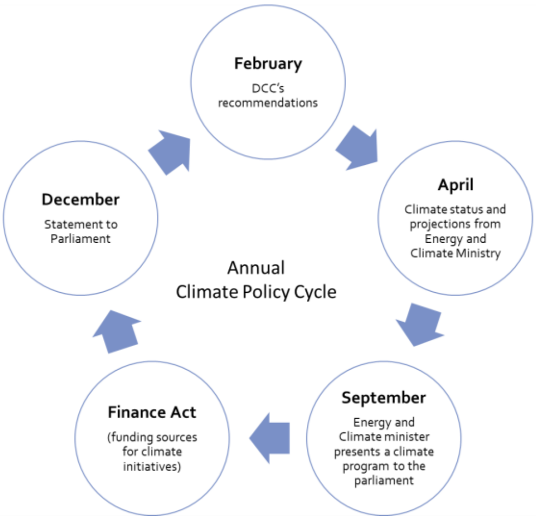
Note: The EU "Fit for 55" legislative package has entered the final stages of inter-institutional negotiation before final approval after the EU Commission has adopted an official position, which will form the basis of negotiation with the EU Parliament.

The Climate Act

As mentioned, the Danish parliament enacted the *Climate Act* in 2020, which, in addition to outlining legally binding targets and obligations (see Table 11-1), defines a governance framework to secure the long-term continuation of climate policy enactment. The *Climate Act* requires the Minister of Climate, Energy and Utilities to establish a new 10-year climate goal every five years, which must be at least as ambitious as the previously established one, and establishes an annual climate policy cycle in which:

- Each February, the DCCC presents their evaluation of whether the government is on track to achieve its binding targets and commitments and provides their recommendations.
- Each April, the Ministry of Climate, Energy and Utilities presents a report on the status and projections of its climate policies, considering a frozen policy scenario.
- Each September, the Minister of Climate, Energy and Utilities presents a Climate Programme, which includes an assessment of short-term and long-term initiatives with regards to emission reduction potentials, costs and various risk factors. Funding sources are also outlined and are subsequently included in the public financing act.
- Each December, the parliament evaluates the initiatives presented at a public debate, and the parliament decides whether the obligations are satisfied, or further action is required.

Figure 11-4 Annual climate policy cycle defined by the *Climate Act*



The *Climate Act* also assigns the Danish Council on Climate Change (DCCC) a role as an impartial expert body with an advisory and supervisory role on Danish climate policy:

- The DCCC advises the Ministry of Climate, Energy and Utilities on Denmark's climate effort, including the establishment of goals and commitments
- The DCCC analyses potential means to transition to a low-carbon society by 2050 and identifies possible measures to achieve GHG reductions while accounting for technical feasibility and socio-economic benefits and costs
- Each year, the DCCC evaluates the government's climate policy and may suggest a review of the action plans presented by the Minister of Climate, Energy and Utilities in case these are deemed insufficient to achieve its goals

- The DCCC contributes to the public debate on climate change and engages with relevant stakeholders such as industry and labour market organisations, as well as representatives of civil society

Climate Programme 2022

The *Climate Programme* is developed annually with the main purpose of making probable that the national climate targets can be achieved.[o] The most recent *Climate Programme* from 2022 indicates that Denmark is almost three quarters of the way towards achieving the 2030 GHG emission target. This is based on the policies implemented per January 1, 2022, and estimations on partial effects of political agreements made since then[54]. The *Climate Programme 2022* moreover identifies potential initiatives for achieving the deficit in carbon emission reductions.

The *Climate Programme* presents four different scenarios for achieving Denmark's target of 70% greenhouse gas reduction by 2030 compared to 1990, and the long-term goal of climate neutrality by 2050, the latest. The scenarios are used, for instance, to show that there are different ways to reach the targets. Table 11-2 gives a short description of the scenario characteristics.

Table 11-2 Climate Programme 2022 scenario description

Scenario	Description
Bioenergy and CCS	Bioenergy and CO_2 storage play a relatively large role in meeting the climate targets. Negative emission technologies are largely utilised to compensate for residual greenhouse gas emissions rather than minimising the emissions.
Electrification	High degree of electrification within society; including e.g., high technological development, cheaper electric transport, and heat pumps etc. (i.e., direct electrification), and Power-to-X technologies (indirect electrification).
Behaviour	Significant climate-conscious behavioural changes among citizens and businesses (modal shifts in transport, energy savings, dietary changes, and increased waste recycling/reuse etc.), increased focus on sustainability within the building and construction sector, and a high degree of energy efficiency and electrification.
New Markets	A high degree of transition in agriculture towards supplying the international markets for plant-based foods, entailing a significant decrease in livestock. Restructuring within construction and facilities takes place concurrently. Biomass consumption is limited to the sustainable potential for Denmark, assuming an even distribution of the global biomass resources across the World. In addition, the scenario includes a high degree of electrification, energy efficiency, and behavioural changes.

[o] The Climate Programme also gives a status regarding the indicative 2025-target.

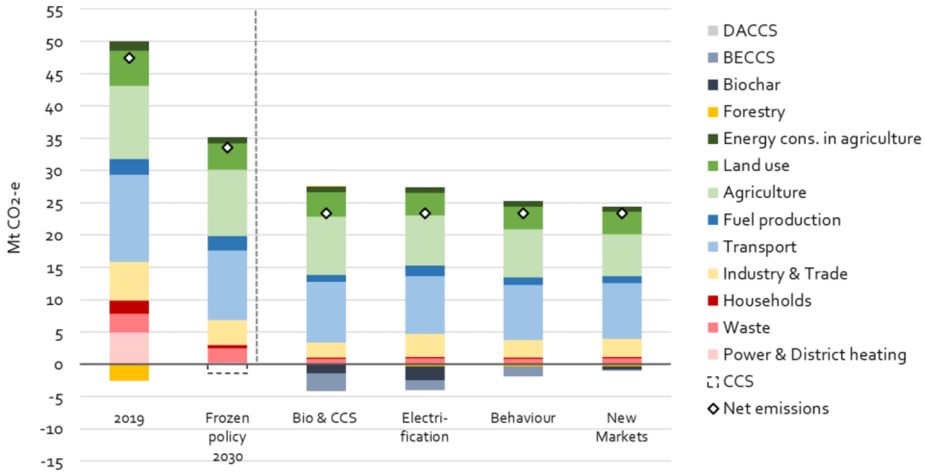
The scenarios illustrate different examples of how Denmark's national climate targets could be met. As part of the scenario work, a model has been developed that keeps track of all Danish greenhouse gas emissions within a consistent framework. As a common basis, all scenarios build upon the frozen policy projection towards 2030[55]. Additional emission reductions in the different scenarios are based on external model inputs (assumptions) and/or economic optimisation, depending on the sector.

As a result of currently adopted political decisions, the respective power and district heating and household sectors are expected to be almost fully decarbonised by 2030. Therefore, additional emission reductions in the scenarios are mainly found in other sectors. The scenarios illustrate significant emission reductions in 2030, particularly within agriculture, land use, transport, industry and trade, waste, and fuel production. CCS and biochar (from pyrolysis) is applied to a varying degree in the scenarios, to provide negative emission contributions and/or to eliminate fossil emissions. The GHG emission target is fulfilled with use of known technologies, though some of the technologies, e.g., biochar technology, DAC[p], and fodder additives in agriculture, are at a relatively early development stage. It should be expected that further development and demonstration of these technologies is required before they can be utilised at larger scales.

By 2050, fossil fuels are almost entirely phased out in the scenarios, primarily due to direct and indirect electrification, renewable energy use, and energy efficiency. Most of the remaining non-energy-related fossil emissions, e.g., from cement production and waste incineration, are removed through carbon capture and subsequent storage and/or utilisation. However, GHG emissions still occur to a varying degree across the scenarios, particularly from agriculture and land use. To compensate for these remaining emissions, a combination of negative emission technologies, such as bioenergy CCS (BECCS), DACCS; biochar and reforestation is required. The scenarios illustrate that climate neutrality by 2050 can be achieved with varying dependence on negative emission technologies. Among other things, the scenarios also illustrate that achieving climate neutrality will require a considerable transition, where a broad spectrum of measures are expected to play a role.

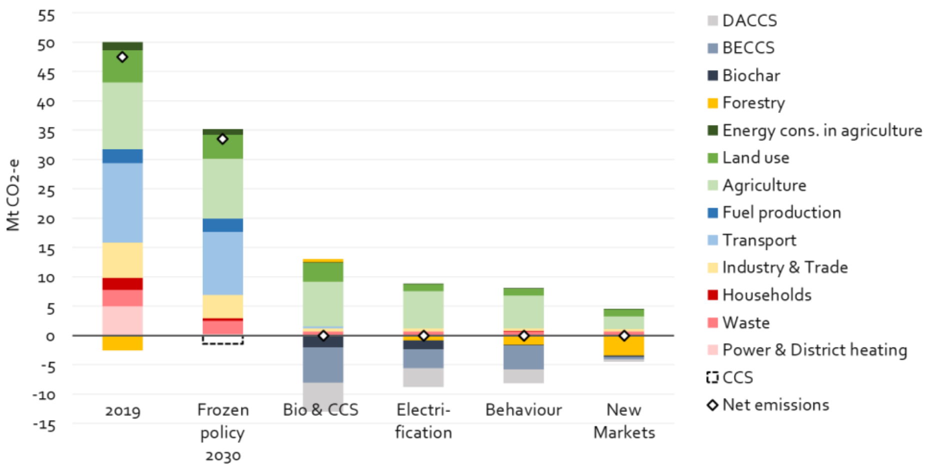
[p] DAC is, however, only assumed to contribute marginally in one of the scenarios in 2030.

Figure 11-5 Greenhouse gas emissions in the four scenarios for 2030 compared to frozen policy emissions[56] and historical emission in 2019



Note: In the scenarios, CCS (fossil) is included in the sector specific emissions, while emission reductions from CCS (fossil/bio) are in the frozen policy projection subtracted from the total emissions.

Figure 11-6 Greenhouse gas emissions in the four scenarios for 2050 compared to frozen policy emissions[57] and historical emission in 2019



Source: In the scenarios, CCS (fossil) is included in the sector specific emissions, while emission reductions from CCS (fossil/bio) are in the frozen policy projection subtracted from the total emissions.

Green taxation reform

Another essential element of Danish climate policy is the recent approval of a broad tax reform that facilitates the green transition in line with the 2030 and 2050 objectives. Although the Danish taxation system has addressed negative environmental externalities derived from economic activity throughout the years, the government identified the need for a more uniform taxation system that deals directly with CO_2 emissions.

Presently, the system consists of separate energy and CO_2 tax components on fuels and the EU ETS quota price applied in several industrial sectors. The effective tax on CO_2 emissions is considerably higher for fuels used in transportation and space heating than for industrial activities.

With the reform, by 2030, a tax will be applied to CO_2 emissions from industries inside and outside the EU ETS quota system. A conversion of the existing energy taxes into a CO_2 tax on fossil fuels will be introduced in 2025. The new taxation system, which has an estimated impact of a 4.3 Mt CO_2e reduction, also accounts for a price floor mechanism that will be applied in case the ETS price is low. Table 11-3 presents an overview of the tax rates to be used.

Table 11-3 Overview of Denmark's Green tax reform

Firm category	Tax rate (EUR/CO_2) in 2030
Outside the EU ETS system	101
Within the EU ETS system	50
Involved in mineralogy processes (cement, glass, mineral wool, brick production, etc.)	17

Note: the tax rates are presented in EUR at an exchange rate of 1 EUR = 7.4381 DKK, published by Denmark's National Bank on 11/10/2022.

Agriculture will not be subject to CO_2 taxes as part of the agreement, but an expert group has been set up to examine how the sector's emissions are most appropriately regulated. The analysis and recommendations by the expert group will investigate policy options to reduce the agricultural sectors' non-energy related emissions, which could include a combination of CO_2 taxes, state aid mechanisms and other regulatory initiatives.

Municipality level planning

Danish municipalities have considerable influence on many of the policies of the citizens living in a specific area and are the primary decision-makers in heat planning and the physical planning for onshore wind and solar plants. Because of this decentralised form of decision-making, Danish municipalities effectively have a considerable impact on their CO_2 footprint. Planning at the municipality level coexists in Denmark with the broader national energy planning, which – among other tasks – defines the overall framework to evaluate projects from a societal cost-benefit perspective.

As an example of planning at the municipality level, 95 of the 98 Danish municipalities have established or are establishing binding agreements to design and formulate their own climate action plans, which live up to the requirements of the *Paris Agreement*.

Electricity grid planning

Denmark is part of the European internal market on electricity. The planning methods for security of electricity supply and market rules are to some extent given by overall legislation from the European Union, but there is also room for specific planning methods in the individual member states. Therefore, there might be minor differences in the planning and calculation methods used in Denmark compared to for example Germany – although the common framework for regulation is set by EU legislation.

The Danish and European electricity systems are undergoing significant changes. Extensive wind and solar power capacity is being integrated in the electricity system, while many traditional thermal power stations are being phased out. As more electricity interconnectors link different countries' electrical grids, the security of electricity supply becomes an increasingly regional issue, instead of simply a national issue.

In a European context, the level of security of supply is monitored as part the pan-European initiative *European Resource Adequacy Assessment* (ERAA). The ERAA was introduced for the first time in 2021 and came because of the heightened focus on the integrated European power market as well as the increasing share of variable renewable energy. The ERAA report is developed by the European Network of Transmission System Operators (ENTSO-E) and its members, covering 37 European states in total. Moreover – and as a prerequisite – The European Union Agency for the Cooperation of Energy Regulators (ACER) oversees the methodologies used in the ERAA, giving input on how to develop the methods and possible changes for future reports.

The assessment is based on two main scenarios:

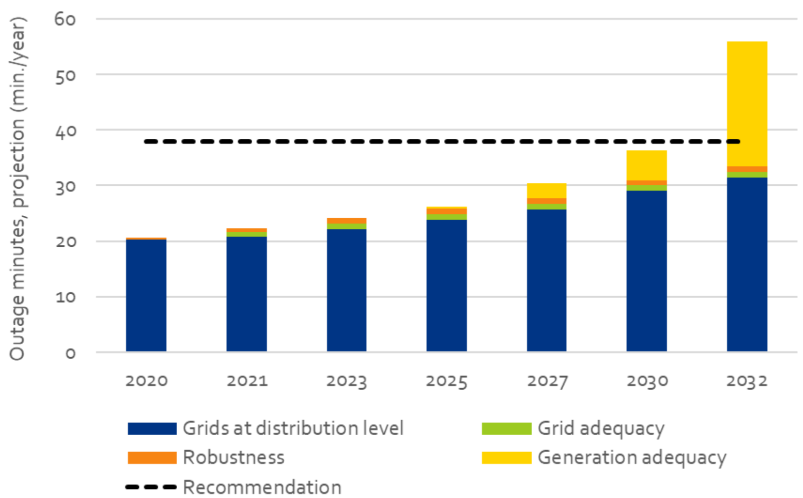
1) Central Reference Scenario without Capacity Mechanism (CM)
2) Central Reference Scenario with CM

Compared to the CNS1/2, the ERAA uses Central Reference scenarios that are based on the National Estimate Scenario, living up to the "Fit for 55" package, reducing greenhouse gas emissions by 55% (compared to 1990) by 2030. Throughout the development of the scenarios, the TSOs are involved and give input on expected trajectories, adequacy, and grid development, making for a more precise and probabilistic assessment.

In Denmark, the national transmission system operator, Energinet, monitors and analyses the development of security of electricity supply. Once a year, Energinet publishes a report on "Security of Electricity Supply" to review the current state and recommend new actions and targets that can support future security of electricity supply. Since the Danish electricity system is relatively small and connected to neighbouring countries, transmission to and from other countries is an integrated element in assessing SoS in Denmark.

Figure 11-7 shows the base-line projection (simulating a business as-usual development) from Energinet's 2022-report on security of electricity supply in Denmark. The forecast of outage minutes per year are shown on a 10-year horizon.

Figure 11-7 Baseline projections for expected outage minutes



Source: Report on Security of Electricity Supply, 2022 (originally in Danish) Energinet (2022).

A degree of uncertainty is naturally associated with such forecasts. Nonetheless, the following overall trends are indicated:

- Disruption at the distribution level will slowly raise due to increasing consumption and ageing grids
- Minor challenges can be foreseen in relation to the grid adequacy and robustness
- Without action, there is a risk of lack of generation adequacy in the longer term – due to concurrently increasing VRE share and decreasing fossil-based thermal capacity

In Denmark, an overall objective for an average level of security of electricity supply is set. A series of follow-up decisions and implementation of various measures are conducted to realise the objective. The planning objective for 2032 is to have no more than 38 outage minutes per year in the case of a "normal year". The grid is not designed to completely avoid special incidents, like extreme weather conditions. Instead, the risk associated with special incidents, and costs of avoiding or mitigating those incidents, is considered during the planning process. It is not possible to predict all possible incidents when planning the electricity system. Public hearings regarding the security of supply report, and regular updates to them, ensure that new targets and measures are prepared through ongoing observations and discussions among relevant actors in the energy sector.

11.4 Challenges facing Denmark's energy transition

Recent challenges

As a result of the economic re-activation after the COVID-19 pandemic, supply chain disruptions and the consequences of expansionary fiscal and monetary policies have resulted in strong inflationary pressures, which have been felt both in Denmark and elsewhere.

The recent geopolitical tensions experienced because of the Russia-Ukraine conflict exacerbated the effects of rising inflation and have ultimately exposed European and Danish consumers to record-high prices, particularly within the electricity and gas markets. Denmark's Consumer Price Index (CPI) escalated by 8.9% in August 2022 – the highest year-on-year price rise since January 1983.

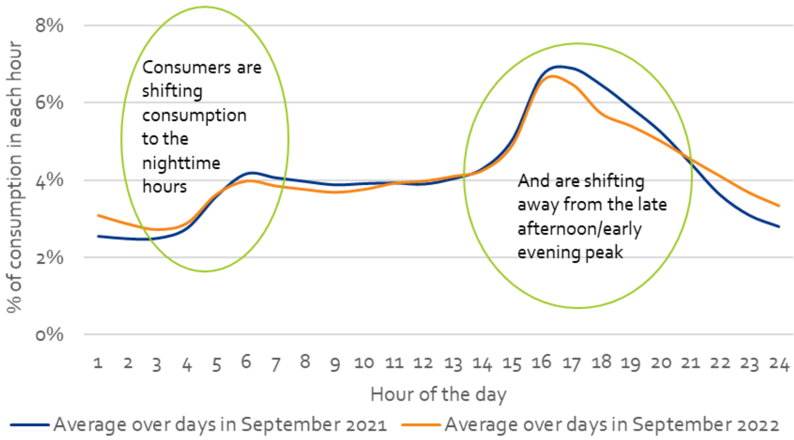
To address the issue, the Danish parliament has decided to allow consumers to postpone part of their payment of energy bills over a more extended period (5 years) and with a low interest rate. When the price of energy (gas, electricity, heat) exceeds a pre-established level (corresponding to the prices of Q4 2021), consumers can postpone the payment of the fraction of the bill that is above this threshold. The mechanism, which will last for 12 months, attempts to balance consumer protection and exposure to price signals, which support much-needed flexibility and energy conservation measures. The Danish state will underwrite consumers' debt and provide liquidity to energy companies in the form of state loans in case these are necessary.

Electricity

The combination of high electricity prices and the fact that all Danish households are metered and billed hourly have increased consumer awareness and helped incentivise flexible electricity consumption. The wholesale price of electricity tends to fluctuate between highs – when gas-powered producers set the price – and lows when there is abundant wind and solar power production.

In a recent analysis, the Danish association for the energy industry, Green Power Denmark, has observed that high prices have motivated consumers to shift consumption away from the most expensive hours of the day into the least expensive ones, proving that price signals work. A similar trend was observed by the Distribution System Operator (DSO) for the Greater Copenhagen region (Radius), which noted that on 5 October 2022, between 14:00 and 15:00, when wholesale prices were virtually zero, consumers increased consumption by 27% relative to the same hour in the previous two days.

Figure 11-8 Average hourly consumption of electricity (in %) during weekdays in September 2021 and September 2022



Source: Green Power Denmark (based on Energidataservice) [58]

Another measure the Danish government took to address recent challenges and potential concerns for the insufficient availability of electricity supplies is the decision to postpone the closure of three fossil-fuelled power plants until 2024. The government has evaluated that the two forthcoming winter periods may be challenging due to the situation in the gas market and has therefore chosen to rely on domestic production to cover possible shortfalls in peak hours.

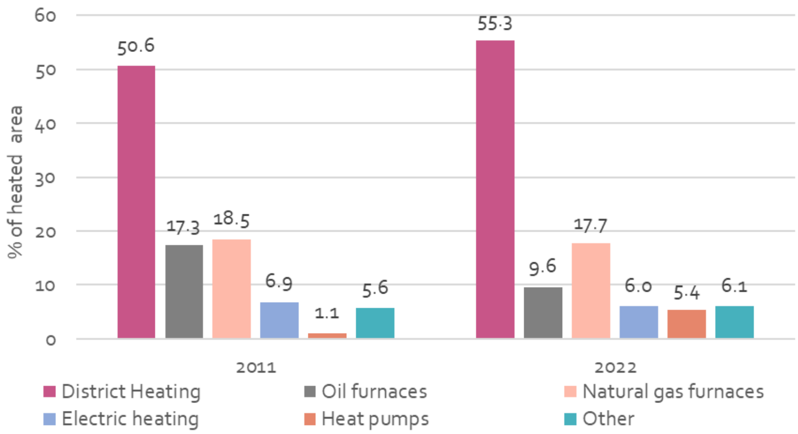
Gas

As a direct result of the Russia-Ukraine conflict, the long-term contract between the biggest Danish gas supplier Ørsted and Russia's Gazprom was terminated in June, leaving the Danish supplier in greater reliance on the European spot market to fulfil its commitments. However, in October 2022, Ørsted contracted with Equinor on supplying the Danish market with Norwegian gas instead. In cooperation with other EU Member States, a direct response from the Danish government has been to find joint alternatives to obtain the required supplies and increase the speed of the green transition.

On the domestic front, the Danish Parliament has declared an ambition on phase-out of natural gas for domestically heating by 2035 and has established a goal to become supplied entirely with green gases by 2030. In 2022, on a yearly average app. One third of the gas in the Danish gas system consist of biomethane.

Presently, there are approximately 380,000 Danish homes that are heated with natural gas boilers and another 50,000 that are heated with petroleum boilers. The magnitude of the conversion challenge can be observed in Figure 11-9, which reveals that the second and third most common forms of space heating are oil-fired and natural gas-fired furnaces. The figure also shows how district heating and individual heat pumps have increased their shares at the expense of oil and natural gas in the past 11 years.

Figure 11-9 Percentage of heated space by heating form (by 01/01/2022 and 01/01/2011)



Source: Statistics Denmark

Where it is technically and economically feasible, these homes will be offered the possibility to switch to district heating – which is supposed to take place by 2028 at the latest. The government estimates that 30-50% of gas-fired homes will switch to district heating, while another 20% will prefer an individual heating solution, such as a heat pump. Gas boilers will continue to exist in 2030 but will be supplied with green gases, from the digestion of manure and organic waste.

11.5 The best case study of energy transition in Denmark

As part of its climate policy goals, Denmark is advancing several climate change mitigation initiatives with particular emphasis on increasing renewable energy production, from e.g., wind and solar, while upholding high security of electricity supply, and the electrification, both directly and indirectly, of society. Transportation and heating are two areas that can be directly electrified, while industrial activities may require a more indirect approach, for example, through Power-to-X solutions.

Energy islands

Since the establishment of the world's first offshore wind farm, Denmark has been committed to advancing offshore wind technology and production. Between 2010 (0.9 GW) and 2022 (2.3 GW), the installed capacity of offshore wind has more than doubled. Based on a broad parliamentary agreement from 2020, Denmark decided to raise its ambitions much further and establish two energy islands in the North Sea (potentially up to 10 GW) and close to the island of Bornholm (3 GW) in the Baltic Sea.

Considering all the relevant parliamentary agreements and earmarking of funds, Denmark has the ambition to expand installed offshore wind capacity to 12.9 GW by 2030[59], which is a fivefold increase relative to the existing capacity.

The islands are planned to be a massive gathering of offshore wind generation capacity, which will serve as a node in the development of a future offshore transmission grid interconnecting the electricity systems of Denmark and neighbouring countries. An agreement had already been reached with Belgium regarding cooperation in the North Sea, while a letter of intent and a memorandum of understanding have been signed with Germany and the Netherlands respectively, regarding potential future cooperation.

Figure 11-10 The location of Denmark's energy islands

Source: The Danish Government

The islands represent a radical paradigm shift away from the radial interconnections approach of the present, in which offshore sites are connected to an onshore point of coupling. In the future, interconnected offshore wind farms will serve the dual purpose of supplying electricity to the local market and transmitting power across international interconnectors. An early-stage example of such hybrid infrastructure is the Kriegers Flak Combined Grid Solution, which interconnects the Kriegers Flak wind farm on Danish waters with the Baltic 1 and Baltic 2 wind farms on German waters.

Furthermore, the islands are expected to play an essential role in developing Power-to-X solutions, as related infrastructure is expected to be placed either directly on the islands or onshore landing zones. Hydrogen is expected to be produced based on wind and solar power and then may be fed into the future European Hydrogen Backbone (EHB) infrastructure in which Denmark takes part or used directly to produce synthetic fuels.

CCUS and Power-to-X

The achievement of Denmark's climate goals and commitments relies, to a certain extent, on the progress of technologies that – although proven – are still in a pre-commercial phase, e.g., CCUS, or in early stage of the commercial phase, lacking large scale implementation, such as PtX.

Concerning CCUS, the Danish Government has established a series of agreements, which aim at supporting the emergence of a CCUS value chain in the country.

To implement the political agreements, several steps have been taken, including:

- Granting permits for CO_2-storage in part of the Danish North Sea and identifying additional potential storage locations in the country.
- Initiating the first competitive tender of state aid to get the CCS value chain started in Denmark. The contract will run over the course of 20 years to support the establishment of an initial CCUS project, which is expected to realise CO_2 reductions of 0.4 Mt CO_2 per year from 2026. Three projects have been pre-qualified to participate in the tender, and a final decision on the project to receive the state aid is expected to be made in the first half of 2023. This first tender will be followed-up by additional aid schemes to be designed and announced at a later stage.

According to PtX, there is an established goal of 4-6 GW [60] electrolyser capacity by 2030. Relative to fossil- and bio-fuel alternatives, this technology is not yet competitive in market terms. Denmark has initiated a series of steps to develop a Power-to-X value chain:

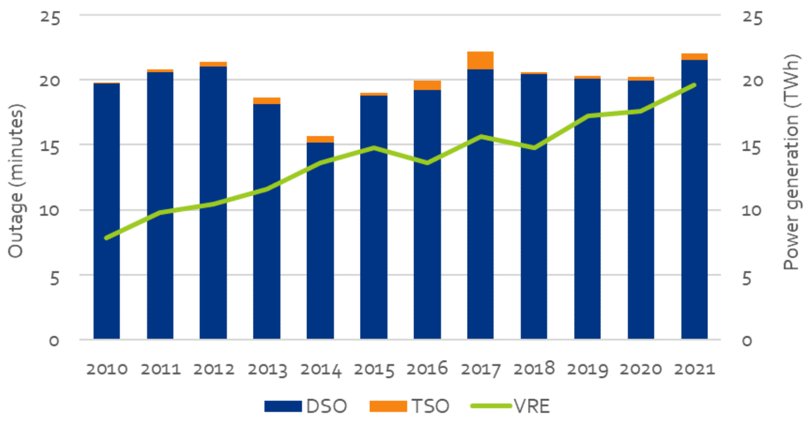
- Competitive allocation of state aid for investments in Power-to-X and hydrogen projects. A bidding round to obtain state aid supporting industrialisation and upscaling of Power-to-X applications is expected to occur in 2023. To support initial Power-to-X projects, 1.25 billion DKK has been allocated, which should support 200-300 MW of PtX projects over a 10-year period.
- Regulatory reforms that improve the economic conditions for projects. For example, the introduction of geographically differentiated tariffs to incentivise optimal scaling decisions and flexible operation of electrolysers.
- Working on introducing direct lines between renewable energy sources and PtX plants to reduce the tariffs imposed upon the latter for utilising power infrastructure.

Security of electricity supply

Denmark has maintained a high level of security of electricity while increasing the share of fluctuating wind and solar energy. On average, Danish electricity consumers experience around 20-21 minutes of outage, corresponding to a security of electricity supply of 99.996%, and most outages are related to local distributions grids. This makes Danish consumers' security of electricity supply one of the highest in Europe and shows that the transition to increasingly RES-based electricity supply does not jeopardise security of supply, nor does it have a negative impact on economic growth. As pointed out in the CETO 2022, "economic growth can be secured by promoting energy efficiency, electrification, and massive renewable energy deployment".

The chart below illustrates the historic development of security of electricity supply measured by number of outages minutes per year and the share of variable renewable energy (VRE) measures by TWh.

Figure 11-11 Expected outage minutes relative to variable renewable energy output



Note: Outage minutes are defined as the average time per year where an average consumer experiences disruption in electricity supply. Source: Report on Security of Electricity Supply, 2022 (originally in Danish) Energinet (2022)

Green heating

One highly relevant area in which municipality-level planning has historically played an important role is the development of district heating. By trench length (30,000 km), coverage of the residential sector (66%), and share of renewables used in the production of heat (69%), Denmark is a leading country in district heating. Energy efficiency and the coupling of sectors (through co-generation and the increasing use of large-scale heat pumps) are among the several benefits of the Danish district heating sector.

Furthermore, district heating – which has an estimated potential of 73% of residential coverage by 2028 – is an essential source of flexibility for the overall energy system and thus facilitates the integration of renewables. In conjunction with co-generation, heat storages support flexible electricity production. Similarly, heat storages, large-scale heat pumps, and electric boilers allow for flexible electricity consumption.

However, district heating is not the only form of green heating available. Individual heat pumps provide very high levels of energy efficiency (measured by the Coefficient of Performance – COP) and are another vital technology for decarbonizing the heating sector and integrating renewable energy.

At a time when the Danish government has decided to phase out natural gas as a space heating fuel by 2030, the country is facilitating the conversion from fossil-fuelled furnaces to both district heating and individual heat pumps (see Figure 11-9). Among the main measures is the taxation reform adopted in June 2022, which includes a reduction of the electricity excise tax paid by all consumers, as well as more funding to expanding district heating. The Danish Government is currently looking into a possible decrease of the electricity tax on heat pumps from 2024, but the measure has not yet been adopted.

Chapter 12

Green finance fuels China's energy transformation

12 Green finance fuels China's energy transformation

12.1 Key messages

- Amid the escalating risks of global climate change, promoting responses to climate change and achieving more sustainable development has also become a key priority of the international community in coordinating national macroeconomic, fiscal, and financial policies. Against this backdrop, green finance has garnered widespread attention, leading to the gradual growth of the global green finance market. As per the latest research by relevant international and banking institutions, the proportion of green finance in the global financial market has risen from 0.1% in 2012 to 4% in 2021. Moreover, the scale of green financing has grown from US$5.2 billion to US$540.6 billion, representing an increase of over 100 times. Green finance is increasingly playing a pivotal role in guiding and promoting the transformation of the energy system, green and low-carbon transformation of traditional energy industries, and the expansion of new energy industries.

- In 2016, the *G20 Green Finance Synthesis Report* was adopted during the G20 Leaders' Summit in Hangzhou, China. The report proposed seven optional measures aimed at accelerating the mobilization of green finance. The G20 Summit in November 2022 prioritised "Sustainable Energy Transition" as one of its three priority issues and endorsed the *2022 G20 Sustainable Finance Report*, proposing further development of sustainable financial instruments to increase the availability of sustainable financing and reduce financing costs.

- Over the past few years, the EU has persistently implemented its *Sustainable Finance Action Plan*, bolstering support for green finance in carbon markets, renewable energy, energy efficiency, and other sectors. Other economies and relevant countries are also vigorously fostering the development of green finance. Nonetheless, the global development of green finance is still beset with inadequacies and imbalances, with a significant disparity in green financing opportunities and funding support between developing and developed countries. Additionally, green finance development is stymied by various obstacles, including lack of knowledge and information, inadequate analytical capabilities, and regulatory risks.

- China holds the distinction of being the first G20 country to address green finance and has been an active proponent and dedicated implementer. Since 2016, China has been enhancing its green financial system, introducing the "five pillars" and "three functions" of green financial development, and actively promoting green financial development. Abiding by the principle of "national unification, international compliance, and clear enforceability," China has progressively advanced the construction of the green financial standards system; underscored the cultivation and expansion of the green finance market; incentivized innovation in green financial products and services; established green finance reform and innovation pilot zones to explore replicable and scalable local paths for green finance development; and deepened international exchanges and cooperation in green finance to create a favourable international environment for its development. The size of China's green loan balance continues to expand as the market space for green credit broadens.

- Promoting green development and energy transition is a key focus of China's green finance policy implementation. China has identified energy conservation and environmental protection, new energy and clean energy, green infrastructure, and green services as critical sectors backed by green finance. The share of green financial products, such as green loans, green funds, and green insurance, directed towards promoting renewable energy and facilitating the transition to clean energy sources has been consistently increasing in China. It is anticipated that green finance will progressively assert a more pivotal role in the creation of a novel energy system in China, aimed at achieving peak carbon and carbon neutrality.

12.2 Global green finance development

In recent years, sustainable finance and green finance have garnered significant attention from the international community, as well as from a growing number of economies and nations across the globe. As the financial industry adapts to global sustainable development and climate change, green financial products such as green credits, green insurance, green bonds, and green funds are steadily gaining popularity.

Green finance sets itself apart from traditional finance by addressing the deficiencies in focus and investment for green development within existing market environments and financial systems. Green investments often produce positive externalities, such as mitigating environmental pollution and preserving ecosystems. However, these externalities are frequently overlooked by market mechanisms, leading to a situation where green investors struggle to achieve corresponding economic returns. In these cases, the market tends to undervalue the significance of green investments, hence resulting in inadequate investment. Furthermore, investors may not have access to comprehensive information regarding green investments, including details about environmental benefits, technological feasibility, and associated investment risks. This lack of complete information makes it difficult for investors to accurately assess the potential returns and risks tied to green investments, which subsequently decreases their willingness to invest. Additionally, green investments generally involve longer return cycles, while the market often prioritises short-term gains. This discrepancy encourages investors to favour traditional industries, which typically offer higher short-term returns, and approach green investments with caution. Globally, green finance is commonly defined as "financial activities related to sustainable development." It aligns the ultimate objectives of financial activities to real economic activities associated with modern sustainable development. Green finance underscores the urgent need for the financial sector to contribute to the growth of green and eco-friendly initiatives while combating climate change. By deploying innovative financial models and instruments, it aims to reduce investment and financing costs, improve access to funding, and guide the transition of the real economy towards a greener, low-carbon path.

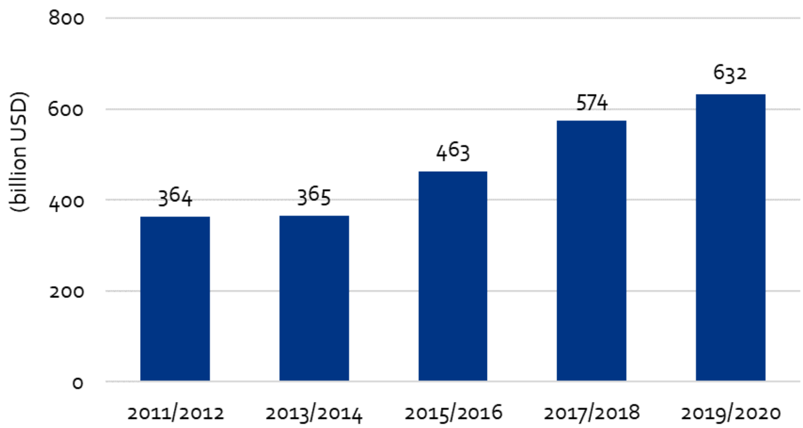
In 2016, the *G20 Green Finance Synthesis Report* was adopted during the G20 Leaders' Summit in Hangzhou, China. The report proposed seven optional measures aimed at accelerating the mobilization of green finance.

Box 12-1 G20's seven optional measures to accelerate green finance mobilization

These measures include: providing investors with a clearer strategic framework and environmental and economic policy signals for green investment, promoting voluntary principles for green finance; expanding capacity building learning networks; strengthening the role of international capacity building platforms such as the Sustainable Banking Network (SBN) promoted by IFC and UN Guidelines for Responsible Investment (PRI); supporting the development of local currency green bond markets; developing international cooperation to promote cross-border green bond investment; promoting exchange of environmental and financial risk issues; improving the measurement of green finance activities and their impacts; promoting research on green finance indicator systems and related definitions based on the experiences of different countries; and analysing the impacts of green finance on the economy and other areas.

On March 8th, 2018, the European Commission published the *Action Plan on Financing Sustainable Growth*, which sets out three main objectives: re-orienting capital flows towards more sustainable economic activities, integrating sustainability into the financial sector's regular risk management, and fostering long-termism while improving market transparency. While the *Action Plan* has a broader scope than "green finance" in the general sense, it also includes specific objectives for green finance development, such as establishing standards and labelling for green financial products. The EU's action plan released clear policy signals for sustainable financial development, which have greatly contributed to the accelerated development of action strategies by financial regulators, the harmonization of business standards related to green finance in Europe, and the improvement of the efficiency of green finance business in financial markets. In recent years, the EU has continued to implement the *Action Plan on Financing Sustainable Growth*, promulgated the *Sustainable Finance Disclosure Regulation* (SFDR) technical standards that are applicable to financial entities and fund investors, proposed the adoption of the Corporate Sustainability Due Diligence (CSDD) Directive, and increased green finance support for carbon markets, renewable energy and energy efficiency.

Figure 12-1 Global climate finance scale



Source: CPI Preview: Global Landscape of Climate Finance 2021, CICC Global Institute

On November 16, 2022, the G20 Leaders' Summit was held in Bali, Indonesia, with "Sustainable Energy Transition" as one of its three priority issues. The summit endorsed the *2022 G20 Sustainable Finance Report*, spearheaded by the People's Bank of China, which was one of the co-chairs of the G20 Sustainable Finance Working Group (SFWG). The report proposes further development of sustainable financial instruments to increase the availability of sustainable financing and reduce financing costs. It also presents a number of practical suggestions for countries and stakeholders to adopt on a voluntary basis, including establishing a framework for transformational finance and strengthening the credibility of net-zero emission commitments by financial institutions.

Box 12-2 The G20 framework for transformative finance

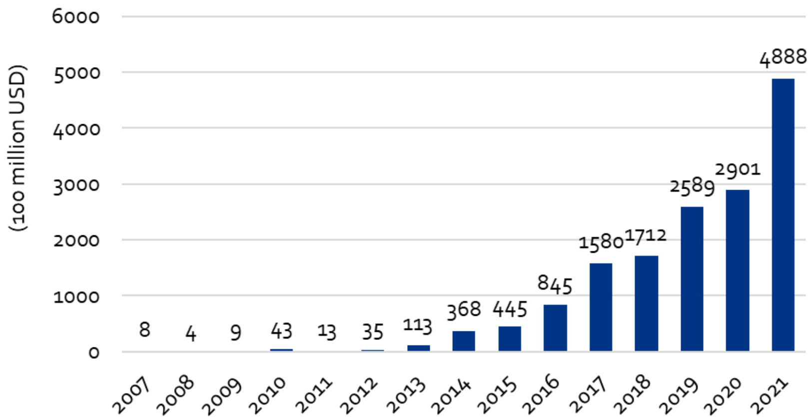
A key element of the *2022 G20 Sustainable Finance Report* is the *G20 Framework for Transformative Finance*. The *Framework*'s primary objective is to promote the financial sector's support for the transition of high-carbon emitting sectors to low and zero carbon. The *Framework* includes 5 pillars and 22 principles, namely: defining criteria for transition activities and transition investments, disclosure of information on transition activities and transition investments, enriching and innovating transition financial instruments, developing and improving various incentive mechanisms and supporting policies, and just transition.

Box 12-3 Enhancing the credibility of voluntary net-zero emissions commitments by financial institutions

The background of this proposal is that in recent years, as more countries and regions have pledged carbon neutrality, many financial institutions and companies have followed suit by setting their own carbon neutrality targets. However, unlike the Nationally Determined Contributions (NDCs) submitted by national governments to the UN Framework Convention on Climate Change (UNFCCC), these targets set by financial institutions and companies often lack binding mechanisms or third-party verification. To enhance the credibility of the near-zero emissions commitments and ensure they are fully realised by the financial institutions, the G20 Sustainable Finance Working Group has incorporated this issue into its study scope and put forward several recommendations for addressing it.

In recent years, global green finance has gradually taken shape, and as per the latest research by relevant international and banking institutions, the proportion of green finance in the global financial market has risen from 0.1% in 2012 to 4% in 2021. Moreover, the scale of green financing has grown from US$5.2 billion to US$540.6 billion, representing an increase of over 100 times. Within this expansion, the total annual global green credit has surged from a base of approximately $432 million to $78.6 billion in 2021, an increase of nearly 200 times. Bloomberg estimates that global green assets are expected to surpass $53 trillion by 2025.

Figure 12-2 Global green bond issuance



Source: CBI, Refinitive, CICC Global Institute

The growth of global green finance, however, is both insufficient and uneven, with the vast majority of developing countries having limited access to green financing and financial support compared to developed nations. Data indicates that among the 20 countries and regions with the largest global green and sustainable bond issuance in 2021, 18 are developed economies, and only two are less developed economies. Additionally, green finance development also encounters various challenges such as inadequate knowledge and information, limited analytical capacity and regulatory risks.

12.3 Current green finance development situation in China

China holds the distinction of being the first G20 country to address green finance and has been an active proponent and dedicated implementer. According to the *Global Green Finance Development Report (2022)* published by the International Institute of Green Finance (IIGF) of Central University of Finance and Economics (CUFE) in February 2023, China ranks fourth, following the UK, France, and Germany, in the Global Green Finance Development Index (GGFDI) covering 55 countries worldwide. As the sole developing country among the top 10, China demonstrates its leading position in constructing its green financial system, nurturing green financial markets, and fostering international cooperation.

Since 2016, China has been enhancing its green financial system, introducing the "five pillars" and "three functions" of green financial development, and actively promoting green financial development.

Box 12-4 "Three Functions" and "Five Pillars" of China's green finance

To improve the high-level design of green finance development, in 2016, the PBoC and other relevant departments jointly issued the *Guiding Opinions on Building a Green Financial System* in 2016. This document helps to establish the "three major functions" and "five pillars" of green finance development.

The "Three Functions" relate primarily to the resource allocation, risk management, and market pricing functions of financial support for green development. Firstly, financial resources shall be directed and leveraged towards low-carbon projects, green transformation projects, carbon capture and storage, and other green innovation projects through monetary policy, credit policy, regulatory policy, mandatory disclosure, green evaluation, industry self-regulation, and product innovation. Secondly, the financial system's ability to manage climate change-related risks shall be enhanced through tools such as climate risk stress tests, environmental and climate risk analysis, and risk weighting adjustments for green and brown assets. Thirdly, the creation of a national carbon emission trading market shall be promoted, with the development of carbon futures and other derivative products, to establish a reasonable price for carbon emissions through market trading.

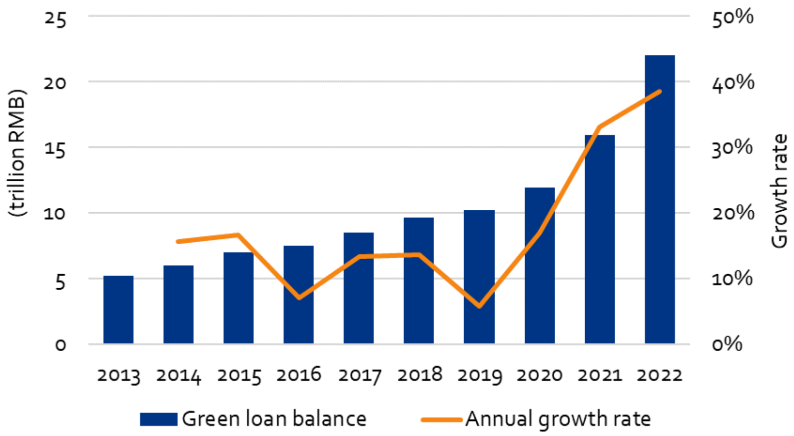
To effectively execute the "Three Functions," it is essential to improve the "Five Pillars" of the green financial system. These pillars include the green financial standard system, environmental information disclosure, incentive and restraint mechanism, product and market system, and international cooperation.

In 2018, the People's Bank of China (PBoC) set up the Working Group on Green Finance Standards for the National Financial Standardization Technical Committee, with the goal of steadily advancing the construction of the green financial standards system based on the principle of "national unification, international compliance, and clear enforceability". four standards have been released, including the *Green Bond Support Project Catalogue (2021 Edition)*, *Environmental Information Disclosure Guide for Financial Institutions*, *Environmental Equity Financing Instrument*, and *Carbon Financial Products*. Additionally, 15 standards are either in development or under consultation, encompassing critical areas such as environmental, social, and governance (ESG) evaluation, carbon accounting for financial institutions, and financial operations. Research is also underway on transformational finance standards to provide standard basis for financial support to green and low-carbon development in traditional energy and industries.

China is also making great efforts to foster an open and transparent market environment for green finance development. The PBoC, for example, has pioneered the establishment of a green financial information management system, utilising financial technology to perform carbon accounting for financial institutions and operations while also reducing the costs of environmental information disclosure and management.

In developing green finance, China has focused on fostering and growing the green finance market. The size of China's green loan balance continues to expand as the market space for green credit broadens. According to the latest data from the PBoC, at year-end 2022, China's green loan balance in domestic and foreign currencies reached RMB 22.03 trillion, increasing 38.5% year over year, 5.5 percentage points higher than year-end 2021 and 28.1 percentage points higher than the growth rate of various loans, with an annual increase of RMB 6.01 trillion. Among these, loans invested in projects with direct and indirect carbon emission reduction benefits amounted to RMB 8.6 trillion and RMB 6.1 trillion respectively, totalling 66.7% of green loans.

Figure 12-3 2013-2022 China's green loan balance scale



Source: PBoC, Chuancai Securities Research Institute

China also encourages innovation in green financial products and services, incentivizing financial institutions to increase their green loan business through policies, and guiding them to create various green bond products, launch green funds, and provide green insurance. As of year-end 2022, the cumulative stock size of China's green bond market was RMB 1,766 billion, with 525 new domestic green bonds issued, totalling RMB 868 billion in issue size. Compared to FY 2021, the number of green bonds issued in China grew by 8.9%, and the size of listed bonds increased by 45.2%. The proportion of green bonds listed relative to total bonds listed is 3.7%, which is approximately 23.4 times the proportion of global green bonds. This indicates that China's green bond issuance rate is among the best in the world.

Green funds are also an integral part of China's green financial system. China's green financial policy supports the creation of various green development funds, managed through market-oriented investment mechanisms. China encourages local governments and social capital to jointly launch regional green development funds, while supporting social and international capital in creating diverse private green investment funds. By the end of Q3 2021, the number of public and private funds dedicated to green, sustainable, ESG, and other related areas in China approached 1,000, amassing a total of over RMB 790 billion. This represents a 36% increase compared to year-end 2020. Over 190 public funds were included, with a management scale exceeding RMB 410 billion, along with more than 800 private funds, with a management scale surpassing RMB 370 billion. Notably, 90% of these funds were equity venture capital funds. In 2021, the issuance of green investment-related funds exceeded 50, surpassing any previous year.

In terms of green insurance, China has established a preliminary green insurance system, providing a total of RMB 4.5 trillion in green insurance coverage to the whole society between 2018 and 2020, disbursing RMB 53.4 billion in compensation. The balance for green investment rose from RMB 395 billion in 2018 to RMB 562 billion in 2020.

In terms of green trusts, as of year-end 2021, China had 665 projects, a decrease from the previous year's level, but with more diverse asset investments and an expanded variety of financial instruments. In 2021, green trust assets were primarily invested in six sectors: energy conservation and environmental protection, clean production, clean energy, ecological environment, green infrastructure upgrading, and green services.

Since June 2017, China has set up nine green finance reform and innovation pilot zones across six provinces (regions), including Zhejiang, Jiangxi, Guangdong, Guizhou, Gansu and Xinjiang, exploring a bottom-up scalable and replicable model for local green finance development. As of end of June 2022, the balance of green loans in these pilot zones reached RMB 1.1 trillion, which was 2.2 percentage points higher than the national average in terms of their proportion in total loans.

China is continually deepening international exchanges and cooperation in green finance to foster a favourable global environment for its development. The PBoC actively engages in international cooperation platforms, such as the G20 Sustainable Finance Working Group, the Central Banks, and Supervisors Network for Greening the Financial System (NGFS), the International Platform on Sustainable Finance (IPSF), and the Green Investment Principles (GIP) for the Belt and Road. These efforts aim to garner international consensus on green finance and lead global discussions on the topic. In June 2022, the PBoC, along with relevant European Union authorities, jointly released the sustainable finance common taxonomy, laying the groundwork for connecting and facilitating green cross-border investment and financing in the China-Europe green bond market.

12.4 China's green financial policies for promoting green development and energy transformation

Since the inception of its green finance system, China has placed a significant emphasis on promoting green development and energy transformation as central elements of its green finance policies. In August 2016, a number of Chinese authorities, including the PBoC, Ministry of Finance, National Development and Reform Commission, Ministry of Environmental Protection, China Banking Regulatory Commission, China Securities Regulatory Commission, and China Insurance Regulatory Commission, issued the *Guiding Opinions on Building a Green Financial System*, which defines green finance as the provision of financial services for project financing, project operations, risk management, and other areas related to environmental protection, energy conservation, clean energy, green transportation, and green buildings.

In February 2019, the National Development and Reform Commission published the *Green Industry Guidance Catalogue (2019 Edition)*, which lists industries such as energy conservation and environmental protection, clean energy, ecological environment, green infrastructure upgrades, and green services as key industries that need to be expanded as part of the efforts to implement green development, with the corresponding green financing support. The industries listed in this catalogue encompass solar, wind, and other clean energy industries that need to be vigorously developed during the energy transformation, including photovoltaic (PV) manufacturing (polysilicon, silicon wafers, cells, modules), wind power manufacturing (complete machines and components), energy storage manufacturing (lithium-ion batteries, lead-carbon batteries, and other new-type energy storage technologies), and various stages of the hydrogen energy industry (production, storage, transportation and fuel cells). Additionally, the catalogue covers new power system industries, distributed and centralised new energy and clean energy development and utilisation projects, such as PV, offshore and onshore wind power, various biomass power generation, geothermal power generation and thermal utilisation, nuclear power, hydrogen refuelling stations, charging piles, and other construction, operation, and maintenance projects. Green credit holds a dominant position in China's green financing. To cultivate a synergistic policy infrastructure that champions green growth and energy transition, pertinent institutions have refined the directives for commercial banks' green investments, drawing upon the *Green Industry Guidance Catalogue (2019 Edition)*. In tandem, there have been significant updates to the *Green Credit Guidelines*, the *Green Credit Statistical System*, and the *Green Credit Evaluation System*, ensuring their alignment with the evolving landscape of sustainable finance.

Green bonds also play a significant role in China's green financial system. Since 2020, the PBoC and other departments have sought opinions from professional institutions and the public regarding the *Green Bond Support Project Catalogue (2020 Edition)*. By fully incorporating feedback, the new *Green Bond Support Project Catalogue (2021 Edition)* was developed. This updated catalogue has several distinctive features. Firstly, it no longer supports clean utilisation projects for fossil fuels such as coal, adopting the internationally accepted principle of "no significant damage" to strengthen the carbon emission reduction constraint. Secondly, it unifies green identification criteria for projects supported by green bonds, reduces the costs of green bond issuance, trading, and management, and improves the pricing efficiency of the green bond market. Thirdly, in terms of the classification of green bonds, the secondary and tertiary directories are consistent with international mainstream green asset classification standards. This helps domestic and foreign entities to identify, inquire, and invest in green assets. The quaternary directory is consistent with the tertiary directory of the *Green Industry Guidance Catalogue (2019 Edition)* issued by the National Development and Reform Commission. This is conducive to green industries to receive "list-type" financial services. Moreover, the *Green Bond Support Project Catalogue (2021 Edition)* reserves space for green bonds to support green agriculture, green buildings, water conservation, and more. The release of the *Green Bond Catalogue (2021 Edition)* highlights China's focus on green and low-carbon development strategies and energy transformation.

In recent years, China's insurance industry has also been actively involved in extending its support for carbon peaking, carbon neutrality, and energy transformation. The insurance industry has expedited its efforts to conduct research and development aimed at creating green insurance products and improving service standards, particularly in the areas of new energy development, green low-carbon technology research and application, and biodiversity conservation. Furthermore, regulatory authorities responsible for overseeing the insurance industry are working to establish criteria and benchmarks to assess green insurance statistics, ensure efficient use of green capital, and evaluate the effectiveness of green insurance policies.

Some provinces and cities that have launched green finance pilot zones, have also proposed incentive measures, such as interest subsidies, fund rewards, and preferential loan support, in the process of building local green finance systems. These measures support the green and low-carbon energy transformation and the green development of related industries.

Meanwhile, China has also initiated research in support of the green and low-carbon development of traditional energy industries, in accordance with the requirements of the "1+N" policy system for peaking carbon and achieving carbon neutrality and accelerating the promotion of fully green development of the economy and society, through transformational finance. In February 2022, the Ministry of Industry, and Information Technology and three other departments jointly issued the *Implementation Guidelines for Energy Conservation and Carbon Reduction Upgrading in Key Areas of High Energy Consumption Industries (2022 Edition)*. This document proposes energy conservation and carbon reduction upgrading plans for 17 key areas in industries such as building materials, petrochemicals, steel, and non-ferrous metals. It provides a path for effectively improving the energy efficiency level of these key industries, reducing energy consumption intensity and carbon emission intensity, and accelerating the green and low-carbon transformation of energy-intensive industries. Additionally, it serves as a basis for determining green finance support for the green and low-carbon transformation of energy-intensive industries.

To support and promote energy transformation, China continuously improves the incentive and constraint mechanisms during its green finance policy implementation. This allows for more and more financial resources to flow to green and low-carbon fields that are associated with energy transformation.

Regarding China's green credit allocation, in 2022, the loan balances for the green infrastructure upgrade sector, the clean energy sector, and the energy conservation and environmental protection sector stood at RMB 9.8 trillion, RMB 5.7 trillion, and RMB 3.1 trillion respectively. This reflects year-on-year increases of 32.8%, 34.9%, and 59.1%. Delving into sector-specific details, the balance of green loans within the electricity, heat, gas, and water production and supply industry reached RMB 5.6 trillion in 2022, marking a 27.4% increase from the previous year. Meanwhile, the transportation, warehousing, and postal services sector saw green loan balances climb to RMB 4.6 trillion, up 10.8% year-on-year. The allocation of green credit in these sectors is intricately linked to initiatives aimed at energy transformation, substitution, conservation, and the enhancement of energy efficiency.

Driven by China's green industry and green finance policies, nearly 70% of the green funds have been allocated to the low-carbon energy conservation field. In 2020, there were 86 new green funds established and registered in China, with 68% of these investments channelled into the low-carbon energy conservation area, thereby leading the field. Investments in ecological and environmental protection accounted for 30%, with 38 funds, while the circular economy sector attracted a modest 2% with just two funds. Looking ahead, the investment strategy for China's green funds is set to become more targeted, with expectations for a continued expansion in both investment institutions and their objectives.

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China Energy Transformation Outlook 2023