China Energy Transformation Outlook

2024

Energy Research Institute of Chinese Academy of Macroeconomic Research

Implementing Unit

中国宏观经济研究院 能源研究所
Energy Research Institute of Chinese Academy of Macroeconomic Research

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Ea Energy Analyses

COLUMBIA | SIPA Center on Global Energy Policy

Unless specified, the data in this report comes from the CETO model database and related analyses.

Feedback on the China Energy Transformation Outlook 2024 report is welcome and should be sent to ceto2024@cet.energy.

"In meeting the climate challenge, no one can be aloof, and unilateralism will get us nowhere. Only by upholding multilateralism, unity and cooperation can we deliver shared benefits and win-win for all nations."

President Xi Jinping
Speech at the Climate Ambition Summit
12 December 2020

" We need to seize the opportunity and build on the sound momentum generated to promote the high-quality development of China's new energy. With greater efforts to provide secure and reliable energy support for China's modernisation, we can significantly contribute to building a clean and beautiful world."

Xi Jinping, General Secretary of the Communist Party of China
Speech at the 12th Collective Study Session of the Politburo of the Central Committee of the Communist Party of China (CPC)
29 February 2024

Preface

On 22 September 2020, at the general debate of the 75th session of the United Nations General Assembly, President Xi Jinping made a significant announcement, that China will "aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060". Over the past four years, various regions and departments in China have comprehensively advanced efforts to reach carbon peaking and carbon neutrality. Through the robust implementation of the "ten major peaking carbon dioxide emissions actions", China has undergone unprecedented changes in various aspects of the economy and society.

At the same time, the situation of global climate change has become increasingly severe in recent years. Frequent extreme weather events, such as floods and heatwaves, are threatening the economic and social development, livelihoods, and secure electricity supply of many countries, including China, and are disrupting daily life. We call on all countries to fully recognize the severity of the global climate crisis and the urgency of global energy transformation. Practical and effective measures must be taken to unite and collectively combat climate change to safeguard our planet.

The *China Energy Transformation Outlook 2024* (CETO 2024) reflects China's latest development situation and, while analysing China's path towards achievement of its peak carbon and carbon neutrality targets, explores the potential impact of enhanced international cooperation on China's energy transformation. Through two scenarios, the report examines the technological pathways and prospects of China's energy transformation under different international cooperation environments. In addition to the scenario analyses, CETO 2024 also carries out thematic studies on hot topics such as building a new energy system, low-carbon industrial transformation of industry, and P-t-X. International partners, including **Danish Energy Agency** (DEA) and the **Centre for Global Energy Policy** (CGEP) of Columbia University provided technical support for the model analyses and thematic studies, providing important support for China to understand the latest progress of the global energy transformation and learn from the latest international experience.

CETO 2024 is an annual think-tank research report that is consistently updated to reflect the latest developments in China and incorporate the most recent assessments of future technological advancements. I sincerely hope that this report will serve as a useful reference for both China and the global community in formulating strategic energy strategies and major policies. By doing so, it can help countries reduce disputes, strengthen cooperation among countries, and collaboratively address the global challenge of climate change.

I would like to express my sincere gratitude to entire team of the **Energy Research Institute** (ERI) and other Chinese participating organizations for their unremitting efforts in researching and drafting this report. Special thanks go to the relevant departments of the **National Development and Reform Commission** (NDRC) and the **National Energy Administration** (NEA), for their valuable feedback and suggestions, which significantly enhanced the report. I also extend my sincere appreciation to the **Danish Energy Agency**, the **Centre for Global Energy Policy** of Columbia University, and **Ea Energy Analyses** (Ea) for their strong support and insightful contributions to this research. Lastly, I deeply thank our long-term partner, the **Children's Investment Fund Foundation** (CIFF), for their ongoing financial support to the Energy Research Institute to conduct this work over years.

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Abbreviations

APEC	Asia-Pacific Economic Cooperation
BCNS	Baseline Carbon Neutrality Scenario
BREP	Belt and Road Energy Partnership
bcm	billion cubic metres
BECCS	Bioenergy with Carbon Capture and Storage
BIPV	Building-Integrated Photovoltaics
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CCUS	carbon capture, utilisation, and storage
CGEP	Center on Global Energy Policy at Columbia University
CIFF	Children's Investment Fund Foundation
CETO	China Energy Transformation Outlook
CETO 2024	China Energy Transformation Outlook 2024
CMA	China Meteorological Administration
CHP	combined heat and power
CHP	combined heat and power
CPC	Communist Party of China
CGE	Computable General Equilibrium
CfD	Contracts for Difference
DEA	Danish Energy Agency
DPA	Defence Production Act
DOE	Department of Energy
DAC	Direct Air Capture
Ea	Ea Energy Analyses
EAF	electric arc furnace
EVs	electric vehicles
EV-V2G	electric vehicles with vehicle-to-grid
EIA	Energy Information Administration
ERI	Energy Research Institute
EPC	engineering procurement construction
ECS	European Committee for Standardisation
EIB	European Investment Bank
FYP	Five-Year-Plan
GADC	Global Annual to Decadal Climate Update
GHG	greenhouse gas
GDP	gross domestic product

HTGR	High-temperature gas-cooled reactor
HSCW	hot-summer/cold-winter
HSCW	hot-summer/cold-winter
ICNS	Ideal Carbon Neutrality Scenario
IRA	Inflation Reduction Act
IIJA	Infrastructure Investment and Jobs Act
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
IMF	International Monetary Fund
ISO	International Organisation for Standardisation
IRENA	International Renewable Energy Agency
IAA	Investing in America Agenda
JTF	Justice Transition Fund
KATS	Korean Agency for Technology and Standards
KSA	Korean Standards Association
LDCs	least development countries
WMO	Meteorological Organisation
MtCO2e	million tonnes of CO2-equivalent
Mtce	million tonnes of coal equivalent
METI	Ministry of Economy, Trade and Industry
MEM	Ministry of Emergency Management
MIIT	Ministry of Industry and Information Technology
NBS	National Bureau of Statistics
NCC	National Climate Centre
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NDCs	Nationally Determined Contributions
NZE	Net Zero Emissions Scenario
NEVs	new energy vehicles
RFNBOs	Renewable fuels of non-biological origin
OECD	Organization for Economic Cooperation and Development
PEDF	Photovoltaic, Energy storage, Direct current, Flexibility
PUE	Power Usage Effectiveness
PwC	Price Waterhouse Coopers
PEM	proton exchange membrane
PSLF	Public Service Loan Forgiveness
R&D	research and development
ROI	return of investment

ERI-EDO	The Electricity and District Heating Optimisation Model
ERI-LEAP	The End-Use Energy Demand Analysis Model
CETPA	The Energy Transformation Socio-Economic Impact Assessment Model
ERA5	The fifth generation European Centre for Medium-Range Weather Forecasts
IEC	International Electrotechnical Commission
tce	tonnes of standard coal
UNCTAD	United Nations Conference on Trade and Development
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WEF	World Economic Forum

Reading guidance for the China Energy Transformation Outlook 2024

The China Energy Transformation Outlook 2024 (CETO 2024) consists of a summary and three major sections (download website https://www.cet.energy).

The *Summary* of *China Energy Transformation Outlook 2024* encapsulates the main report's key findings and communicates the core essence, allowing it to be read independently.

In the full report

Part I provides a brief analysis of the global climate change and energy transformation landscape (Chapter 1) and reviews the significant changes in China's system of energy production and consumption over the past decade (Chapter 2).

Part II presents scenario analyses of the outlook for China's energy system transformation up to 2060, with the goal of achieving carbon neutrality.[1] This section is divided into four chapters. Chapter 3 summarises the outlook for China's energy system transformation, including the scenario design and main conclusions. Chapter 4 explores the outlook for energy transformation for end-use sectors, including industry, buildings, and transportation. Chapter 5 analyses the outlook for power sector transformation, with a focus on focusing on the development prospects of renewable energy and flexible resources. Chapter 6 examines the impact of China's energy transformation on its economic transformation and social development.

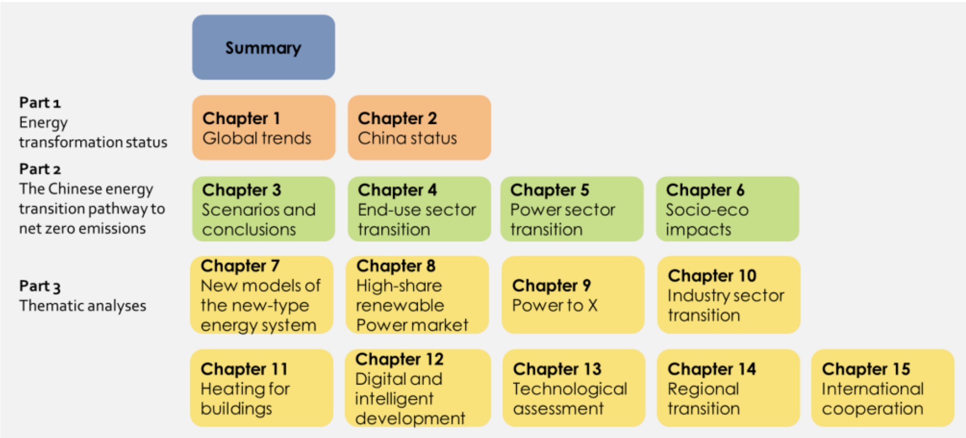
Part III addresses key topics that have undergone significant changes in recent years and attracted widespread attention in China. It is divided into nine chapters. Chapter 7 describes the new energy models and new business forms related to China's efforts to build a new energy system. Chapter 8 discusses how to build a power market compatible with a high penetration of renewable energy. Chapter 9 showcases the latest developments in the production of Power to X (incl. hydrogen, ammonia, and methanol fuels) in China and globally. Chapter 10 analyses the prospects for low-carbon, zero-carbon industrial transformation in China. Chapter 11 examines the pathways for low-carbon transformation of space heating in China's buildings. Chapter 12 showcases the latest policies and cases of China's promotion of digital and intelligent development in the energy sector. Chapter 13 evaluates the synergies of the effects of key technologies in reducing environmental pollution and carbon emission. Chapter 14 introduces the typical approaches taken by two provinces in central and western China (Shanxi and

[1] Unless otherwise stated, the relevant data in Part II of the report (including base year data) are based on the CETO database and model measurements.

Yunnan) in promoting the energy transformation. Finally, Chapter 15 analyses the key areas of China's international cooperation in strengthening the energy transformation.

The analyses in Part III provide more extensive policy, information and technical support for the model development and transformation pathway analysis in Part II.

Figure 1 Structure of the China Energy Transformation Outlook 2024



For readers interested in the modelling analysis, Part II of CETO 2024 provides a more comprehensive and in-depth exploration of the analysis process and detailed conclusions for each key sector. For those interested in specific topics, Part III offers standalone chapters that can be read individually. Chapters 9, 10, and 11 are fully translated to English. Summaries are provided for the other chapters in Part III. For details, please refer to the Chinese version of this report.

We hope our outlook report helps you better understand the latest developments in China's energy transformation and discover new opportunities for enhanced cooperation. Enjoy your reading! We warmly welcome your feedback on the report's content. Please send your comments to ceto2024@cet.energy.

The CETO24 report reflects the research findings of the China Energy Transformation Outlook (CETO) project team and does not represent the views or positions of the supporting organisations or governments.

Summary: Key findings and recommendations of the scenario analysis

Research Background

The China Energy Transformation Outlook 2024 (CETO 2024) investigates the pathway and prospects for China's energy transformation up to 2060. China has set the strategic goal of building a fully modernised socialist society by mid-century. The first stage is to basically realise socialist modernisation from 2020 through 2035. The second stage is to build China into a great modern socialist country that is prosperous, strong, democratic, culturally advanced, harmonious, and beautiful from 2035 through the middle of this century. With its vast population, China aims to achieve common prosperity for all while emphasising the balance between material and spiritual progress, harmony between humans and nature, and a commitment to peaceful development. As a result, China's modernisation shares common traits with other countries but also includes unique aspects based on its national conditions.

China is committed to reaching peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. This commitment is an important component of China's modernisation strategy and an important contribution to addressing global climate change. The promotion of China’s energy transformation is both an effective response to the climate change challenge and an opportunity to transform its economic structure and enhance industrial competitiveness, making China's modernisation more harmonious, prosperous and sustainable. This study details the blueprint for building a new energy system by integrating China's energy transformation with its modernisation in Chinese fashion. It draws on the best international experience and integrates this with China's economic and social development and carbon emission targets and visions.

CETO 2024 reviews China's energy transformation over the past decade, highlighting its latest achievements. It systematically analyses the prospects for the transformation of energy production and consumption while exploring pathways and technological solutions for achieving net-zero carbon emissions under different scenarios.

Considering China’s specific circumstances, the research group used three models—China's End-Use Energy Demand Analysis Model (ERI-LEAP), the Electricity and District Heating Optimisation Model (ERI-EDO), and the Energy Transformation Socio-Economic Impact Assessment Model (CETPA)—to analyse the impacts of end-use energy consumption, power and heat supply, and the socio-economic and environmental effects of the energy transformation. The overall aim is to support the fulfilment of simultaneous imperatives of economic development, social development, energy security, and carbon emission reduction.

Two scenarios for the energy transformation

The Project Team set up two scenarios for its analysis of China's energy transformation towards 2060. Both scenarios share the goal of China reaching peak carbon emissions before 2030 and achieving carbon neutrality before 2060. Given the growing urgency of global climate change and the increasing complexity and volatility of the international political and economic landscape, the group developed the **Baseline Carbon Neutrality Scenario (BCNS)** and **the Ideal Carbon Neutrality Scenario (ICNS)**.

The Baseline Carbon Neutrality Scenario (BCNS) envisions that, with significant efforts, China will achieve its medium- and long-term development goals, including the dual carbon objectives. The international political and economic landscape grows more complex with recurring geopolitical conflicts. In some countries, addressing climate change may become a lower priority. Climate-change-related trade disputes will likely rise, complicating agreements. Collaboration on low-carbon and zero-carbon technologies will face significant challenges. It is more difficult to reduce the cost of new technologies due to global market segmentation. In this international environment, China stays committed to its goals of peaking CO_2 emissions before 2030 and achieving carbon neutrality before 2060. By advancing its medium-and-long term efforts, China's energy transformation makes a decisive contribution to reaching a carbon-neutral society.

The Ideal Carbon Neutrality Scenario (ICNS) envisions that, through substantial efforts, China's medium- and long-term economic and social development goals, along with its carbon neutrality and peak emissions targets, are achieved on schedule. The severity of global climate change has spurred a strong international response, with countries prioritising accelerated energy transformation despite occasional political and economic conflicts in certain regions. Despite occasional political and economic conflicts in certain regions, most countries remain committed to addressing climate change by enhancing cooperation in areas such as politics, economics, trade, industry, technology, finance, human resources, and knowledge and data sharing. This collective effort aims to reduce the cost of developing low-carbon, zero-carbon, and carbon-negative technologies, enabling their large-scale adoption sooner and at a lower cost. This will also support developing countries with limited capacity, reinforcing China's role as an important player in global cooperation. As a member of the "global village", China will provide technology, equipment, and capacity-building support to other countries to the best of its ability. Together, these efforts will drive the global energy transformation and preserve the shared home of humankind.

Main findings

The main conclusions of the group through the scenario analysis are as follows:

With significant efforts, the energy transformation can make a decisive contribution to China's efforts to achieve a carbon-neutral society before 2060. By 2060, China's economy should grow between 3.3 to 3.6 times its 2020 level. Total primary energy consumption (accounted using the calorific value method) first increases and then decreases, with consumption falling by about one-third from its peak by 2060**. Under the Baseline Carbon Neutrality Scenario (BCNS) and the Ideal Carbon Neutrality Scenario (ICNS), with the accelerated development of energy transformation technologies (including negative carbon technologies such as carbon capture) and related industries, China's energy system can achieve net-zero carbon emissions before 2060,** paving the way to make the Chinese society as a whole carbon neutral before 2060.

Through modelling analysis and thematic research, the group came to five important conclusions:

I. Energy conservation and efficiency are prerequisites for the energy transformation, and sustained electrification is an effective way to move towards carbon neutrality.

Without effective energy conservation, the energy transformation would demand significantly **greater** deployment of green energy sources, making it difficult to achieve the necessary pace. Therefore, energy conservation and efficiency are essential prerequisites and the foundation for the successful energy transformation. **In the context of energy conservation and efficiency,** the narrow definition focuses on improving the technical efficiency of energy supply and utilisation, while the broader definition encompasses enhancing the economic efficiency of energy, reducing the dependence of economic growth on energy consumption. China's primary energy consumption (calculated using the calorific value method) will first rise and then fall, and primary energy consumption will drop by about one-third from the peak by 2060. **In terms of electrification**, **direct electrification** refers to the direct use of electricity in the end-use sector, and **electrification in a broader sense includes secondary electrification**, e.g. the use of electricity to produce synthetic fuels, or commercialised heat supply generated from electricity, to satisfy end-use demands for energy. In 2023, China's direct electrification and broad electrification rates were around 28%, and it is projected that **China's direct electrification rate in 2060 will increase to between 59% and 62%, while the broad electrification rate will increase to between 79% and 84%**. The transportation sector will experience the fastest growth in electrification, while the building sector will achieve the highest overall electrification rate. In 2060, some fossil fuels will still be needed to support certain industries, freight transport, and aviation, these fields with the greatest difficulty in reducing emissions. Based on the modelling results, enhancing international cooperation on the energy transformation will help promote the latest energy-efficient and electrification technologies both in China and globally, accelerating the low-carbon transformation in the industrial, building, and transport sectors.

II. Building a power system with wind and solar as the mainbody is a necessary choice for energy transformation.

Decarbonising the energy supply is a key of energy transformation, and replacing fossil fuel power with non-fossil sources is the core priority. In 2023, non-fossil sources comprised 53.9% of China's power generation capacity, while fossil sources accounted for 46.1%. **By 2060**, China's total installed power generation capacity needs to reach between 10,530 GW and 11,820 GW, about four times the 2023 level. The installed renewable energy power capacity will reach about 96%, and the renewable share of power generation will reach 93%-94%. In 2060, the installed capacity of nuclear power and pumped storage will be needing to reach 180 and 380 GW, respectively. Bioenergy with Carbon Capture and Storage (BECCS) will have an installed capacity of more than 130 GW. Energy transformation should always adhere to the principle of "establishing the new before abolishing the old", on the basis of the growth of new and renewable energy power generation capacity and the gradual enhancement of power system control capabilities, coal power gradually shifts from a baseload source to a regulating and backup power source while being naturally decommissioned. Modelling results show that strengthening international cooperation on energy transformation will help China to further improve its non-fossil energy supply capacity and grid security.

III. Building a highly intelligent power grid is a central measurement to establishing a new type of power system.

The construction of a new power system is a core component of China's energy transformation. A coordinated nationwide approach must be adopted, integrating all resources—generation, grid, demand, storage, and hydrogen—to create a power grid that enables large-scale interconnection as well as lower-level balancing. **Firstly, the grid layout shall be optimised**, with the completion of the national backbone grid by 2035, enabling West-to-East and North-to-South power transmission with inter-regional mutual support. By utilising digital and intelligent technologies, the grid will be able to adapt flexibly to changes in power supply and demand. By 2060, the total scale of electricity exports from the Northwest, Northeast, and North China regions will increase by 140% to 150% compared to 2022. **Secondly, continuously enhancing the construction of distribution grids** to adapt large-scale distributed new energy and promote the transformation of distribution grids from a unidirectional distribution grid without power resources into a two-way interactive systems with power resources, focusing on locally consumed renewable energy sources for industrial, agricultural, commercial and residential use, to create numerous zero-carbon distribution grid hubs to provide strong support for the development of more than 5,000 GW of distributed wind power and solar PV. **Thirdly, coupling of multiple energy networks will be advanced**, drawing on international cooperation experiences to create a new-type energy network where electricity and hydrogen serve as key hubs, fully integrating power, heat, and transportation systems. By 2060, the scale of green hydrogen will need to reach 340–420 million tonnes of coal equivalent (Mtce), with hydrogen and e-fuel production through electrolysis will become an important means to support grid load balancing and facilitate seasonal grid balancing. Chemical storage capacity will reach 240–280 GW, and the number of electric vehicles will reach 480–540 million, with vehicle-to-grid interaction capacity reaching 810–900 GW, providing real-time responsiveness to the power system.

IV. Scientific and technological innovation is the driving force of the energy transformation, and new energy productivity breeds vast market opportunities.

The development of new productivity is a distinctive feature of China's energy transformation. Low-carbon, zero-carbon, and negative-carbon technologies, equipment, and industries related to energy production and consumption offer broad market potential and present significant investment opportunities. **From the perspective of energy equipment demand**, by 2060, China's installed wind and solar power capacity is expected to reach around 10,000 GW. The annual investment demand for power supply and heat supply equipment such as wind power, solar power and heat pump equipment in China will grow from approximately 2 trillion RMB per year in 2023 to around 6 trillion RMB per year by 2060, with cumulative investment needs over the next 30 years exceeding 160 trillion RMB. **From the perspective of energy-using equipment demand**, the energy transformation will require China to update or retrofit energy-using equipment across various sectors, including industry, buildings, and transportation, over the next 30 years. Low-carbon and zero-carbon equipment such as electric arc furnaces for steel production, hydrogen-based steelmaking furnaces, green hydrogen chemical processes, ultra-low energy buildings, high-efficiency heat pump heating systems, electric vehicles, and fuel cell vehicles will generate unprecedented market demand. **From the perspective of zero-carbon and negative-carbon technologies needed to achieve carbon neutrality,** the development of technologies such as carbon capture and storage (CCS) and industrial carbon dioxide recycling is an essential means of reaching carbon neutrality. Research and planning for these technologies must begin now. Over the next 30 years, China’s energy system will enter an accelerated phase of equipment upgrades and retrofits, with the scale of demand for such improvements continuing to grow, providing sustained driving force for China’s economic growth. Strengthening international cooperation on the energy transformation will help China and other countries reduce the manufacturing, service, and usage costs of new energy transformation technologies, enabling both China and the world to achieve carbon neutrality sooner.

V. Energy system and mechanism reforms must continue to deepen while simultaneously establishing a legal framework to drive the energy transformation.

The energy transformation requires reforms in the energy system as a fundamental prerequisite. **From the perspective of energy legislation**, the laws and regulations developed during the era of fossil fuel dominance are no longer adequate for the needs of the energy transformation. A new legal system aligned with the goals of peak carbon and carbon neutrality must be established, with clear accountability, strengthened legal obligations, and formulation of incentive and penalty mechanisms. **From the perspective of energy market reform**, it is necessary to break down regional barriers, establish a unified national power market, and gradually build a market system that accommodates the characteristics of high renewable energy penetration. **From the perspective of energy price reform**, carbon pricing should play a guiding role in directing energy activities, while reforms in the pricing of electricity, coal, oil, and natural gas should continue. **From the perspective of foundational systems like energy statistics**, there is a need to improve data and statistics for non-fossil energy sources such as renewable energy power and heat, biomass, and hydrogen. The green electricity certificate system must be refined, and certification systems for green hydrogen, green ammonia, and green methanol should be established. Strengthening international cooperation on the energy transformation will benefit China to facilitate in-depth exchanges with countries around the world on legislative and energy governance, providing better policy support for China's energy transformation.

China faces a series of difficulties and challenges in advancing its energy transformation. **The main ones include**: **First, the weight of heavy industries in the economic structure.** Energy-intensive industries such as steel, cement, and chemicals hold a significant position in China's economy, making economic restructuring and industrial transformation both difficult and demanding. **Second, coal-dominated energy structure.** As the largest energy consumer in the world, more than half of China's energy consumption comes from coal. There is no historical precedent for bypassing the "oil and gas era" and directly replacing coal on a large scale with new and renewable energy sources. **Third, rapid power demand growth increases the difficulties of power system transformation.** In recent years, China's electricity demand has grown rapidly. The power system must not only become greener and more low carbon but also ensure security and affordability. Particularly in recent years, while power demand has surged, renewable energy development is constrained by limited land availability, insufficient system capacity for integrating renewable energy, and relatively high storage costs, making further acceleration difficult. **Fourth, the market-driving force of energy transformation needs to be strengthened**. For a long time, carbon-intensive energy products in China have been relatively cheap, while low-carbon energy is more expensive, with significant regional differences in energy prices. Using market mechanisms to drive the energy transformation is a particularly challenging task.

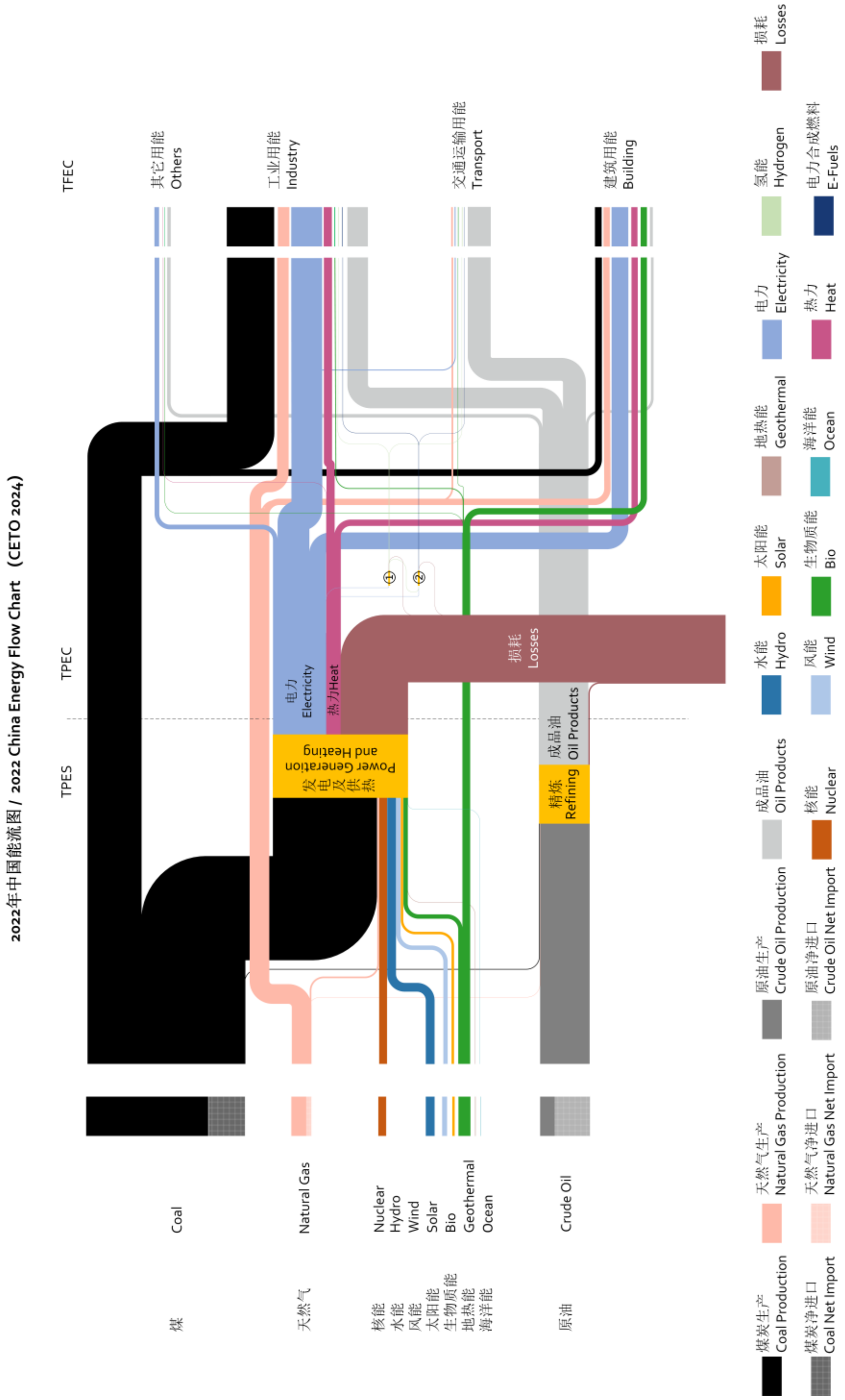
Looking ahead, there are uncertainties about China's low-carbon energy transformation. The main uncertainties are: Firstly, there is significant uncertainty around future adjustments to the industrial structure. Changes in the production of energy-intensive products such as steel, cement, electrolytic aluminium, and chemicals will have a major impact on China's energy supply, demand, and transformation prospects, making accurate predictions difficult at this stage. Secondly, the extent to which digitalisation and smart technologies will drive electricity demand growth in China and the scale of power consumption related to these technologies is currently hard to assess. Thirdly, the maturity, security, and economics of zero-carbon and carbon-negative technologies in the medium and long term remain uncertain and difficult to predict. Fourthly, the prospects for industrial development, international trade and industrial chain supply chain development related to international cooperation on energy transformation are still subject to certain uncertainties.

In summary, China's energy transformation is a long-term and challenging societal project. Unlike Europe and the United States which have long since peaked their carbon emission and are moving towards carbon neutrality, within less than forty years, China must first surpass its peak carbon emissions and then achieve carbon neutrality. The challenges are immense, and it is a difficult task. This requires policymakers to face these challenges head-on, find solutions, and seek clarity amid uncertainty, ensuring that China's energy transformation stays on the right path and progresses steadily.

China must simultaneously advance its energy transformation across five areas: electrify energy consumption and improve energy efficiency, decarbonise energy supply, enhance interaction between energy supply and demand, commercialise energy technologies, and modernise energy governance. At the same time, China should strengthen international cooperation on energy transformation, exploring pathways together with the global community. In doing so, China will not only ensure the smooth progression of its own energy transformation but also contribute significantly to the global effort.

China energy flow charts

Figure 2 China energy flow chart in 2022



注 Notes: ①电制氢 Hydrogen Production; ②电制合成燃料 E-Fuels Production; ③电制热 Heat Production; ④碳捕集 Carbon 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 China energy flow chart in 2060 – BCNS

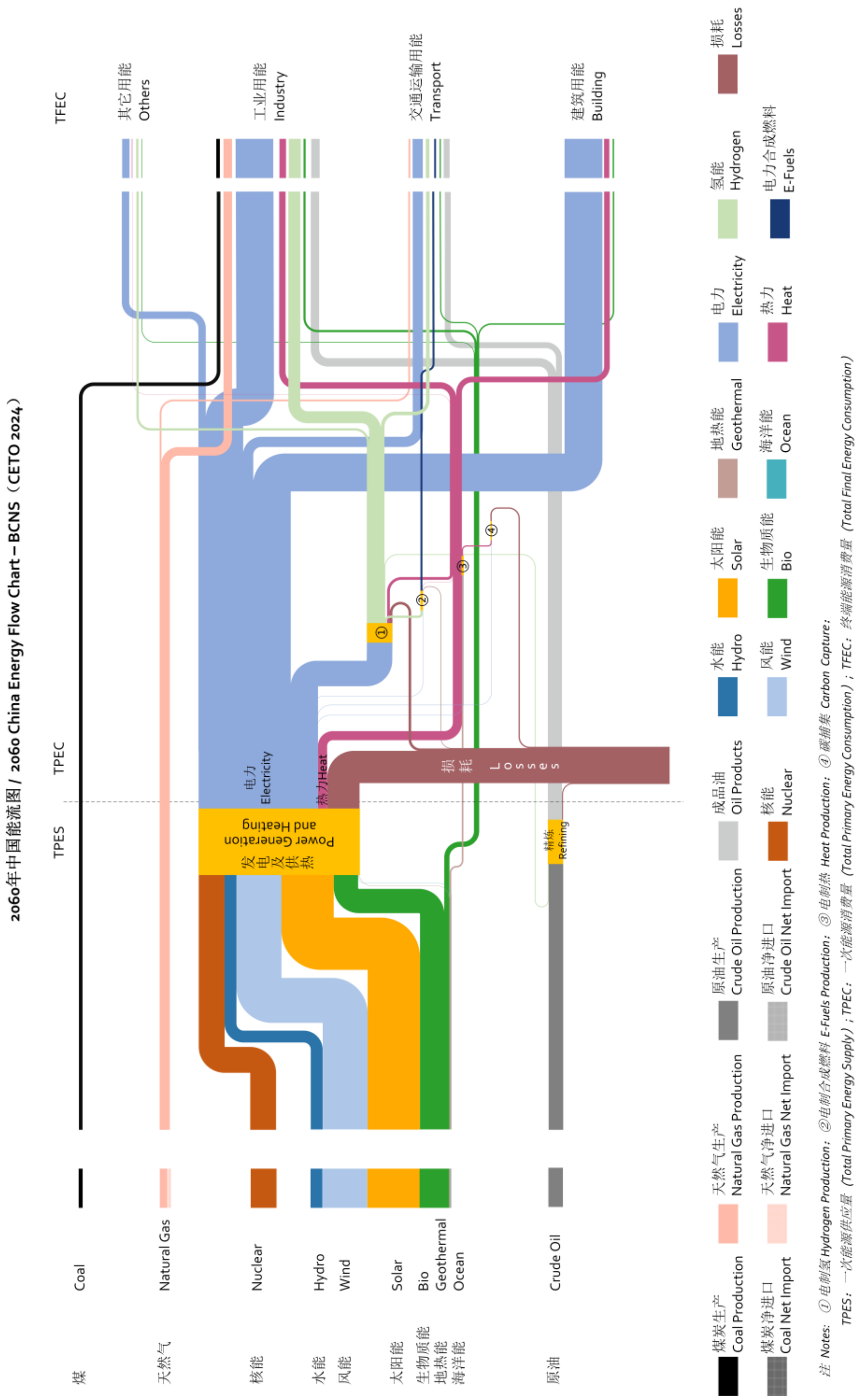
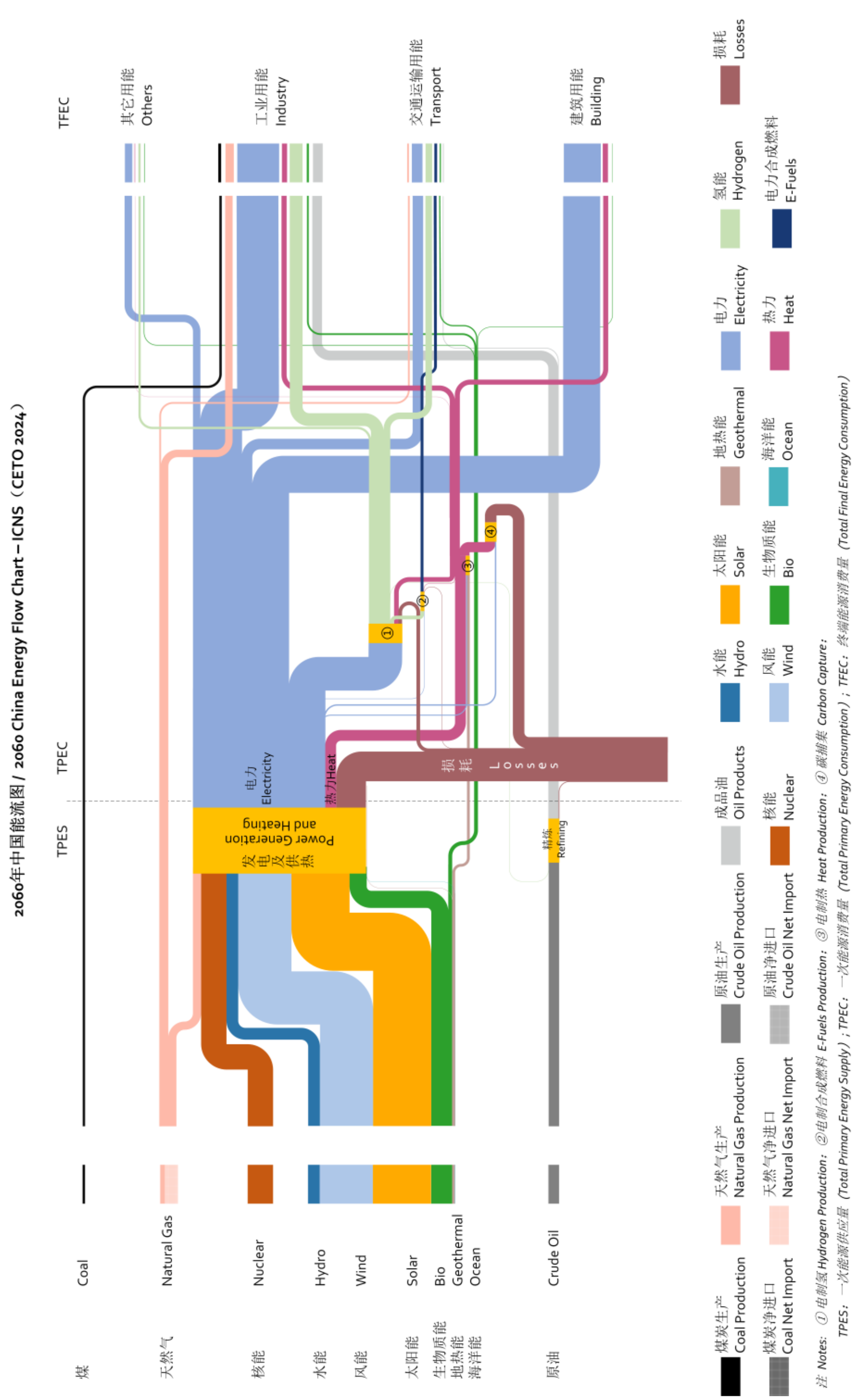


Figure 4 China energy flow chart in 2060 - ICNS



Part I Global and Chinese energy transformation status

1 Progress in global energy transformation

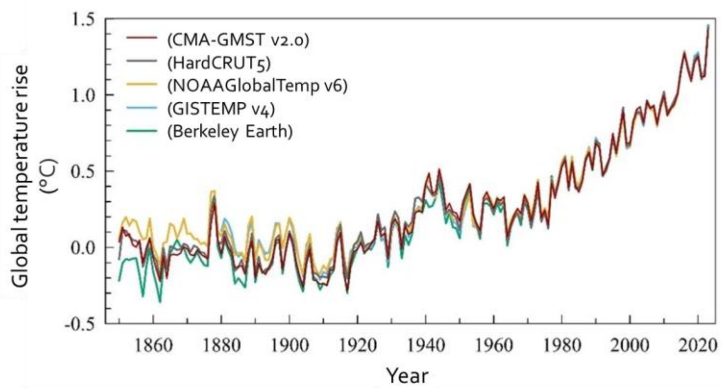
1.1 Global climate change situation and its impact on energy

Global climate change situation: temperature rise accelerated and impact intensified

Global climate change is one of the major challenges faced by the world today. In early 2024, the World Meteorological Organisation (WMO) issued a press release formally recognising 2023 as the hottest year since meteorological records began. In March, the WMO released its *Global Climate Situation 2023* report, which showed that the global average temperature in 2023 will be 1.45°C higher than pre-industrial levels, and that records for greenhouse gas (GHG) levels, surface temperature, ocean heating and acidification, sea level rise, and retreat of Antarctic marine ice caps and glaciers are once again being broken, in some cases dramatically, and the rate of change is set to accelerate (as shown in Figure 1-1). In June, the *Global Annual to Decadal Climate Update* (GADC) report released by WMO projected that global average near-surface temperatures will be between 1.1°C and 1.9°C above the 1850-1900 baseline each year from 2024 to 2028. According to the fifth generation European Centre for Medium-range Weather Forecasts (ERA5) dataset, the global daily average temperature on 22 July reached a record high of 17.15°C, beating the previous record of 17.09°C set on the previous day and the record of 17.08°C set a year earlier on 6 July 2023. On 4 July, the China Meteorological Administration (CMA) released the *China Climate Change Blue Book (2024)*, which noted that China's average temperature also reached a record high since complete meteorological observations were made. The National Climate Centre (NCC) predicts that the average temperature in the next 30 years will reach a record high. The NCC predicts that over the next 30 years, China's regional average extreme maximum temperatures will increase by 1.7 to 2.8°C, with the largest increases in eastern China and western Xinjiang, and that the average number of days with high temperatures and heat waves in China will increase by 7 to 15 days.

The acceleration of global temperature rise indicates an accelerating process of climate change, and the 15 tipping point markers delineated by the Intergovernmental Panel on Climate Change (IPCC) continue to be activated. Nine have been activated as early as 2020, including Arctic sea ice, boreal taiga, Greenland ice sheet, permafrost, Amazon rainforest, Atlantic meridional overturning circulation, West Antarctic ice sheet, warm-water corals, and parts of the East Antarctic. Judging from the current trend, the only six remaining tipping points, including accelerated extinction of species, depletion of groundwater, melting of alpine glaciers, spatial fragmentation, intolerable high temperatures, and uninsurable future are also very difficult for humans to hold on to. Once all 15 climate tipping points are breached, mankind will be confronted with global temperature anomalies, and the frequency of extreme weather events will become more frequent and disorderly, and even no longer suitable for human survival.

Figure 1-1 Global temperature rise after industrialisation (compared to the average level between 1850 and 1900)



Source: China Blue Book on Climate Change (2024)

In fact, since 2024, the frequency, scope and intensity of extreme weather occurrences have further expanded globally. On April 17, Dubai was hit by the worst rainstorm in 75 years, with rainfall in one day equal to the local average of a year and a half, leading to the closure of the Dubai International Airport for three days. On April 27, Guangzhou was hit by strong thunderstorms, locally heavy rainfalls, and tornadoes, which led to five deaths and 33 injured and 141 factories damaged. In northern India, high temperatures in June approached 50 degrees Celsius, with the capital New Delhi experiencing 38 consecutive days of highs of 40 degrees Celsius or more since May 14, resulting in more than 40,000 people suffering from suspected heatstroke and at least 110 deaths. on June 23, the Saudi government issued a news release stating that 1,300 people had died in the country during the Hajj pilgrimage due to the extreme heat, with peaks of temperatures in July and August forecast to soar above 50 degrees Celsius. In July, Brazil's southernmost state, Rio Grande do Sul, was hit by ″80-year floods″ that left at least 171 people dead, more than 800 injured and more than 60 missing. Overall, the frequent occurrence of extreme weather events in the world in 2024 has not only caused huge losses to human society, but also sounded the alarm for addressing climate change. The latest *Global Risks Report* released by the World Economic Forum (WEF) bluntly states that in the next 10 years, the top global risk is not armed conflict or social polarisation, but extreme weather events.

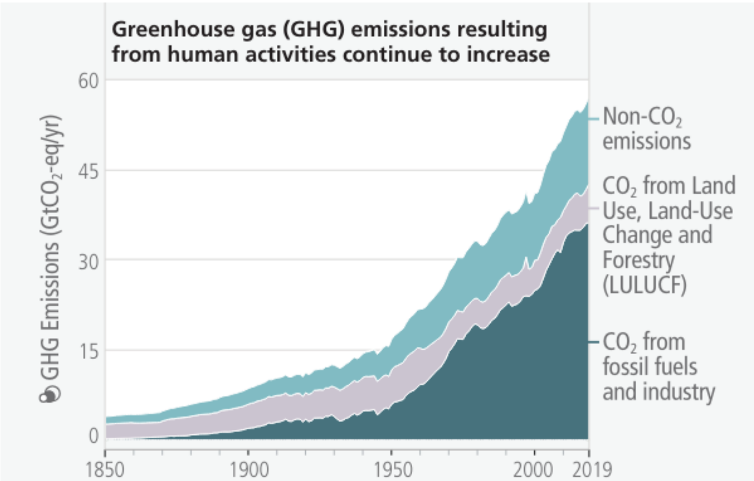
Asia is the region of the world most affected by climate change, with floods and storms causing the highest number of casualties and economic losses, and the impacts of heat waves are being further exacerbated. China has also endured huge economic losses and even human casualties. According to the statistics of the Ministry of Emergency Management (MEM), all kinds of natural disasters in China throughout the year of 2023 caused 95,444,000 person-time to be affected to varying degrees, with 691 dead and missing as a result of the disasters, and 3,344,000 people were relocated in emergencies;

209,000 houses collapsed, 623,000 were seriously damaged, and 1,441,000 were generally damaged; 10,539,300 kilo hectares were affected by crops; and the direct economic losses were RMB 345.45 billion. Policy action to mitigate climate change is urgent.

Carbon dioxide emissions from global energy activities: apparent rebound and continued growth

Human activities are an important cause of climate change, the highest share of GHGs, carbon dioxide, is mainly a product of burning fossil energy, and the long-life infrastructure of fossil fuels puts enormous pressure on the clean and low-carbon transformation of the energy system (as shown in Figure 1-2).

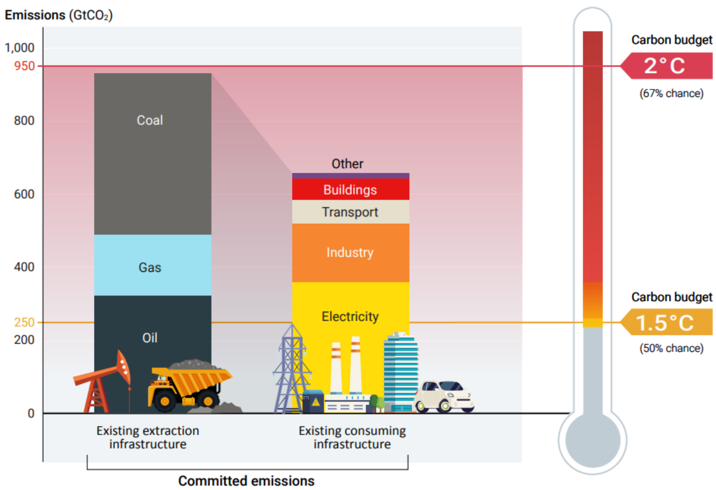
Figure 1-2 Energy consumption and human activities are the primary contributors to global climate change



Source: Climate Change 2023 Synthesis Report, Intergovernmental Panel on Climate Change (IPCC)

According to the *Emissions Gap Report 2023* published by the United Nations Environment Programme (UNEP), energy consumption contributes 86% of global carbon dioxide emissions. To limit global temperature rise to 1.5°C and not exceed, or only marginally exceed, this range, GHG emissions would need to peak by 2025 at the latest, and then decline rapidly, by 43% by 2030 compared to 2019 levels, and by 60% by 2035. However, future CO_2 emissions from existing and planned fossil energy long-life infrastructure globally (around 850 Gt CO_2) already exceed the total cumulative net CO_2 emissions to reach the 1.5°C target and are close to the mean cumulative emissions to achieve the 2°C target. Fossil energy long-life infrastructure will lock society into carbon-intensive lifestyles and practices, affecting the speed of the transformation (as shown in Figure 1-3).

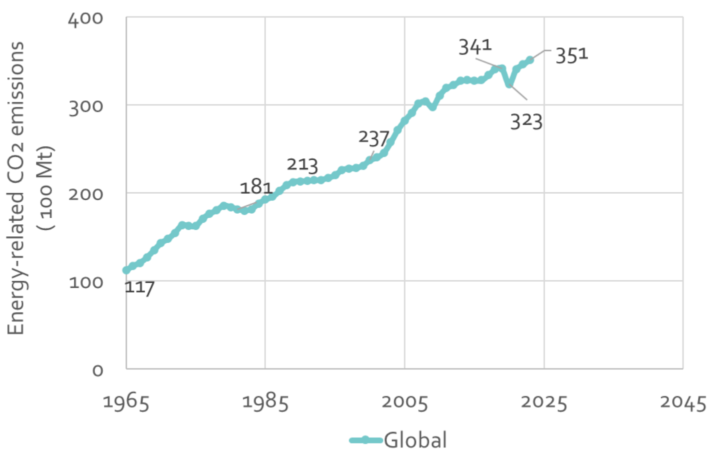
Figure 1-3 Technology lock-in effects affect the speed of energy transformation and climate change



Source: Emissions Gap Report 2023, United Nations Environmental Programme (UNEP)

Global CO_2 emissions from energy activities experience a significant decline in 2020 under the influence of weakened global economic activity caused by the COVID epidemic and, in particular, a significant reduction in the use of fossil fuels. However, with the gradual containment of the epidemic and economic recovery, global CO_2 emissions rebound significantly in 2021 and continue to grow in subsequent years (as shown in Figure 1-4).

Figure 1-4 Global energy-related CO_2 consumptions



The main drivers of the rebound in CO_2 emissions due to global energy activities include the following:

- **First,** the economy is recovering rapidly. As the global economy recovers rapidly from the COVID epidemic, the demand for energy is increasing rapidly, especially the use of fossil fuels, which is directly contributing to increased carbon dioxide emissions.
- **Secondly,** there has been a significant increase in demand for electricity and an increase in the use of coal. Increased emissions from the power system and a shift from natural gas to coal in many regions as a result of soaring natural gas prices have led to a significant increase in coal consumption.
- **Thirdly,** the growth of renewable energy is insufficient. Renewable energy is not growing fast enough to cover the increase in energy demand and thus displace fossil fuels, so carbon dioxide emissions are still on an upward trend.
- **Fourth** is the recovery of transport activities. With the gradual relaxation of outbreak control measures, there has been a gradual resumption of activities in the transport sector, in particular the recovery of international aviation, which has led to an increase in demand for oil and a corresponding increase in carbon dioxide emissions.
- **Fifth** is the growth in emissions from the industrial and construction sectors. Globally increased economic activity in the industrial and construction sectors has led to a corresponding increase in CO_2 emissions.
- **Sixth** is the impact of climate extremes and unusual weather. Unfavourable climatic and weather conditions exacerbate energy demand while reducing the level of renewable energy output, for example, droughts reduce hydropower generation and require more thermal power to supplement the electricity supply, further increasing electricity-related emissions.

Impact of global climate change on energy development: demand growth and pressure on supply

The energy sector is both a major source of GHGs contributing to climate change and a vulnerable sector to climate change, especially as extreme weather phenomena result in increased demand for cooling and heating, tight supply and demand, and pressure on power grids, which challenge the safe and stable operation of energy systems.

Since 2024, extreme weather events have become more frequent and more intense globally, adversely affecting power supply. Beginning in January, South America was hit by a severe drought, which led to a significant reduction in power generation from hydropower plants. Major hydropower plants in Brazil and Paraguay experienced record lows in power generation due to reduced precipitation and runoff. In February, a cold snap in Texas, the United States, drastically reduced natural gas production, resulting in soaring natural gas and electricity prices, and fossil-fuelled power systems struggled to secure supply due to disruptions in transport and production. In April, extreme rainfall and flooding in Europe and East Asia not only impacted hydropower generation, but also caused direct damage to power infrastructure. In Germany and Belgium, severe flooding forced many power facilities to shut down, and in June, high temperatures led to the collapse of power grids in many countries in the Balkans, paralysing power outages and traffic. For China, climate change has reduced annual precipitation in the eastern and southern parts of the southwestern region, while Sichuan and Yunnan, as large hydropower provinces, have a high proportion of hydropower in their energy mix, resulting in insufficient local power supply and limited electricity for domestic and industrial use. China's summer 2024 northern regions have recently experienced widespread high temperatures, and the nation's highest power load is expected to increase by more than 100 GW year-on-year, placing some pressure on power supply. Heavy rainfall and triggered flooding in Dongting Lake in Hunan Province from June to July caused severe damage to power facilities, with power grids in several areas damaged, resulting in power outages and difficulties in power supply.

From a demand perspective, extreme weather events brought about by climate change, such as extreme heat, cold, heavy rainfall and blizzard disasters, on the one hand result in a surge in direct energy or power demand for a short period of time for cooling or heating, and on the other hand, the recovery of the industrial chain and the supply chain in the wake of a disaster implies a large demand for energy. Therefore, global climate change puts higher demands on the resilience of the power system to adapt to dramatic fluctuations in power demand. From the perspective of supply, under the existing technical conditions, renewable energy generation, such as solar PV, wind power or hydropower, is highly dependent on weather and climatic conditions, and weather conditions such as irradiance, wind speed and precipitation directly determine the level of output of wind, solar and hydropower generation; and the security of supply of conventional energy sources is likewise threatened by the obstruction of fuel supply under extreme climatic conditions. Catastrophic weather conditions such as typhoons, high winds, strong convection, rain, snow and ice can even affect the safety of power generation equipment and energy supply networks, and renewable energy power supply is highly unstable. Electricity and energy supplies need to be made more stable and flexible, while increasing their resistance to extreme weather disasters.

Energy transformation is therefore a key way for the world to address climate change and achieve low-carbon development, while climatic conditions equally constrain the energy transformation process. While promoting the energy transformation, the world is strengthening the resilience of energy systems to ensure a smooth and sustainable energy supply under complex and volatile climatic conditions. These additional measures will require the investment of significant financial and technological resources, which will raise the cost of the energy transformation.

1.2 Progress and prospects for the global energy transformation

Green and low-carbon transformation of the global energy system: a growing trend that cannot be reversed

Under the dual pressures of addressing climate change and energy security, and in order to stimulate economic development and create more employment opportunities, governments and multilateral organisations are actively promoting a green and low-carbon energy transformation and implementing international commitments under the Paris Agreement, a trend that has become a global consensus. Major countries or economies, represented by the European Union, China and the United States, have adopted multi-level, multi-disciplinary and all-encompassing policies and actions to accelerate the green and low-carbon energy transformation.

The EU has legally recognised its Nationally Determined Contributions (NDCs) with the Green Deal, and has proposed a "Fit for 55" package and a "REPowerEU" programme, among others. The latter directly sets out a 13% energy efficiency improvement target and renewable energy development targets, including a 13% energy efficiency improvement target for 2030 (compared to the 2020 reference scenario), a 45% share of renewable energy target in energy consumption, an increase in installed power generation capacity to 1,236 GW, as well as reductions in demand for natural gas and mandatory reductions in peak electricity use, and is implemented through diversification of the energy supply, securing affordable energy supplies, saving energy and investing in renewable energy. The EU integrates multi-channel funds from state aid programmes, the European Investment and Development Bank, carbon trading revenues and mobilisation of private sector investment, and introduces fiscal and financial incentives to motivate countries and enterprises to take positive action, while strengthening international cooperation to safeguard and accelerate the green and low-carbon transformation in energy. Through the Justice Transition Programme under the Invest EU programme, the Justice Transition Fund (JTF), and the Public Sector Loan Facility (PSLF) supported by the European Investment Bank (EIB), EU will help to mitigate the negative impacts on the interests of the regions, industries, citizens and workers within the EU member states that are affected by the low-carbon transformation, and to ensure a smooth transformation for the economy and the society. In 2023, the EU's installed renewable energy power generation capacity reached 614 GW, with a 44% share of total electricity generation.

In 2021, in its latest NDC submission, China proposed a target of carbon peaking before 2030 and further emphasised its commitment to achieving carbon neutrality before 2060, and also raised its carbon intensity reduction target for 2030 from 60%-65% to more than 65% (compared to the 2005 level) , while the share of non-fossil energy sources in primary energy consumption reaches around 25%, and the installed capacity of wind and solar power reaches 1,200 GW above. China will lead the overall green transformation of the economy and society with the dual-carbon control target (i.e. total energy consumption and energy consumption per RMB 10,000 of gross domestic product (GDP)), build a "1+N" policy system of carbon peak attainment and carbon neutrality, strengthen strategic planning and institutional construction, and adhere to the simultaneous efforts from both the production side and the consumption side, so as to accelerate the green and low-carbon transformation of the energy system. In 2023, China gradually shifted from dual-control targets for energy consumption to dual-control targets for carbon emissions, leaving more space for the development of low-carbon energy and accelerating the green and low-carbon transformation. In 2023, China's total installed capacity of renewable energy reached 1,470 GW, and the share of power generation reached 31.8%, highlighting the results of China's energy restructuring and green and low-carbon transformation.

In 2021, the United States returned to the Paris Agreement and submitted an updated NDC, committing to reduce GHG emissions by 50%~52% of 2005 levels by 2030, and to achieve net-zero emissions in the power sector by 2035. To support these goals, the United States passed the Infrastructure Investment and Jobs Act (IIJA), the Inflation Reduction Act (IRA) and other legislation under the macro-policy framework of the Investing in America Agenda (IAA), to ensure the achievement of the above goals and stimulate economic growth and employment, of which the former focuses on infrastructure construction, such as transportation and power grids, and the latter focuses on supporting the innovation and industrialisation of clean energy technology and the transformation of traditional energy communities to promote the transformation of the United States to a cleaner and low-carbon energy system. Specific initiatives include direct investment, tax subsidies, preferential loans and loan guarantees. Funding sources include the United States Government's USD 2 trillion infrastructure programme, investments by the United States Department of Energy, and the mobilisation of private sector investment, of which USD 173 billion has been invested in electric vehicles and batteries, USD 77 billion in clean energy manufacturing and infrastructure, and USD 155 billion in clean power.

Achievements in the global green and low-carbon energy transformation: a great deal to be achieved and a promising future to look forward to

Countries around the globe have taken a series of policy actions and international cooperation to change their energy production and consumption patterns and accelerate their own green and low-carbon energy transformation, and have achieved impressive results in the control of total carbon emissions, the reduction of fossil energy consumption, the development of renewable energy sources and technological innovation.

The most significant results of the global energy transformation are reflected in the renewable energy power generation and electric vehicle sectors, where renewable energy development and electric vehicle sales are growing rapidly, and the costs of renewable power generation and electric vehicles are gradually becoming competitive. According to the *Clean Energy Market Monitor* report released by the International Energy Agency (IEA), global clean energy deployment reached a new high in 2023, solar PV and wind power grew by 85% and 60% respectively compared to 2022, and new installed capacity reached nearly 540 GW; electric vehicle sales increased by 35%; heat pump sales grew for two consecutive years in 2021 and 2022, reaching record levels in 2022 but declining slightly (3%) in 2023; and global installed capacity of hydrogen production electrolysers exceeded 1 GW, reaching 1.3 GW, a growth rate of 360%. While China has long led the way in renewable energy development and electric vehicle sales growth, the EU also presented satisfactory results. According to the *Renewable Energy Target Achievement Report for 2020* published by EU in 2022, the EU exceeded its target, with the share of renewable energy in total end-use energy consumption reaching 22.1%.

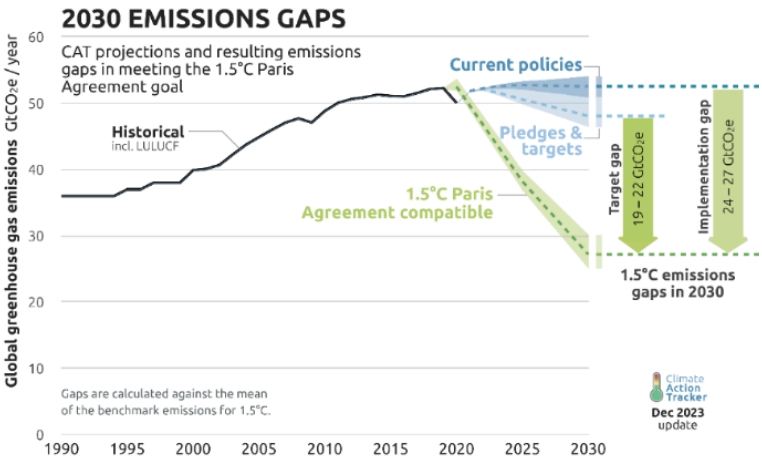
Although total global carbon emissions and energy-related carbon emissions are still on an upward trend, developed economies such as the European Union, the United States and Japan have already achieved a certain degree of reduction in total carbon emissions, and emerging economies such as China and Brazil are basically showing a downward trend in carbon emission intensity. According to Ember data, EU's carbon emissions reduced by 19% year-on-year in 2023, with the power sector accounting for only 4.6% of global emissions. According to the analysis of the Energy Information Administration (EIA) of the United States, the country's energy-related carbon emissions in 2023 were reduced by 3%, of which the power sector emissions were cut by 7%, contributing to 80% of the reduction, mainly due to the substitution of solar energy and natural gas power generation resulting in the reduction of coal-fired power generation. China's carbon emission intensity has maintained a downward trend for ten consecutive years.

The importance of fossil energy in the energy mix is gradually declining as the share of renewable energy increases and the electrification of end-use energy increases. From 2015 to 2022, coal power generation in advanced economies represented by the G7 countries decreased by 35%, with the UK and France leading the way with 93% and 63% decreases, respectively; although the G7 countries' reliance on natural gas remains high, the growth rate has slowed down, especially as the gas crisis of 2022 has made the G7 countries realise the vulnerability of natural gas supplies and reconsider their dependence.

Global green low-carbon energy transformation: insufficient synergies, need for increased consensus

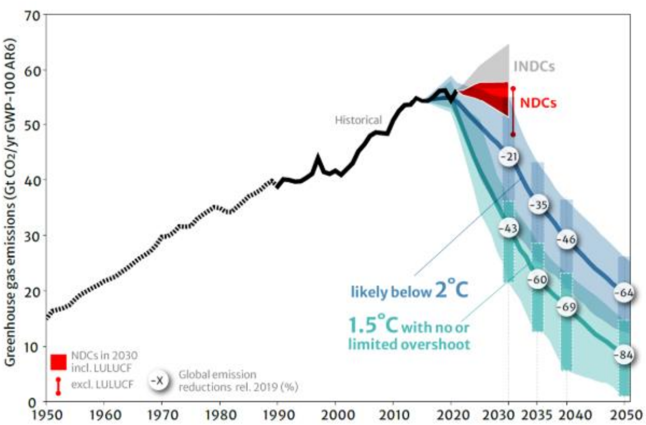
As the most important means of combating climate change, countries' commitments to a green and low-carbon energy transformation fall far short of temperature rise control targets. Climate Action Tracker analyses show that the gap between scenario emission pathways constructed according to the NDCs submitted by countries to the United Nations Framework Convention on Climate Change (UNFCCC) by December 2023 and the 1.5°C-compatible pathway in 2030 is between 19,000~22,000 million tonnes of CO_2-equivalent ($MtCO_2e$) (the target gap, as illustrated in Figure 1-5).The *First Global Stocktaking Report* released by UNFCCC in 2023 states that even if all current NDC targets are fully implemented, the global average temperature rise in 2100 can only be contained within the range of 2.1 to 2.8°C, and that global GHG emissions would need to be reduced by 43% and more than 60% in 2030 and 2035, respectively, on a 2019 basis, in order to achieve the goal of keeping temperature rise in the 1.5°C range (as shown in Figure 1-6).The *Emissions Gap Report 2023* published by the UNEP gives similar estimates of the need for further emission reductions.

Figure 1-5 Gaps between countries' commitments and action pathways and 1.5°C compatible pathways



Source: Climate Action Tracker

Figure 1-6 Achieving 2/1.5°C will require further emission reduction efforts



		Reductions from 2019 emission levels (%)			
		2030	2035	2040	2050
Limit warming to1.5°C (>50%) with no or limited overshoot	GHG	43 [34-60]	60 [49-77]	69 [58-90]	84 [73-98]
	CO_2	48 [36-69]	65 [50-96]	80 [61-109]	99 [79-119]
Limit warming to 2°C (>67%)	GHG	21 [1-42]	35 [22-55]	46 [34-63]	64 [53-77]
	CO_2	22 [1-44]	37 [21-59]	51 [36-70]	73 [55-90]

Source: Technical Report on the First Global Stocktaking, United Nations Framework Convention on Climate Change (UNFCCC)

The actual policies and actions taken by some countries are also insufficient to support the achievement of their NDC targets. As most countries' climate commitments are not translated into actual strategies and plans and implemented through policies and regulations, the gap between current actions and the two pathways of the NDC target scenarios will reach 24,000~27,000 $MtCO_2e$ by 2030. The International Renewable Energy Agency (IRENA) predicts that this gap will continue to widen and even reach 34,000 $MtCO_2e$ by 2050, further highlighting the urgency of comprehensive action to accelerate the transformation. Therefore, countries need to make concerted efforts to raise the goal of combating climate change and a green and low-carbon energy transformation, and more importantly, to strengthen practical policies and actions.

The global green and low-carbon energy transformation is a complex process that requires the full cooperation of all countries around the world in terms of finance, technology and capacity-building, but international cooperation on the global energy transformation faces many conflicts and challenges because it involves the distribution of responsibilities among countries. Whether for climate change mitigation or adaptation, the importance of finance is self-evident, but developing countries are under great pressure for economic development and are less likely to be able to afford climate expenditures, and developed countries, which have the obligation to provide financial support to developing countries, have failed to honour their commitments to climate financing. Under the *Cancun Agreements*, developed country parties committed to a goal of mobilising USD 100 billion a year in climate finance by 2020, but in reality, according to the Organization for Economic Cooperation and Development (OECD) calculations, developed countries have provided and mobilised a historic high of USD 83.3 billion in 2020, below the pledged target, and the "cumbersome systems and bureaucracy" made it difficult for the least development countries (LDCs) to access funds. The innovation cooperation and technology transfer in the context of "great power games" and "counter-globalisation" are even more fraught with obstacles. Under the influence of geopolitical interference, conflicting economic interests and legal restrictions, the politicisation of science and technology, the prevalence of trade protectionism, the misuse of technology bans and other behaviours have hindered cooperation in technology research and development (R&D), large-scale deployment and innovation in business application models, limiting the further improvement of the level of innovation and productivity in the industry, and inadvertently increasing the cost of the global energy transformation to a cleaner and lower-carbon environment.

Perspectives on the global green and low-carbon energy transformation: focusing on action, focusing on commitment

According to the Climate Action Tracker's assessment, only a few economies such as Norway, Ethiopia, Morocco, Nigeria and others with a very low contribution to GHG emissions are able to support their NDC targets with domestic policy actions, while the sum of all the countries' efforts falls short of the strength required for a 1.5°C compatible pathway. Therefore, all parties around the world need to strengthen their sense of responsibility, increase their commitment, enhance their domestic policy efforts, and raise the level of international cooperation in order to promote a just, orderly and equitable green and low-carbon transition of the energy system.

Policy support is the basic guarantee for promoting a green and low-carbon energy transformation. Countries should improve their domestic institutional systems and formulate specific transformation goals, strategies and action plans to give stakeholders clear policy expectations. They should effectively promote the development of renewable energy and energy efficiency and provide incentives through fiscal and tax incentives to encourage participation in the transformation, especially by the private sector. In addition, governments should optimise regulatory and support mechanisms to create an innovation-friendly environment, and the impact on innovation and competition should be fully considered in the process of policy formulation and adjustment, encouraging potential new entrants and leading established players to develop more promising innovative and transformative technologies and business models, so as to make the policy better serve the deployment of technological innovation and commercialisation.

Upgrading technology and achieving leapfrog breakthroughs is a fundamental way to achieve a green and low-carbon transformation of energy. According to the *Net Zero by 2050: A Roadmap or the Global Energy Sector* issued by the IEA, although it is possible to achieve the 2030 emissions reduction target by relying on existing technologies, if the 2050 net-zero emissions target is to be achieved, half of the emissions reduction must come from technologies that are currently still in the demonstration or prototype stage, especially in areas that are difficult to reduce emissions, such as heavy industry and long-distance transport, where the problem is more prominent. In terms of long-term development, countries across the globe should act to encourage and support technological innovation and large-scale application in sectors such as energy, industry and transport, including key segments or areas such as power generation, power transmission and distribution, energy storage, energy conversion, green hydrogen, and key minerals.

Reforming and rebuilding the financial system are an indispensable support for achieving a green and low-carbon energy transformation. According to estimates by the International Monetary Fund (IMF) and Deloitte, to achieve net-zero emissions by 2050, investment in the low-carbon transition will need to increase to USD 5-7 trillion per year, while current investment in this area is less than USD 2 trillion per year, and investment in the low-carbon transformation is facing a huge shortfall. According to the IMF and the Price Waterhouse Coopers (PwC), developing countries face a larger and growing financing gap due to higher investment risks and lower investor interest. The IEA estimates that emerging market and developing economies will need to invest USD 2 trillion per year by 2030 to achieve net-zero emissions by 2050, while the United Nations Conference on Trade and Development (UNCTAD) estimates that the investment gap in the energy sector alone is as high as USD 2.2 trillion per year. Therefore, countries should fully mobilise investment in energy transformation and developed countries in particular should demonstrate their responsibility and accountability by strengthening financial transfers to developing countries to support their energy transformation and climate change mitigation. PwC believes that there is limited room for growth in public investment, and that the private sector must make a significant contribution by providing 80% of the required investment. It is necessary for countries and multilateral cooperation platforms to set up a transformation-friendly financial framework system, build a financial incentive mechanism for low-carbon transformation, and innovate diversified financial products, so as to mobilise the private sector to participate in the energy transformation investment.

Strengthening international cooperation is an effective path to improving the efficiency of energy transformation efforts, including but not limited to dimensions such as improving policies, technological R&D and promoting investment. Countries and international multilateral organisations should help countries and regions with urgent transformation needs to strengthen capacity building, especially in the formulation of systems and standards, so as to provide a better environment for industrial transformation; developed countries should accelerate the transfer of financial resources to developing countries, expand the public sector's commitment to climate finance and strengthen the fulfilment of targets; promote technology transfer to developing countries, giving full consideration to the situation of local energy transformation, and cooperate in promoting the implementation of technically effective and economically viable technologies.

2 Progress in China's energy transformation

On June 13, 2014, General Secretary Xi Jinping pointed out at the Sixth Meeting of the Central Leading Group for Finance and Economics that China is facing challenges such as huge pressure on energy demand, more constraints on energy supply, serious ecological and environmental damage caused by energy production and consumption, and a general backwardness in the level of energy technology. At the meeting, General Secretary Xi Jinping put forward a five-point request on promoting a revolution in energy production and consumption: first, promote a revolution in energy consumption and curb unreasonable energy consumption. Second, promote the energy supply revolution and establish a diversified supply system. Third, promote the energy technology revolution, drive industrial upgrading. Fourth, promote the energy system revolution, and open the fast track of energy development. Fifth, strengthen international cooperation in all aspects to achieve energy security under open conditions.

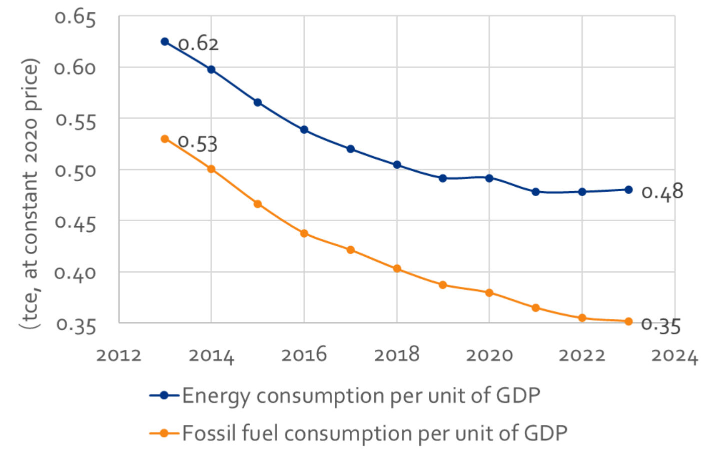
Over the past decade, China has promoted energy transformation in five areas: energy consumption, energy supply, energy technology, energy institutions and international energy cooperation; the dependence of economic development on energy consumption has steadily declined; the capacity of energy supply has been significantly improved; the capacity of energy science and technology and industry has been markedly strengthened; energy market-oriented reforms have been pushed forward in a solid manner; and international energy cooperation has been deepened in a comprehensive manner.

2.1 Energy consumption revolution

Steady decline in dependence on fossil energy consumption for economic development

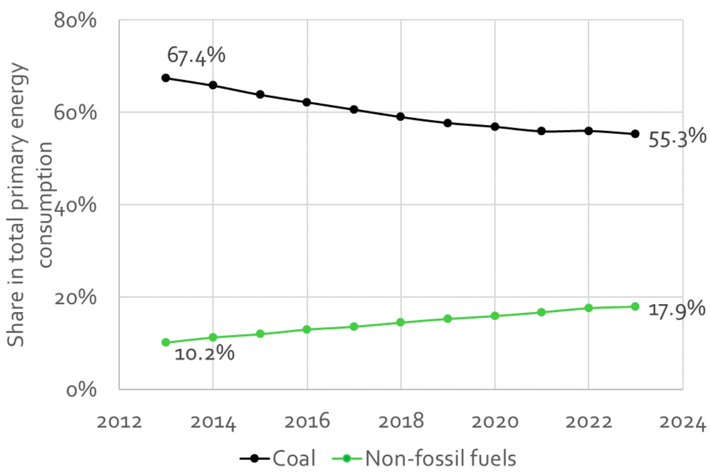
From 2014 to 2023, China's average annual growth rate of energy consumption of 3.2% supports the average annual growth rate of China's economy of 6.0%. In 2023, China's GDP reached RMB 126.1 trillion, energy consumption reached RMB 5,720 Mtce, and energy consumption per unit of GDP was 0.48 tonnes of standard coal (tce)/RMB 10,000 (at comparable prices in 2020); in 2013, China's GDP was RMB 59.3 trillion, energy consumption was 4,170 Mtce, and energy consumption per unit of GDP was 0.62 tce/RMB 10,000. Using 2013 as the base year, the cumulative decrease in energy consumption per unit of GDP in 2023 reached 23.2% (as shown in Figure 2-1), creating a cumulative energy saving of 1,220 Mtce. Against the backdrop of the global move towards carbon neutrality, China's economic development has gradually reduced its dependence on fossil fuel consumption. from 2014 to 2023, China's GDP grew by 78.5%, but fossil energy consumption only grew by 37.2%, and fossil fuel consumption per unit of GDP declined from 0.53 tce/RMB 10,000 in 2013 to 0.35 tce/RMB 10,000 in 2023, a decline of 33.7%. The intensity of fossil fuel consumption has been reduced by more than one third, and the dependence of economic development on fossil fuel consumption has continued to decrease.

Figure 2-1 Changes in China's energy consumption per unit of GDP in the past ten years



The structure of energy consumption continues to improve. From 2014 to 2023, the share of non-fossil energy in China's primary energy consumption increased from 10.2% in 2013 to 17.9% in 2023, an increase of 7.7 percentage points. Among them, the share of coal in primary energy declined from 67.4% in 2013 to 55.3% in 2023, a decrease of 12.1 percentage points (as shown in Figure 2-2).

Figure 2-2 Share of non-fossil energy and share of coal in total primary energy consumption in China in the past ten years



Steady improvement in energy efficiency

Energy efficiency in key industrial sectors has steadily improved. The industrial sector is an important pillar of China's economic development, accounting for more than 30% of its GDP; at the same time, industry is the most important area of China's energy consumption, accounting for more than 60% of China's total energy consumption in the long term. In the past ten years, China has, on the one hand, continued to phase out backward production capacity, accelerated the development of advanced manufacturing capacity, and promoted the upgrading of industrial structure to high-end, green and digital. On the other hand, China has continued to promote energy-saving and low-carbon technologies, replacing traditional technologies with advanced and efficient technologies. In 2022, China's coal consumption per kilowatt-hour (kWh) of power generation in thermal power plants and the overall energy consumption per tonne of cement production decreased by 7.4% (as shown in Figure 2-3) and 9.5%, respectively, compared with 2013. The overall energy consumption per tonne of steel production and the overall electricity consumption per tonne of electrolytic aluminium of medium and large-sized enterprises (as shown in Figure 2-4) in China both have already reached the world's advanced level.

Figure 2-3 Coal consumption per kWh of power generation in China's thermal power plants in the past ten years

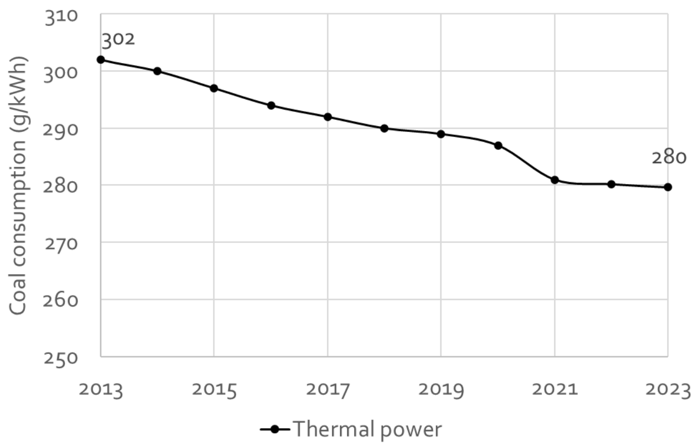
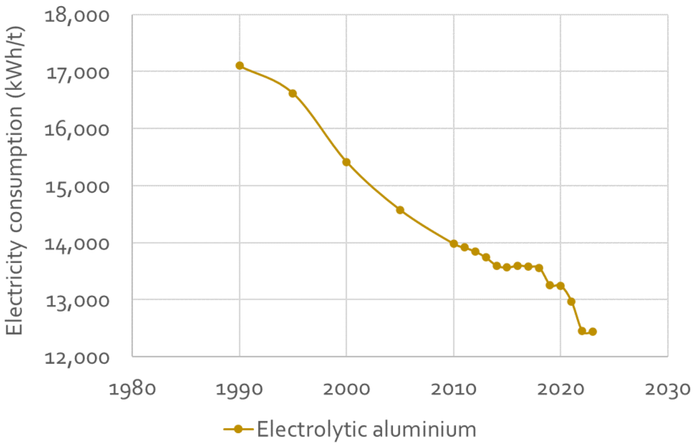


Figure 2-4 Overall electricity consumption per tonne of electrolytic aluminium in China



Accelerated green transformation of energy consumption

The promotion of electric vehicles has been accelerated. Energy consumption in the transport sector accounts for about 10% of China's total energy consumption. As a transport alternative to petrol and diesel vehicles, China's ownership of new energy vehicles has continued to increase from about 20,000 in 2013 to 20.41 million in 2023, which is about 1,000 times that of 2013. In 2023, China's production of new energy vehicles reached 9.51 million, ranking first in the world, and the market penetration rate has already exceeded 30% (as shown in Figure 2-5 and Figure 2-6). Matching this, China's charging infrastructure has grown from almost negligible in 2014 to 8.6 million units in 2023, and the convenient charging infrastructure has effectively increased Chinese consumers' acceptance of electric vehicles (EVs).

Figure 2-5 Stock of new energy vehicles in China in the past ten years

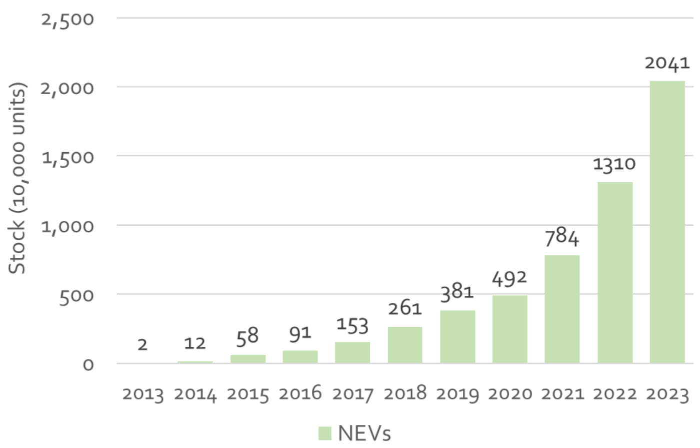
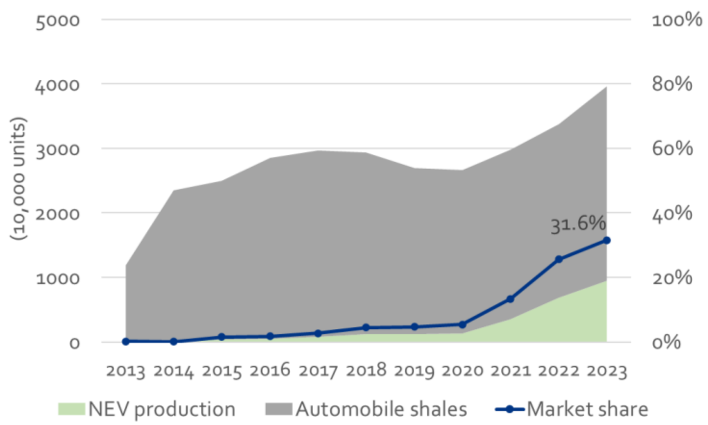


Figure 2-6 Market penetration rate of new energy vehicles in China in the past ten years

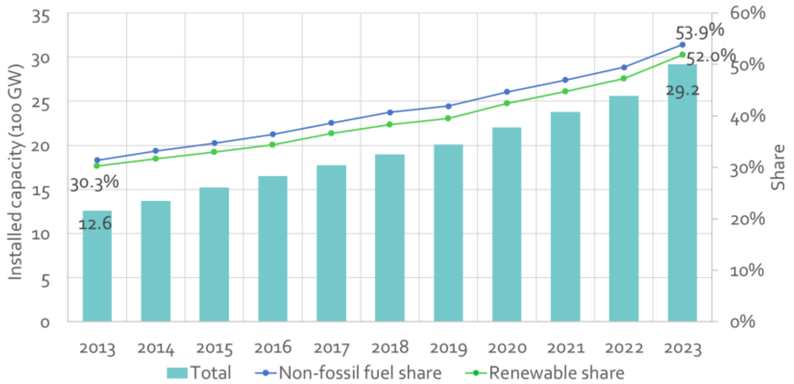


2.2 Energy supply revolution

Significant increase in new energy generation capacity

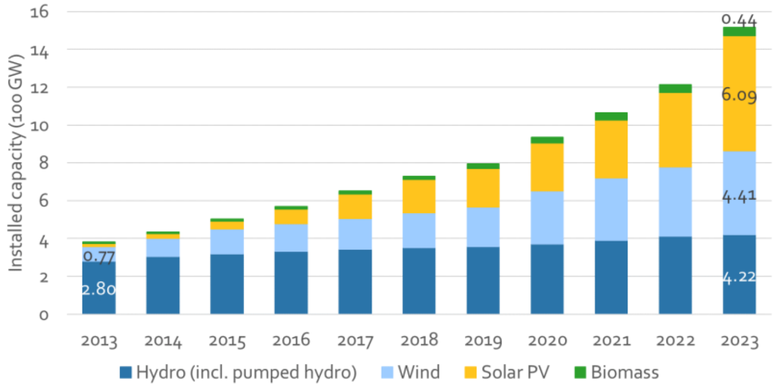
China's new and renewable energy power generation has been growing at a rapid pace. over the past ten years, the installed capacity of renewable energy power generation in China has maintained a high annual average growth rate of close to 15%. In 2023, China's installed capacity of renewable energy power generation has historically surpassed that of thermal power capacity, and its share in total installed power generation capacity exceeded 50%. In 2023, the share of China's non-fossil energy power generation capacity including renewable energy and nuclear power has reached 53.9% of total installed power generation capacity (as shown in Figure 2-7).

Figure 2-7 China's total installed power generation capacity and the share of non-fossil fuels and share of renewable energy in the past ten years



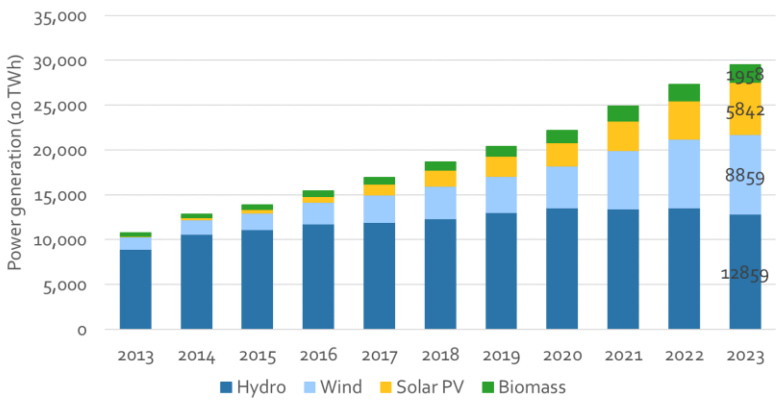
solar PV and wind power have been the hotspots of China's new energy development in the past ten years. in the ten years from 2013 to the present, China's installed capacity of wind power has continuously ranked first in the world; since 2015, China's installed capacity of solar PV has remained the world's first for eight consecutive years, and the installed capacity of biomass power has ranked the world's first for seven consecutive years. In 2023, the total installed capacity of hydropower including pumped storage reached 420 GW, 1.5 times that of 2013; the installed capacity of wind power reached 441 GW, 5.8 times that of 2013; the installed capacity of solar PV reached 609 GW, 38.4 times that of 2013; and the installed capacity of biomass reached 44 GW, 5.7 times that of 2013 (as shown in Figure 2-8).

Figure 2-8 Installed capacity of various types of renewable energy power generation technologies in China in the past ten years



Renewable energy power generation has grown from very minor to provide one-third of the country's power generation. In 2023, China's renewable energy power generation has exceeded 3,000 TWh, accounting for about one-third of the total electricity consumption of the whole society (as shown in Figure 2-9). From 2014 to 2023, the average annual growth rate of China's wind and solar PV power generation has remained above 10 percentage points for ten consecutive years. In 2023, the sum of China's wind and solar PV power generation reached 1,450 TWh, or about 16% of the total electricity consumption of the whole society, which equivalent to the 1.4 billion people in China, who consumed 1,000 kWh of wind and solar PV power per person per year.

Figure 2-9 China's renewable energy generation in the past ten years



Accelerated development of nuclear energy and natural gas

Nuclear power plays an important supporting role in meeting the growth of power loads in coastal areas. Nuclear power is a power generation source with high energy density, good stability and low carbon emissions, and its large-scale development is crucial to optimising the power mix of China's coastal areas, enhancing the ability to secure power supply and lowering carbon emissions in coastal areas. From 2014 to 2023, China's installed nuclear power generation capacity continued to increase. In 2023, China had a total of 55 nuclear power units in operation, with an installed capacity of 56.91 GW, accounting for about 2% of the country's installed power generation capacity. In 2023, China's installed nuclear power capacity grew by 42.25 GW compared to 2013, with the installed capacity reaching 3.9 times that of 2013 (as shown in Figure 2-10). China's installed nuclear power capacity in operation ranks third in the world after the United States and France. In addition, the installed capacity of nuclear power units under construction in China is 43.42 GW, ranking first in the world.

Figure 2-10 Installed capacity of nuclear power in China in the past ten years

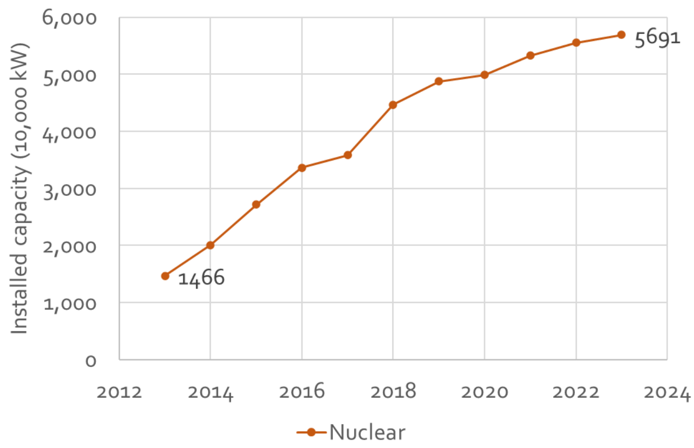
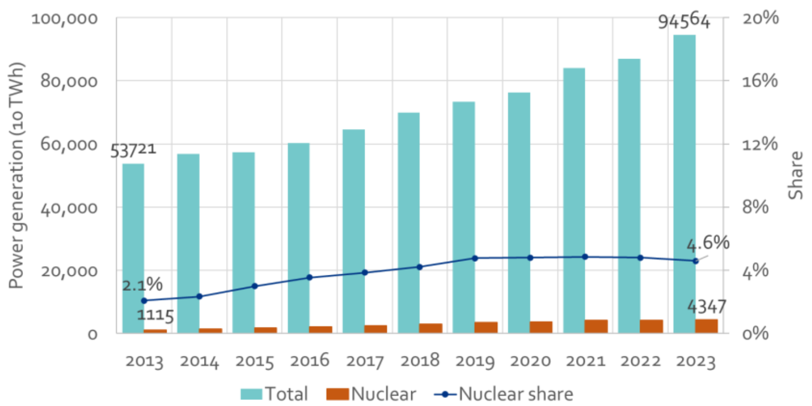


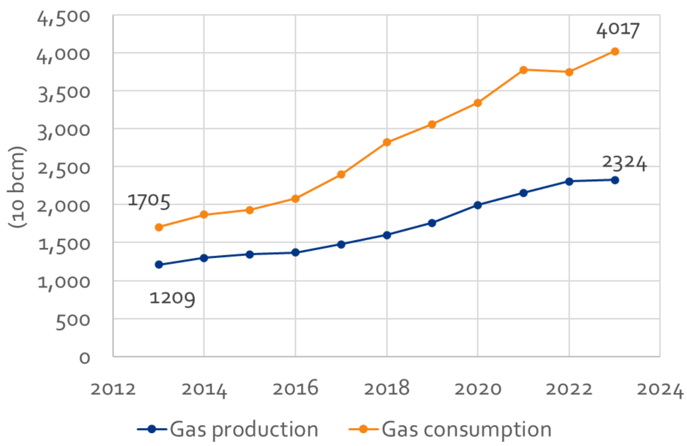
Figure 2-11 China's nuclear power generation and its share in national power generation in the past ten years



Natural gas plays an important role in replacing coal. Natural gas is a clean and low-carbon fossil energy source, and from 2014 to 2023, China has regarded the development of natural gas as an important solution for replacing coal, and has formulated a number of policies such as the *Air Pollution Prevention and Control Action Plan*, the *Three-year*

Action Plan for Defending the Blue Sky, and the *Implementation Plan to Facilitate Clean Heating in the Northern Region*, and has completed the world's largest engineering project of "replacing coal with gas". China's natural gas consumption has rapidly increased from 170.5 billion cubic metres (bcm) in 2013 to 401.7 bcm in 2023, a 136% increase in ten years, with an average annual increase of 23.1 bcm. The scale of China's natural gas market has achieved a "three-stage jump" in the past decade, crossing the three big steps of 200 bcm, 300 bcm and 400 bcm consecutively. China has become the world's third largest natural gas consumer. At the same time, China's natural gas production has also continued to increase. In 2023, the national natural gas production reached 232.4 bcm, 1.9 times that of 2013, almost doubling its production in ten years (as shown in Figure 2-12).

Figure 2-12 China's natural gas production and natural gas consumption in the past ten years



Continued diversification of electricity supply

The diversification of power supply has increased significantly. After ten years of development, the power structure has changed from the past pattern of "coal power as the mainstay and hydropower as a supplement" to a new pattern of "accelerated development of renewable energy, nuclear power and gas power, supported by grid interconnection, energy storage and demand-side response, and with thermal power providing ancillary services and being the ballast stone of power supply". In the past ten years, China's renewable energy has accelerated its development, with the installed capacity of wind and solar power developing from 92 GW in 2013 to 1,050 GW in 2023. China's natural gas power generation capacity reached 125 GW in 2023, which was mainly distributed in the power load centres such as the Pearl River Delta, Yangtze River Delta, Beijing-Tianjin-Hebei region and Sichuan-Chongqing. Gas power plays an important role in enhancing the power supply capability during peak load periods in the local areas (as shown in Figure 2-13).

Electricity flexibility resources have become more abundant. By the end of 2023, the installed capacity of China's pumped storage power plants had reached 50 GW, about double that of 2012, with 160 GW approved and under construction, and the installed pumped storage capacity built and under construction ranked first in the world. In 2023, the installed capacity of China's lithium-ion battery storage, compressed air energy storage, and other new-type energy storage projects has reached 31.39 GW/ 66.87 GWh (the average energy storage duration is more than 2 hours), which has completed the planning target of 30 GW in 2025 three years ahead of schedule (as shown in Figure 2-14). China's thermal power plants have accelerated the implementation of "three retrofits" including energy-saving and carbon-reducing retrofit, flexibility retrofit, and heat supply retrofit. The country launched flexibility retrofit pilots for 17 GW of coal power units in 2016, followed by a comprehensive promotion of the "three retrofit". From 2020 to 2022, China cumulatively implemented the flexibility retrofit of 188 GW of coal power units, completing about 90% of the *Five-Year Plan* target. After the retrofit, the load regulation capacity of coal power units has been greatly improved, providing important support for renewable energy development and grid security.

Figure 2-13 Electricity generation mix in China in the past ten years

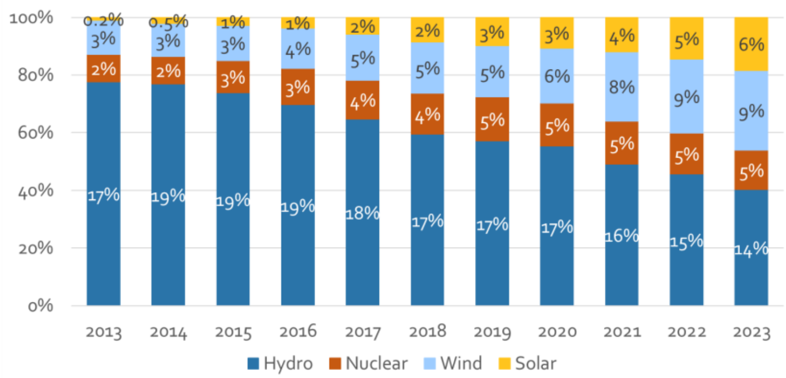
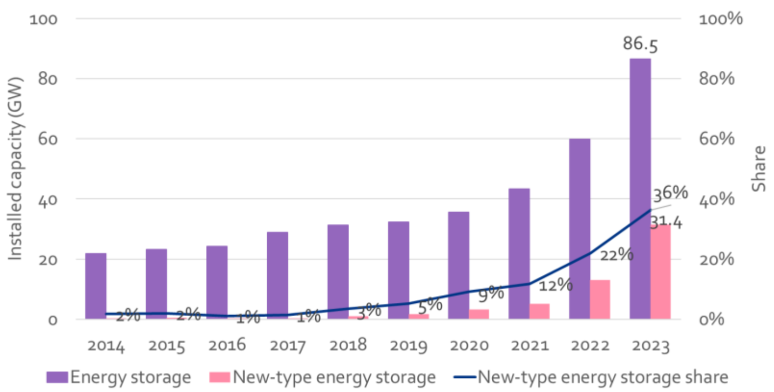


Figure 2-14 Development of new-energy storage in China in the past ten years

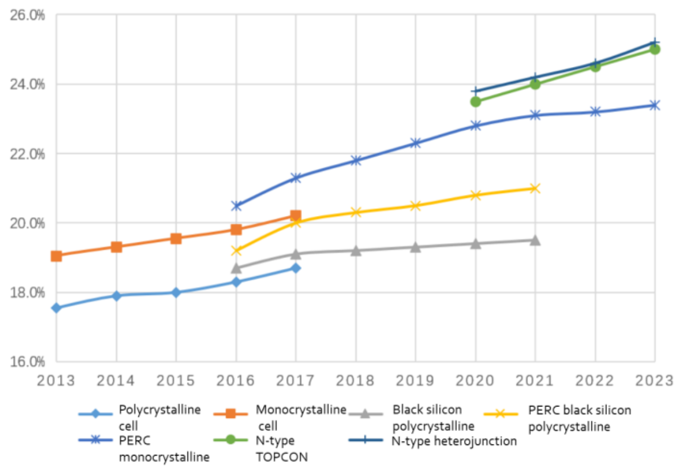


2.3 Energy technology revolution

Breakthroughs in R&D of new technologies

In the last decade, China has made a series of new achievements in renewable energy technological innovation. In 2023, the efficiency of crystalline silicon-calcite cells independently developed by Chinese solar PV enterprises achieved the world's highest PV power generation efficiency record of 33.9%. With the development of N-type cell and large-size wafer technology, the single-chip power of PV modules was upgraded from 600 W to more than 700 W in 2023 (as shown in Figure 2-15).

Figure 2-15 Variation in efficiency of crystalline silicon solar cells



Source: China Photovoltaic Industry Association

The world's first commercial demonstration of the fourth-generation nuclear power technology. High-temperature gas-cooled reactor (HTGR) is a fourth-generation nuclear power technology with unique "inherent safety" of no leakage, no loss of control and no meltdown. In 2023, the world's commercial HTGR nuclear power plant - Shandong Shidao Bay HTGR demonstration project was officially put into operation, marking China's fourth-generation nuclear power technology in R&D and application reaching the world's leading level. At the same time, China has made positive progress in the R&D of multi-purpose small reactors and micro-reactors, which indicates that China's R&D of new-generation nuclear energy systems is basically in sync with that of the United States, Russia and Europe.

New-type power transmission technologies are constantly making breakthroughs. In terms of flexible direct current (DC) transmission, in the past ten years, China has built and put into operation flexible DC transmission projects such as Hebei Zhangbei and Jiangsu Rudong projects. Unlike traditional DC transmission, flexible DC transmission can realise the decoupling control of active power and reactive power, and independently regulate voltage and frequency, which can better adapt to the fluctuation and uncertainty of new energy power generation. In addition, it has the characteristics of small line loss, long transmission distance and strong environmental adaptability of flexible DC transmission, which can operate stably in more complex environments. Flexible DC transmission technology continues to make breakthroughs and lays a solid foundation for the enhancement of renewable energy transmission and grid regulation ability.

Significant improvement in energy equipment manufacturing and project engineering capability

In the past ten years, China's renewable energy equipment manufacturing capacity has improved significantly. In terms of wind turbine manufacturing, China has mastered the manufacturing technology of 15 MW onshore and 22 MW offshore ultra-large-capacity wind turbines, and the low wind speed and typhoon-resistant wind turbine technologies rank the forefront in the world. China has formed the most complete industrial chain in the world, and the costs of the complete machine and key components are relatively low, which gives them a certain competitive advantage in the market.

China has made the leap from second-generation nuclear power to independent developed third-generation nuclear power technology. In the area of nuclear power, through digestion, absorption and re-innovation, China has developed third-generation nuclear power technologies with independent intellectual property rights, such as Hualong-1 and Guohe-1. Several Hualong-1 units have been put into operation nationwide, and the Guohe-1 demonstration project is progressing in an orderly manner. At present, China has formed the ability to supply about ten sets of nuclear power plant units with complete sets of main equipment every year. At the same time, the construction management level of China's nuclear power continues to improve, with the engineering and construction capacity to build multiple nuclear power units at the same time, and the engineering construction and engineering procurement construction (EPC) capacity has entered the world's advanced ranks.

A number of world-class large-scale hydropower projects with high technical content and difficult construction conditions have been built. In the past ten years, China has built the world's largest hydropower unit with a single capacity of 1 GW, and has completed major hydropower projects such as the Baihetan and Wudongde hydropower stations, with an installed capacity of 16 GW and 10.2 GW, respectively, and with scales and technological levels that rank among the world's foremost.

Accelerated development of new technologies, models and forms of business

It is actively trying out new application scenarios such as nuclear energy heat supply and nuclear energy desalination. In China, in areas such as Shandong Haiyang, Zhejiang Qinshan and Liaoning Hongyanhe, China has started to use the waste heat of nuclear power plants to provide heat services and heating services for nearby customers, realising the inter-regional interconnection and sharing of zero-carbon heat sources. In 2023, the Shandong Haiyang Nuclear Power Plant provided nuclear heating services for the cities of Haiyang and Lushan, with a total heating area of 12.5 million square metres to meet the winter clean heating needs of a total of 400,000 people in the two cities. In March 2023, the Huaneng Shidao Bay High Temperature Gas-cooled Reactor also started to provide heating services for neighbouring residents.

New models and new forms of business in energy services are accelerating. In 2013, the number of energy-saving service companies in China was 4,852. By the end of 2023, the number of energy-saving service companies grew to 12,000, and the output value of this industry was more than RMB 500 billion, which is about double that of 2013. Since China accelerated the implementation of clean heating in 2016, China's heating industry has entered an accelerated period of development, with a large number of enterprises using clean energy technologies such as solar, geothermal and biomass energy to provide heating services for cities, towns and industrial enterprises. By 2023, the number of enterprises engaged in clean heating in China reached 8,350, the total output value of the clean heating industry was RMB 920 billion, and the number of employees reached 1.25 million. Among the 24.5 billion square metres of heating area in China's northern region, 18.6 billion square metres have achieved clean energy heat supply, the coverage rate reached 76%.

2.4 Energy system revolution

Steady progress in power market reform

China's power market reform is accelerating. Prior to the reform, China's power industry had long been managed by administrative plans, and power grid enterprises implemented the business model of "unified purchase and sale" and "integration of transmission, distribution and sale", with power prices set by the government, i.e. benchmark feed-in tariffs implemented on the power generation side, and listed electricity prices implemented on the user side, with prices determined according to the voltage level and type of user. Since 2015, China has further promoted power market reform in accordance with the idea of "regulating the transmission session and liberalising both generation and end-use sides".

The varieties and platforms for power trading in China are getting diverse. In 2021, China officially abolished the industrial and commercial listed electricity prices, industrial and commercial users started to purchase power at market prices, and the price packages are getting diverse. As of 2023, China has built a power market system covering medium- and long-term transaction, spot transaction, ancillary services and other trading varieties, and formed two levels of markets, namely intra-provincial and inter-provincial. At present, medium- and long-term transaction is the mainstay of China's power market system, which has achieved normal operation nationwide. In recent years, the trading scale and trading volume of medium- and long-term transactions have been increasing, and the trading cycle has been covered from multi-year to multi-day, which has played an important role in stabilising the supply and demand of electricity. As of 2023, China has launched two batches including 14 spot power market pilots, and the southern regional spot power market has realised the trial operation of region-wide settlement, and the role of the spot power market in discovering real-time electricity prices has gradually emerged. In terms of the ancillary service market, in 2023, China's ancillary service market has covered 6 regions and 33 provincial power grids. These markets have established a variety of products such as peak-load shaving, frequency regulation and reserves, and the economic value of flexibility resources in the power market has been initially reflected. In terms of power trading institutions, since 2015, China has established two regional power trading centres in Beijing and Guangzhou as well as 32 provincial power trading centres, forming a relatively independent, fair and standardised power market trading platform.

In addition to the power market, China has also built a green certificate market and a specialised green power trading market. In 2017, China started to certify green certificates and implement voluntary subscription for green certificates. in September 2021, green power trading was officially launched. In recent years, the trading scale of green power and green certificates has continued to expand, and the environmental premium has been rising. By the end of 2023, China had achieved 105.9 TWh of green power trading and issued 176 million green certificates.

Energy price reform restores energy to commodity properties

In the past ten years, China has taken "market-determined energy prices" as the direction of reform and has promoted energy price reform on the basis of the idea of "regulating the transport section and liberalising production and consumption sides".

On the one hand, prices have been approved for energy segments that are natural monopolies. For example, in accordance with the principle of "permitted costs + reasonable returns", a price system has been established for natural monopolies in the power and natural gas sectors. In the power sector, a multi-level power transmission and distribution price system has been established, including provincial power grids, regional power grids, and inter-provincial and inter-regional power transmission. In the area of natural gas prices, on the basis of a review of the costs of cross-provincial natural gas pipelines, natural gas pipeline transport prices have been approved in accordance with four price zones: north-west, north-east, central-east and south-west.

On the other hand, China has taken the initiative to liberalise prices in competitive areas and segments. With regard to feed-in tariffs, the market-based price mechanism of "baseline tariff + upward and downward fluctuations" has been implemented for coal power feed-in tariffs. With regard to power transmission tariffs, the price has been formed through negotiation or market-based methods in accordance with the principle of "risk-sharing and benefit-sharing" in inter-provincial and inter-regional power transactions. In the case of natural gas, the prices of gas supplied from upstream sources, gas supplied directly to users, gas purchased and sold from storage facilities and natural gas publicly traded in trading centres have been formed by the market.

2.5 International cooperation on energy

Actively promoting a green and low-carbon global energy transformation

To provide the world with energy equipment with reliable performance and reasonable price. China's mega-market size and complete industrial system provide favourable conditions for energy equipment manufacturers. According to the *Renewable Energy Capacity Statistics 2024* released by the IRENA, over the past ten years, the average cost of wind power and solar power generation worldwide has cumulatively declined by more than 60% and 80%, respectively, with a large portion of the decline attributed to Chinese innovation, Chinese manufacturing and Chinese engineering. China's new energy industry provides a large number of high-quality and high-efficiency energy equipment for the world, especially for the vast number of developing countries, and supports the global green transformation. In 2023, the key component production capacity in China's solar PV and vehicle-mounted battery industries accounted for more than 70% of the world, the wind power manufacturing production capacity accounted for more than 50% of the world, and electrolyser shipments accounted for nearly 80% of the world. In 2023, China's “three-new” exports including new energy vehicles, lithium batteries and PV products exceeded RMB 1 trillion for the first time. China's wind power and solar PV products have been exported to more than 200 countries and regions around the world, helping these countries and regions, especially the vast number of developing countries, to undergo green transformation.

Actively promoting international cooperation on green energy. While vigorously promoting the development of the domestic new energy industry, China has continued to strengthen international cooperation. Overseas new energy investments by Chinese enterprises cover wind power, solar PV, hydropower and other fields, which have strongly supported the green transformation and green industrial development of relevant countries and regions. In terms of equipment manufacturing, China has cultivated a number of international first-class energy equipment manufacturing enterprises, four of the world's top five wind power machine manufacturers are Chinese enterprises, and six of the top ten electric vehicle battery manufacturers are Chinese enterprises, which have become an important force in stabilising the global supply of clean energy.

Promotion of cooperation on energy transformation on the basis of the *Belt and Road Initiative*

Supporting energy transformation in Asian countries. In Southeast Asia, the Nam Ou River Basin cascade hydropower station in Laos is the first basin-wide overall planning, investment and construction project by a Chinese enterprise overseas, and has cumulatively delivered more than 12 TWh of clean power to Laos. **In Central Asia,** China and Kazakhstan have jointly constructed the largest wind power project in Central Asia, the 100 MW wind power project in the Jambul region, while the 100 MW solar PV power plant in Navoi, Uzbekistan, constructed by Chinese enterprises, is the first large-scale solar PV power plant built in the country. **In the Middle East**, the Al Dhafra solar PV power plant in the United Arab Emirates, which Chinese enterprises participated in the construction, is the world's largest single solar PV power plant project, and is known as the "Light of Abu Dhabi". The Nouaux III 150MW tower-type CSP plant in Morocco, in which Chinese enterprises participated, is the world's largest tower-type CSP plant in terms of single-unit capacity, and was awarded the "Social Contribution Prize" and the "Economic and Employment Promotion Prize" by the Moroccan government.

Supporting energy transformation in Europe and South America. In Central and Eastern Europe, the Mozura wind power project in Montenegro, jointly built by a Chinese company and the Government of Malta, has been hailed as a benchmark and exemplary project in the wind power industry in Central and Eastern Europe. **In South America**, the Gauchari PV power plant in Jujuy Province, Argentina, is the first project constructed in Argentina since the launch of the *Belt and Road Initiative* and is also the largest solar PV power plant in South America.

Support for Africa's energy transformation. In Africa, China has jointly constructed a large number of hydropower projects with Angola, Burundi, Mali, Guinea, Ethiopia, Tanzania and other countries; jointly carried out the construction of wind power projects with South Africa, Ethiopia, Kenya and other countries; and cooperated in solar PV projects with Algeria, Nigeria, Morocco and other countries. Among these, the Cagulou Kabassa hydropower plant in Angola, the Adama wind power farm in Ethiopia and 233 MW solar PV power plant in Algeria are the largest hydropower, wind power and solar PV projects in Africa, respectively.

Relying on international cooperation platforms to promote global cooperation on energy transformation

Build a comprehensive exchange and cooperation platform for green development. In April 2019, Chinese and international partners jointly launched the Belt and Road International Alliance for Green Development. Through sharing green concepts and policies, knowledge and data on ecological environmental protection and pollution prevention, as well as cooperation on green technologies, the alliance will bring together international development institutions, think tanks, enterprises, social organisations and other stakeholders to build a green Silk Road. So far, more than 150 partners from 43 countries are already involved.

Establish a professional exchange and cooperation platform in the energy sector. In April 2019, China initiated the establishment of the Belt and Road Energy Partnership (BREP) with 29 countries to conduct in-depth studies and solutions to major issues in energy development through the annual Belt and Road Energy Ministers' Meetings and talent training programmes. By holding annual the *Belt and Road* energy ministers' meetings and carrying out talent training programmes, the Partnership has conducted in-depth research and solved major problems in energy development, and the number of member countries has reached 33, making it the first international cooperation platform in the field of energy initiated and established by the Chinese side.

Relying on the regional energy cooperation platform to carry out work. Over the past ten years, China and relevant countries and regions have jointly established five regional energy cooperation platforms, including the Asia-Pacific Economic Cooperation (APEC) Sustainable Energy Centre, the China-Arab League Clean Energy Training Centre, the China-Central and Eastern European Countries Energy Project Dialogue and Cooperation Centre, the China-African Union Energy Partnership, and the China-Association of Southeast Asian Nations (ASEAN) Clean Energy Cooperation Centre, focusing on policy communication, planning, capacity building, technical exchanges and joint research, and promoting the common development and prosperity of the relevant countries and regions in the field of energy.

Over the past decade, China's energy production and consumption systems have changed significantly. Looking ahead, China has set the long-term goal of "striving to peak carbon dioxide emissions before 2030 and striving to achieve carbon neutrality before 2060". China will adhere to the principle of "establishing the new before abolishing the old", and will actively promote energy transformation while ensuring energy security and economic sustainability, so as to work together with other countries in the world to address global climate change.

Part II China’s path towards a zero-carbon energy system

3 Zero-carbon development pathway of the energy sector

3.1 Main findings

- **Energy transformation is a critical pillar in building China's carbon-neutral society.** With the accelerated development of energy transformation technologies (including negative carbon technologies such as carbon capture) and related industries, there will be significant changes in the structure of China's primary energy demand and electricity demand. The energy structure will transform from one in which fossil energy accounts for more than 80% of the total in 2022 to one in which non-fossil energy accounts for more than 80% of the total primary energy demand in 2060, enabling China's energy system to achieve net-zero carbon emissions and will help building China's carbon-neutral society by 2060.

- **Electrification and energy efficiency are important ways for end-use sectors to move towards carbon neutrality.** In the near to medium term, the energy transformation in end-use sectors will primarily rely on high-quality economic development, industrial restructuring, and enhanced energy efficiency. In the medium to long term, the focus will shift to electrification and the adoption of low-carbon and zero-carbon fuels. Additionally, flexible energy use and supply-demand interaction within end-use sectors will be key priorities in the energy transformation.

- **Building a wind- and solar-based new power system is an inevitable choice for energy transformation.** By 2060, with the establishment of a new power system with wind and solar at the core, and balancing development and security, the country's total installed power capacity will reach 10,530–11,820 GW. Of this, wind and solar installations will account for 9,320–10,700 GW. Additionally, flexible resources such as advanced energy storage and hydrogen production through electrolysis will reach capacities of 5280–5870 GW, providing critical support for the safety and stability of the power system. Furthermore, cross-regional power exchange capabilities will improve significantly, leading to an optimized national grid structure.

- **Energy transformation creates new opportunities for investment growth, industrial upgrading, and employment.** Over the next three decades, investment demand in sectors such as wind and solar power, as well as heat supply, will exceed RMB 160 trillion. As China's energy transformation progresses, it will drive down the costs of new technologies, contributing to reduced global energy transformation costs. The shift to low-carbon energy and industrial upgrading will mutually reinforce and support each other, facilitating economic growth while decoupling it from carbon emissions. This transformation will also contribute to higher employment levels and improved wage rates.

- **China's energy transformation is not easily achieved.** China faces four major challenges in its energy transformation: the weight of heavy industries in the economic structure, coal-dominated energy mix, the difficulty of simultaneously managing rapid power system development as well as transformation, and the market-driving force of energy transformation needs to be strengthened. Additionally, numerous uncertainties surrounding China's low-carbon energy transformation should merit close attention.

3.2 Scenario design for CETO2024

The targets of economic-social development and the vision of carbon peak and carbon neutrality

The general idea of the report "China's Energy Transformation Outlook 2024" is to promote the construction of a new type of energy system based on China's national conditions, drawing on international experience, and integrating China's economic and social development and carbon emission targets and visions, so as to lead China's energy transformation with a Chinese-style modernisation.

China has set the strategic goal of building a comprehensively modern socialist power by the middle of this century, which is divided into two steps: the first step is to basically achieve socialist modernisation from 2020 to 2035; and the second step is to build a rich, strong, democratic, civilised, harmonious and beautiful socialist modernising power from 2035 to the middle of this century. China has a large population, aims at the common prosperity of all its people, attaches importance to the coordination of material and spiritual civilisation, stresses the harmonious coexistence of human beings and nature, and adheres to the road of peaceful development, so China's modernisation has the general characteristics of modernisation of all countries, but also Chinese characteristics based on China's national conditions.

China is committed to reaching peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. This commitment is an important component of China's modernisation strategy and an important contribution to addressing global climate change. The promotion of China’s energy transformation is both an effective response to the climate change challenge and an opportunity to transform its economic structure and enhance industrial competitiveness, making China's modernisation more harmonious, prosperous and sustainable.

Two scenarios for energy transformation

In its analysis of China's energy transformation by 2060, the group set up two scenarios. The common denominator of the two scenarios is that China will peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. Considering that the global climate change situation is becoming more and more urgent, but the international political and economic situation is becoming more and more complicated and volatile, the group set up the baseline carbon neutral scenario (BCNS) and the ideal carbon neutral scenario (ICNS).

Table 3-1 CETO2024 Scenario names

Chinese name	English name	Abbreviation
基准碳中和情景	Baseline Carbon Neutrality Scenario	BCNS
理想碳中和情景	Ideal Carbon Neutrality Scenario	ICNS

The Baseline Carbon Neutrality Scenario (BCNS) envisions that, with significant efforts, China will achieve its medium- and long-term development goals, including the dual carbon objectives. The international political and economic landscape grows more complex with recurring geopolitical conflicts. In this environment, addressing climate change may become a lower priority, reducing some countries' efforts. Climate-change-related trade disputes will likely rise, complicating agreements. Collaboration on low-carbon and zero-carbon technologies will face significant challenges. It is more difficult to reduce the cost of new technologies due to global market segmentation. In this international environment, China stays committed to its goals of peaking CO_2 emissions before 2030 and achieving carbon neutrality before 2060. By advancing its medium- and long-term energy transformation, China makes a decisive contribution to reaching a carbon-neutral society.

The Ideal Carbon Neutrality Scenario (ICNS) envisions that, through substantial efforts, China's medium- and long-term economic and social development goals, along with its carbon neutrality and peak emissions targets, are achieved on schedule. The severity of global climate change has spurred a strong international response, with countries prioritising accelerated energy transformation despite occasional political and economic conflicts in certain regions. Despite occasional political and economic conflicts in certain regions, countries remain committed to addressing climate change by enhancing cooperation in areas such as politics, economics, trade, industry, technology, finance, human resources, and knowledge and data sharing. This collective effort aims to reduce the cost of developing low-carbon, zero-carbon, and carbon-negative technologies, enabling their large-scale adoption sooner and at a lower cost. This will also support developing countries with limited capacity, reinforcing China's role as an important player in global cooperation. As a member of the "global village", China will provide technology, equipment, and capacity-building support to other countries to the best of its ability. Together, these efforts will drive the global energy transformation and preserve the shared home of humankind.

Box 3-1 Design Concepts for ICNS

The group has imagined a scenario based on the idealised factors of the current global energy transformation from a positive perspective, in light of the various real risks involved. The aim is to advocate win-win cooperation in the international community and to instil confidence in green and low-carbon development. The preconditions for this scenario include: firstly, the global energy transformation is actively and steadily promoted, and no country is 'going backwards'; secondly, the energy transformation embodies world unity and close cooperation, and advanced international technologies can be popularised in China in a timely manner, while the advantages of China's energy transformation can also be fully utilised globally; thirdly, major national policies are moving in the same direction, and countries' energy transformations complement each other's strengths, promoting exchanges and trade, and making the exchange of knowledge and technology for energy transformation smoother; and fourthly, global energy security is promoted in a coordinated manner to maintain common security without mutual damage.

3.3 Scenario key assumptions and boundary conditions

According to the scenario definition, both scenarios meet the goals of consistent economic development and carbon peaking and carbon neutrality. Specifically, the two scenarios face the same resource and environmental constraints and energy security requirements, which are mainly reflected in the consistent upper limits on wind and solar energy resources, ecological and environmental protection red lines, and power system safety requirements. In terms of specific parameters, the two scenarios have the same population and urbanisation rate, but parameters such as the economic growth rate and the cost of key technologies related to energy production and consumption differ under different scenarios due to the different intensity of international cooperation.

Table 3-2 Key scenario settings and assumptions for the CETO2024

	Baseline carbon neutral scenario (BCNS)	Ideal carbon neutral scenario (ICNS)
Economic and social development goals		
Vision for economic and social development goals	By 2035, socialist modernisation will be realised; by the middle of this century, a rich, strong, democratic, civilised, harmonious and beautiful modern socialist China will be built.	
Carbon Peaking and Carbon Neutrality objective	Carbon dioxide emissions peaking by 2030, Carbon neutrality by 2060	
Resources, environment and energy security constraints		
Resource potential for hydropower	Equal	
Resource potential for wind energy	Equal	

Resource potential for solar energy	Equal	
Resource potential for biomass	Equal	
Ecological red line and environmental protection	Equal	
Security requirements of power system	Equal	
Key assumptions		
Macroeconomic social and policy parameters		
GDP per capita	Adoption of baseline assumptions	Greater
Population	Equal	
Urbanisation rate	Equal	
Prospects for international cooperation	Adoption of baseline assumptions	Tighter and smoother
Energy demand side		
Industrial sector		
Value added by industry	Adoption of baseline assumptions	Greater
Share of value added of energy-intensive industries	Adoption of baseline assumptions	Lower
Production of energy-intensive products	Adoption of baseline assumptions	Lower production of steel, cement, etc.; higher production of olefins, non-ferrous metals, etc.
Transport sector		
Transport passenger and freight turnover	Adoption of baseline assumptions	Greater
Vehicle ownership	Adoption of baseline assumptions	Greater
Electric vehicle penetration	Adoption of baseline assumptions	Greater
Building sector		
Gross floor area	Adoption of baseline assumptions	Greater
Proportion of ultra-low/near-zero energy buildings	Adoption of baseline assumptions	Greater
Energy supply side		
Costs of energy transformation technologies	Adoption of baseline assumptions	Lower
Costs of power system flexibility technologies	Adoption of baseline assumptions	Lower
Costs of carbon capture, utilisation and storage technologies	Adoption of baseline assumptions	Lower
Financing costs of the energy transformation	Adoption of baseline assumptions	Lower

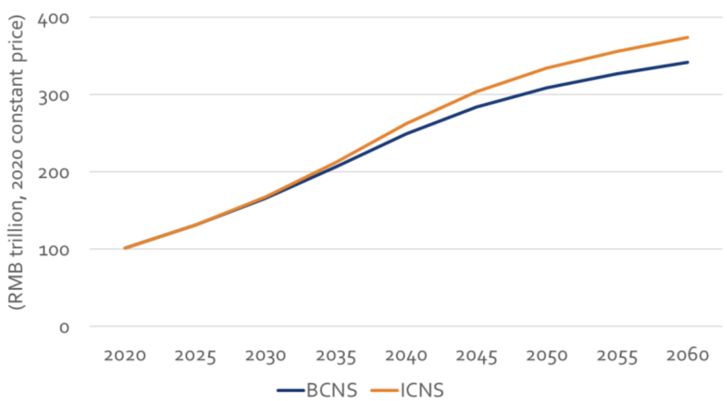
Installed capacity of nuclear power	Equal
Installed capacity of pumped storage	Equal
Fossil fuel prices	Equal

Macroeconomic and social parameters

Economic growth

China's development goals are as follows: By 2035, the country aims to achieve significant growth in economic strength, scientific and technological capabilities, and overall national power, with its per capita GDP reaching levels comparable to those of a moderately developed country. By the middle of this century, China envisions transforming itself into a modern socialist power that is prosperous, strong, democratic, culturally advanced, harmonious, and beautiful. Based on the goal of building a modernised and powerful country in the Chinese style, the economic growth parameters are mainly represented by per capita GDP, and different economic growth parameters are set for the two scenarios in stages. In BCNS and ICNS scenarios, the annual GDP growth rates from 2023 to 2035 are set at 4.7% and 4.9% respectively. By 2035, per capita GDP will reach RMB 144,000 and 151,000, respectively, more than double the 2020 levels, matching the level of a moderately developed country. From 2035 to 2060, the GDP growth rate will slow down. By 2060, the per capita GDP will reach RMB 268,000 and RMB 295,000, respectively (as shown in Figure 3-1).

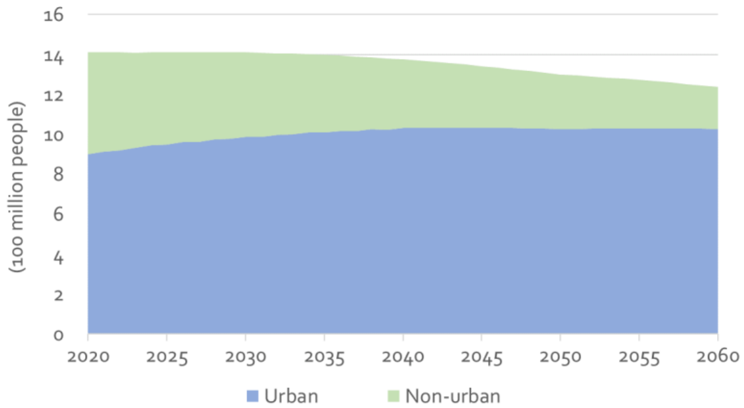
Figure 3-1 Assumptions for GDP, 2020-2060



Population and urbanisation

Population size and urbanisation have a significant impact on energy production and consumption. In terms of population size, China's population is entering a stage of slow growth. In 2022, China's population experienced negative growth for the first time in 60 years, and in 2023, it is 1.41 billion people. According to forecasts, China's total population will peak between 2025 and 2030 and enter a period of negative growth. Driven by the new urbanisation strategy, China's urbanisation rate of the resident population is expected to increase from 53.10% in 2012 to 66.16% in 2023, with 933 million urban residents. According to studies by the Institute of Social Studies of the China Academy of Macroeconomic Research, the World Bank and others, in the future, as China's urbanisation moves into the later stages of the rapid development phase, there will still be room for improvement, albeit at a slower rate of growth. Considering the impact of population policies in the near to medium term, the two scenarios use consistent parameters for population and urbanisation rate, with a population of 1.24 billion and an urbanisation rate of 83% in 2060 (as shown in Figure 3-2).

Figure 3-2 Assumptions of total population and urbanisation rate, 2020-2060



3.4 Scenario analysis results

With significant efforts, the energy transformation can make a decisive contribution to China's efforts to achieve a carbon-neutral society before 2060. By 2060, China's economy should grow between 3.3 to 3.6 times its 2020 level. Total primary energy consumption (accounted using the calorific value method) first increases and then decreases, with consumption falling by about one-third from its peak by 2060. Under the Baseline Carbon Neutrality Scenario (BCNS) and the Ideal Carbon Neutrality Scenario (ICNS), with the accelerated development of energy transformation technologies (including negative carbon technologies such as carbon capture) and related industries, China's energy system can achieve net-zero carbon emissions before 2060, paving the way to make the Chinese society as a whole carbon neutral before 2060.

Significant changes in the structure of total primary energy demand and electricity demand will occur

After the energy transformation, China's energy mix will shift from more than 80% fossil energy to more than 80% reliance on non-fossil energy. In 2022, the total national primary energy consumption (calculated by the calorific value method, which is used also used in the following) was 4,900 Mtce. Growth will continue and then decline by about one-third by 2060 (as shown in Figure 3-3). In 2022, non-fossil energy accounted for 17.6% of primary energy consumption, while fossil fuels made up 82.4%. By 2060, non-fossil energy is projected to account for around 85% of primary energy consumption, with fossil fuels making up around 15%. This represents a dramatic shift in the ratio of non-fossil to fossil energy, moving from "2:8" to "8:2." International cooperation on energy transformation will help accelerate China's progress, enabling the country to achieve a higher share of non-fossil energy consumption by 2060 (as shown in Figure 3-4).

Figure 3-3 Total primary energy demand and structure, 2022-2060 (based on the calorific value method)

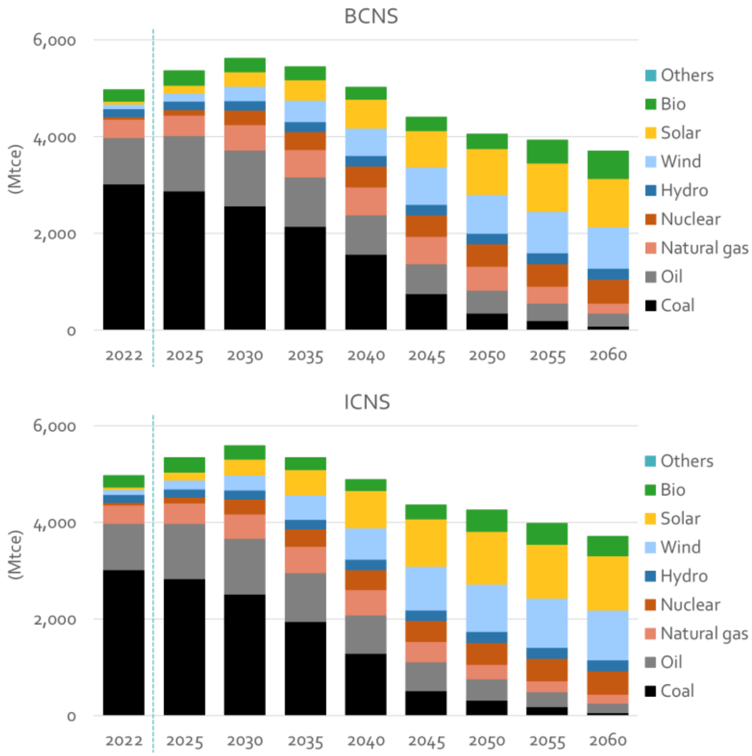
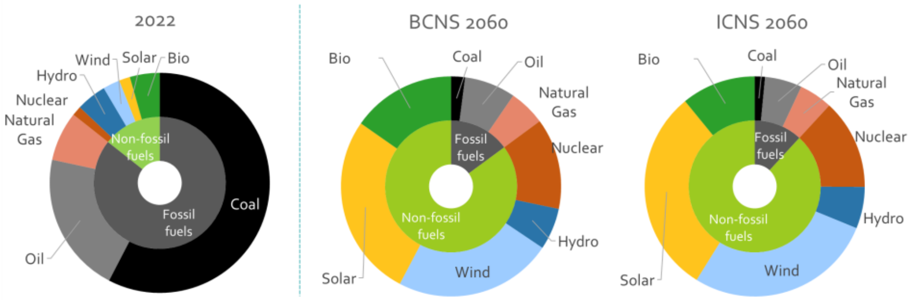
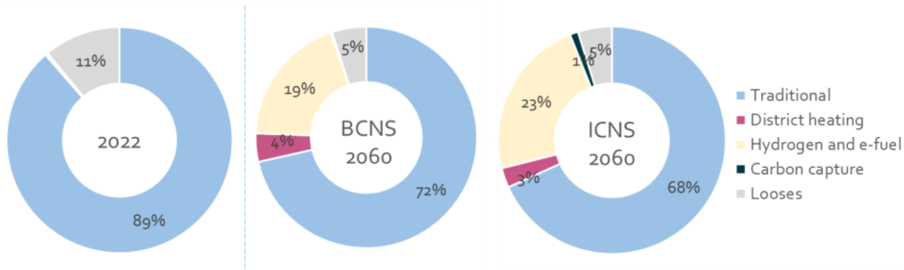


Figure 3-4 Comparison of primary energy demand structure between 2022 and 2060



After the energy transformation, the share of the traditional end-use sector in the total electricity consumption of the whole society will decrease to 68%-72%. The total electricity consumption will increase to 20,000-22,200 TWh in 2060. The share of electricity demand from traditional end-use sectors (mainly industry, buildings, and transport) will decrease from 89% in 2022 to 68%–72% by 2060. In the coming decades, the share of electricity used for processing and conversion (such as for hydrogen production, electric heating, and synthetic fuel production) will steadily increase. Among these, in 2060, electricity consumption for hydrogen and e-fuel production is projected to be 4,100-5,400 TWh, accounting for around 21% of total electricity consumption, while electricity use in district heating is expected to consume 660-870 TWh, making up about 4% (as shown in Figure 3-5).

Figure 3-5 Comparison of electricity demand structure between 2022 and 2060



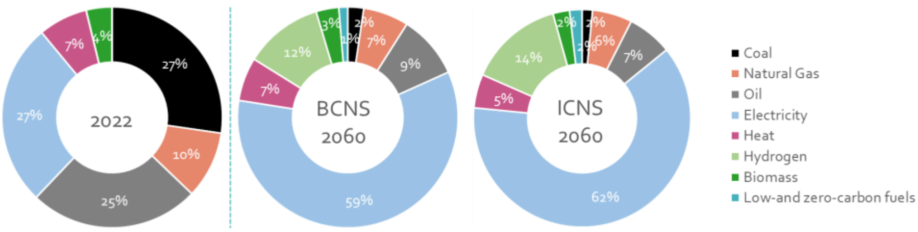
Energy transformation is a critical pillar in building China's carbon-neutral society

With the accelerated development of energy transformation technologies (including carbon-negative technologies such as carbon capture) and related industries, China's energy system could achieve net-zero carbon emissions by 2060. Energy-related activities accounted for 86.5% of the country's total carbon dioxide emissions in 2018. Most of China's energy-related carbon emissions come from end-use sectors and energy processing and conversion. The model analysis shows that carbon dioxide emissions from China's energy system will peak before 2030, providing important support for China's goal to achieve carbon peaking across its economy and society before 2030. After 2030, carbon emissions from the energy system will gradually decline. Under the BNCS and ICNS scenarios, with accelerated development of renewable energy, the accelerated transformation of end-use energy consumption, and the popularisation of zero-carbon and negative-carbon technologies such as carbon capture and storage (CCS) and industrial carbon cycling, China's energy sector is able to achieve net-zero carbon emissions before 2060, providing decisive support for China to achieve carbon neutral society before 2060.

Electrification and energy efficiency are important ways for the end-use sector to move towards carbon neutrality

The transformation of the end-use energy sectors will primarily rely on high-quality economic development, industrial restructuring and improved energy efficiency in the near to medium term, and on electrification and low- and zero-carbon fuel substitution in the medium to long term. Based on the calorific value method, China's end-use energy demand will increase first, followed by a gradual decline, with 2060's value being roughly 30% lower than the peak (as shown in Figure 3-6). During this transformation, the most important driver of end-use energy demand growth is the rapidly increasing electricity demand.

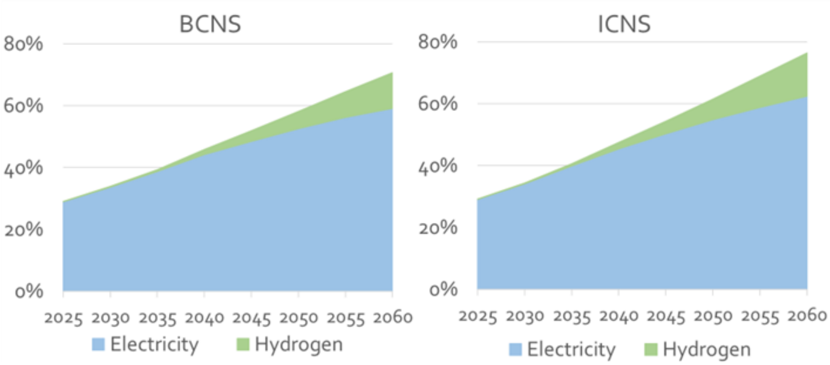
Figure 3-6 Comparison of end-use energy variety structure between 2022 and 2060



Note: Low-carbon and zero-carbon fuels mainly include synthetic fuels from electricity and biofuels.

Electricity and hydrogen will become the dominant energy carriers in China's low-carbon end-use energy transformation. During the *14th Five-Year Plan* period, electricity will replace coal as the most dominant energy source of China's end-use energy demand. The share of electricity in end-use energy demand will increase from about 28% in 2023 to 44%-45% in 2040 and 59%-62% in 2060. Hydrogen's share is also expected to grow from today's roughly 0% to approximately 2% in 2040 and 12% to 14% in 2060 (as shown in Figure 3-7). By 2060, hydrogen will become the second-largest energy resource in China's end-use energy demand.

Figure 3-7 Share of electricity and hydrogen in end-use energy demand, 2025- 2060



Electrification in end-use sectors will progressively expand and ultimately lead to a high level of electrification across all the energy demand throughout the analysed period. Electrification of end-use sectors includes both narrow and broad forms: Narrow electrification refers to the direct use of electricity in end-use sectors, while broad electrification includes the use of electricity, electricity-derived synthetic fuels and electricity-generated heat. Among the different end-use sectors, the transport sector will see the fastest growth in electrification. From 2022-2060, the narrow electrification rate in transportation will increase from 4% to 42%-45%, and the broad electrification rate will rise from 4% to 64%-83%. In industry, the narrow electrification rate will increase from 28% to 49%-53% and the broad electrification rate from 28% to 73%-76%. The building sector will remain the most electrified, with the narrow electrification rate increasing from 37% to 84%- 87% and the broad increasing from 37% to 92%-93%

The share of electric vehicles is rising rapidly, becoming an example for China's energy transformation. By 2060, the number of electric vehicles will reach 480-540 million, accounting for close to 100% of the passenger car fleet. Together with the charging infrastructure that provides flexibility services to the grid, electric and smart vehicles will become an important mean to China's energy consumption transformation.

“Flexible energy use" and "supply-demand interaction" in end-use sectors will be key components of the energy transformation. Industries such as non-ferrous metals, chemicals, light industry, and electrical equipment need to be modified to match cheaper yet fluctuating renewable power. In the building sector, technologies such as PEDF (Photovoltaic, Energy storage, Direct current, Flexibility) building, it is necessary to develop technologies for intelligent public building groups and flexible household energy management to support grid stability under a high share of renewable energy. In the transportation sector, technologies such as smart charging and vehicle-to-grid (V2G) interaction need to be promoted to support power system flexibility and reliability. In the next three decades, the end-use sectors must develop a series of new technologies for "flexible energy use" and "energy demand-response interaction", to enable flexible regulation of loads in the daily power balancing. These technologies will be essential to meet the future needs of the energy transformation.

Building a wind- and solar-dominated new power system supports a comprehensive green transformation of the economy and society

Achieving green power with wind and solar as the core

Developing a new power system dominated by wind and solar energy is an inevitable step in energy transformation. Decarbonizing energy supply is the primary pathway for transforming the energy supply side, with replacing fossil fuel-based electricity with non-fossil energy electricity as the core task. In 2023, non-fossil energy accounted for 53.9% of China’s installed power capacity, while fossil energy accounted for 46.1%. By 2060, China's total installed power generation capacity is projected to reach 10,530-11,820 GW, about four times the 2023 level (as shown in Figure 3-8). The installed renewable energy power capacity will reach about 96%, and the renewable share of power generation will reach 93%-94% (as shown in Figure 3-9). In 2060, the installed capacity of nuclear power and pumped storage will be needing to reach 180 and 380 GW, respectively. In 2060, bioenergy with carbon capture and storage (BECCS) will have an installed capacity of more than 130 GW.

Energy transformation must adhere to the principle of "establishing the new before abolishing the old". Coal-fired power must transform gradually from serving as a baseload power source to becoming a flexible or backup source, while also naturally phasing out as renewable energy generation capacity and power system control capabilities improve. Strengthening international cooperation on energy transformation will help China to further improve its non-fossil energy supply capacity and grid security.

Wind and PV installations are growing significantly, with distributed PV offering the greatest potential. In 2060, China's combined wind and PV power capacity needs to reach 9,320-10,700 GW, of which wind power makes up 2,950-3,460 GW, and PV makes up 6,370-7,240 GW. This means solar PV accounts for roughly two-thirds of China's combined wind and PV power capacity. Among the installed capacity of PV, distributed PV accounts for 70%, which is dominant. Distribution grids need to transform from a unidirectional distribution grid without power sources, into a two-way interactive system with power sources, to create numerous zero-carbon distribution grid hubs to provide strong support for the development of more than 5,000 GW of distributed wind power and solar PV.

Figure 3-8 Comparison of installed power capacity mix between 2022 and 2060

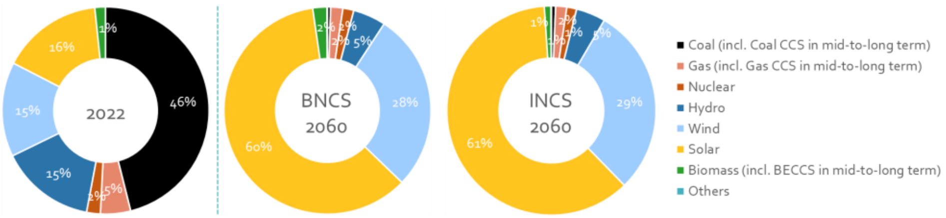
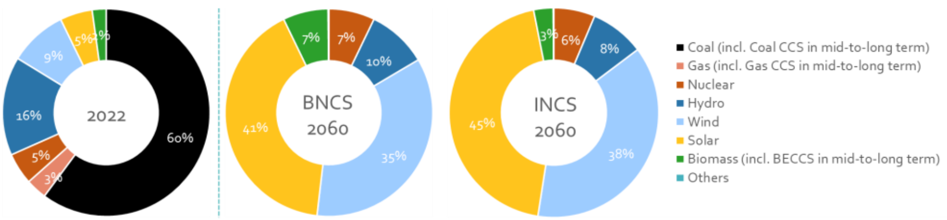


Figure 3-9 Comparison of power generation mix between 2022 and 2060

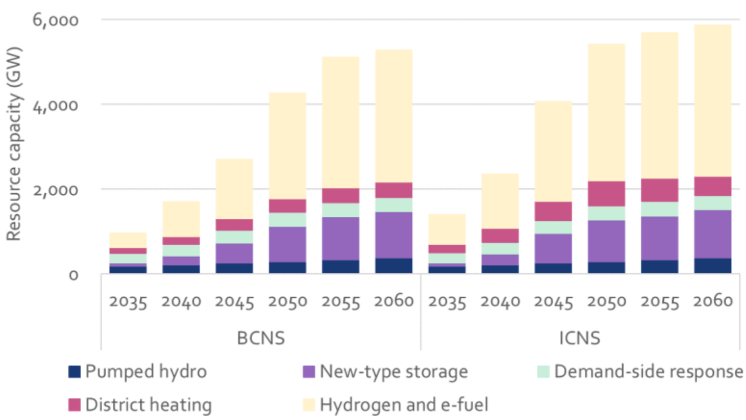


Building a flexible and secure new power system

By 2060, a flexible and secure new power system will be established. By 2035, China's pumped storage and new energy flexibility resources are expected to reach a combined capacity of 950-1,400 GW. Meanwhile, flexible coal power and pumped storage play an important role for real-time balancing. Additionally, industrial demand response will be essential for providing flexibility services during peak load periods. By 2060, China's flexibility resources will need to be expanded to 5,280-5,870 GW. As the matching of electricity supply, demand and storage progresses, new-type storage technologies and hydrogen and e-fuel production will become key power system flexibility resources, significantly reducing the reliance on coal power (as shown in in Figure 3-10).

The large-scale development of advanced energy storage and power-to-hydrogen systems will provide essential support for the safety and stability of the power system. By 2060, the capacity for hydrogen and e-fuel production needs to be increased to 3,110-3,560 GW, thereby accounting for about 60% of all new flexible resources. While participating in real-time balancing, hydrogen and e-fuel production will also take on the new role of providing "inter-seasonal balancing" for electricity. By 2060, new energy storage is expected to contribute about 20% of China’s new flexibility resources, including around 500 million electric vehicles with vehicle-to-grid (EV-V2G) interaction capacity reaching between 810-900 GW. Electrochemical storage stations will be widely adopted across power supply, grid, and charging, reaching a capacity of 240-280 GW.

Figure 3-10 The requirements of flexibility resource scale and structure, 2035-2060



Note: New flexibility resources include new-type energy storage (electrochemical storage stations and EV-V2G), industrial demand response, electric heat production (electric boilers and heat pumps), and hydrogen and e-fuel.

Adhering to the principle of “establishing the new before abolishing the old”, coal power gradually shifts from a baseload source to a regulating and backup power source before eventually being gradually decommissioned. As of today, China's coal power plants have become an important resource for flexibility. By 2035, coal power is expected to take on an increasingly significant role as a balancing resource for power system flexibility, while its generation hours continue to decline. During this process, energy transformation should always adhere to the principle of "establishing the new before abolishing the old", on the basis of the growth of new and renewable energy power generation capacity and the gradual enhancement of power system control capabilities, coal power gradually shifts from a baseload source to a regulating and backup power source while being naturally decommissioned. By 2050, coal power will preliminarily serve as an emergency and backup resource for the grid, providing essential support in critical power events.

The cross-regional interconnection capacity significantly improves, leading to further optimisation of China's electricity grid. In the next 30 years, China's electricity grid structure will gradually evolve, seizing opportunities of the smart grid development. By 2035, the deployment of the national backbone grid following the strategy of West-to-East and North-to-South power transmission with inter-regional mutual support is complete, enabling the power grid to balance power supply and demand across different regions, functioning as a flexibility resource. By 2060, the total scale of electricity exports from the Northwest, Northeast, and North China regions will increase by 140-150% compared to 2022.

Energy transformation creates new opportunities for investment growth, industrial upgrading, and employment

China's low-carbon energy transformation and industrial upgrading reinforce each other, driving economic growth while gradually decoupling it from carbon emissions and fostering new opportunities for industrial development. As a major manufacturing country, China's energy transformation investments promote the advancement and cost reduction of energy technologies and equipment, contributing to lowering global energy transformation costs. This transformation not only reduces carbon emissions and environmental pollution at the source, supporting the construction of a Beautiful China, but also enhances social welfare and improves employment opportunities.

Energy transformation could create new market demands and significant investment opportunities

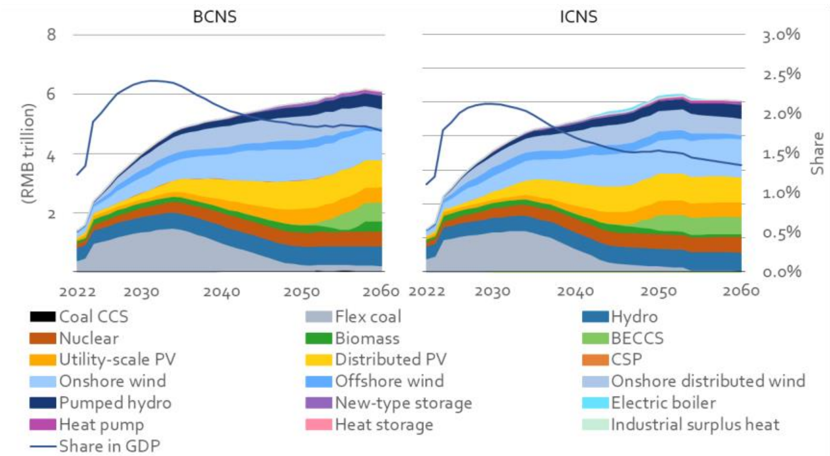
China's energy transformation drives extensive market demand for low-carbon, zero-carbon, and negative-carbon technologies, equipment, and industries related to energy production and consumption. This transformation presents vast investment opportunities, providing sustained endogenous momentum for economic growth.

From the perspective of zero-carbon and negative-carbon technologies essential for achieving carbon neutrality, advancing technologies such as CCS and industrial CO_2 recycling is indispensable. Immediate research and planning are necessary to accelerate their development.

In terms of energy equipment demand, energy transformation over the next 30 years will require updating or retrofitting energy-using equipment across industries, buildings, and transportation. Key technologies and products such as electric arc furnaces, hydrogen-based direct reduction steelmaking, green hydrogen chemical production, ultra-low energy buildings, high-efficiency heat pumps, electric vehicles, and fuel cell vehicles are poised to generate substantial market demand.

Regarding the financial needs for energy equipment manufacturing, by 2060, China's combined wind and solar power capacity will reach approximately 1,000 GW. The annual capital demand for wind, solar, heat pump and other power and heat supply equipment is expected to grow from2 trillion RMB in 2023 to about 6 trillion RMB by 2060, with cumulative investment demand exceeding 160 trillion RMB over the next three decades (as shown in Figure 3-11).

Figure 3-11 Energy Transformation Investment Requirements,2022-2060 (Electricity and Heat Supply Sector)



*Note: *New energy storage in the figure includes electrochemical energy storage and electric vehicle grid interaction. **GDP is calculated at constant 2020 prices.*

China's energy transformation helps reduce the costs of global energy transformation

China's large-scale development of wind and solar energy continuously drives down the costs of renewable energy and related technologies. Economies of scale also accelerate cost reductions in flexibility technologies such as energy storage.

In ICNS, favourable international collaboration in industries and technology exchange enables larger global energy transformation investments, lower financing costs, and faster declines in technology development costs. This fosters the widespread adoption of energy transformation technologies. With disruptive technologies like perovskite photovoltaic cells is becoming widely adopted between 2030 and 2035, cost of solar photovoltaic in BCNS will fall by more than one-third by 2060 compared to 2023 levels, and by approximately half in ICNS.

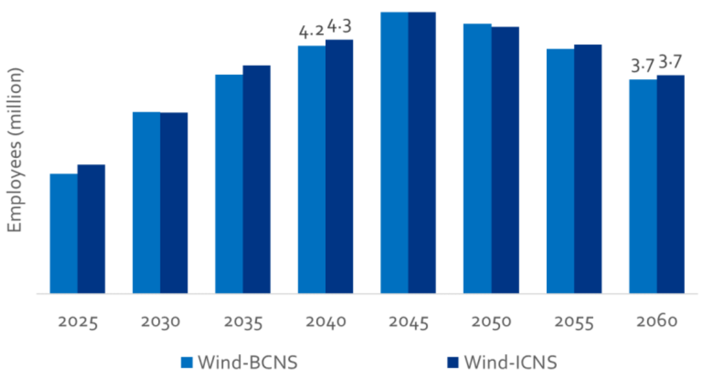
Strengthening international cooperation on energy transformation allows China and other nations to reduce manufacturing, service, and usage costs for new energy technologies, accelerating global progress toward achieving carbon neutrality.

Energy transformation boosts the economy, society and jobs

China's energy transformation has promoted the green and low-carbon development of society and economy. The large-scale and high-quality development of non-fossil energy sources, through the continued substitution of fossil energy, can effectively reduce carbon emissions and environmental pollutants at source and provide energy security for economic and social development. This provides critical support for achieving the goals of a Beautiful China, carbon peaking, and carbon neutrality. At the same time, the energy transformation can create new jobs in the energy sector, with rising wages and increased social welfare, demonstrating that the transformation promotes social equity and supports a just transition.

A comparison of the simulation results under the two energy transformation scenarios shows that, under the Ideal Carbon Neutrality Scenario (ICNS), China's energy transformation generates a higher positive socioeconomic impact compared to the Baseline Carbon Neutrality Scenario (BCNS). This highlights the promising outlook for China, in cooperation with the international community, to create the conditions necessary to follow an ideal path for the energy transformation (as shown in Figure 3-12 and Figure 3-13).

Figure 3-12 Size of employment related to wind and solar power industry, 2025-2060



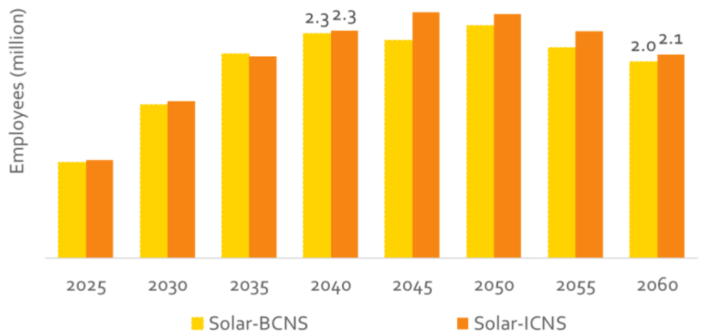
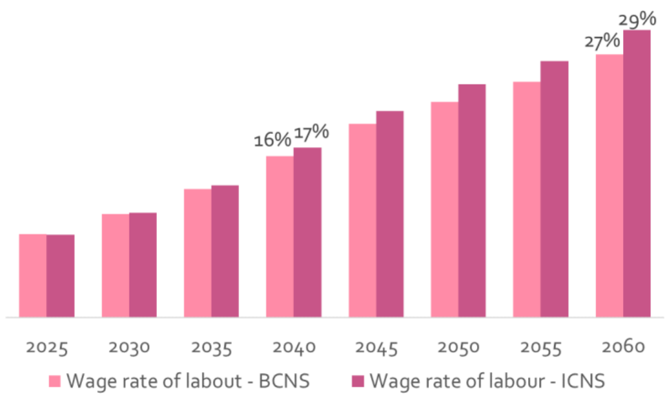


Figure 3-13 Trends in labour wage rate growth, 2025- 2060



Analysis of difficult challenges and uncertainties

China faces a series of difficulties and challenges in advancing its energy transformation. The main ones include:

- **First, the weight of heavy industries in the economic structure.** Energy-intensive industries such as steel, cement, and chemicals hold a significant position in China's economy, making economic restructuring and industrial transformation both difficult and demanding.
- **Second, coal-dominated energy structure.** As the largest energy consumer in the world, more than half of China's energy consumption comes from coal. There is no historical precedent for bypassing the "oil and gas era" and directly replacing coal on a large scale with new and renewable energy sources.
- **Third, the challenge of rapid power system transformation during rapid economic growth.** In recent years, China's electricity demand has grown rapidly. The power system must not only become greener and more low carbon but also ensure security and affordability. Particularly in recent years, while power demand has surged, renewable energy development is constrained by limited land availability, insufficient system capacity for integrating renewable energy, and high storage costs, making further acceleration difficult.
- **Fourth, the market-driving force of energy transformation needs to be strengthened.** For a long time, high-carbon energy in China has been relatively cheap, while low-carbon energy is more expensive, with significant regional differences in energy prices. Using market mechanisms to drive the energy transformation is a particularly challenging task.

Looking ahead, the uncertainties surrounding China's low-carbon energy transformation warrant close attention. The main uncertainties are:

- First, there is significant uncertainty around future adjustments to the industrial structure. Changes in the production of energy-intensive products such as steel, cement, electrolytic aluminium, and chemicals will have a major impact on China's energy supply, demand, and transformation prospects, making accurate predictions difficult at this stage.
- Second, the extent to which digitalisation and smart technologies will drive electricity demand growth in China and the scale of power consumption related to these technologies is currently hard to assess.
- Third, the maturity, security, and economics of zero-carbon and carbon-negative technologies in the medium and long term remain uncertain and difficult to predict.
- Fourth, the prospects for industrial development, international trade and industrial chain supply chain development related to international cooperation on energy transformation are still subject to certain uncertainties.

In summary, China's energy transformation is a long-term and challenging societal project. Within less than forty years, China must first surpass its peak carbon emissions and then achieve carbon neutrality. The challenges are immense, and it is a difficult task. This requires policymakers to face these challenges head-on, find solutions, and seek clarity amid uncertainty, ensuring that China's energy transformation stays on the right path and progresses steadily.

China must simultaneously advance its energy transformation across five areas: electrify energy consumption and improve energy efficiency, decarbonise energy supply, enhance interaction between energy supply and demand, industrialise energy technologies, and modernise energy governance. At the same time, China should strengthen international cooperation on energy transformation, exploring pathways together with the global community. In doing so, China will not only ensure the smooth progression of its own energy transformation but also contribute to the global effort.

4 Energy transformation in the end-use sector

4.1 Main findings

- **End-use energy demand will first rise and then decline.** End-use energy demand, measured using the equivalent calorific value method, is expected to peak around 2030. By 2060, it will decrease by approximately 30% from its peak level. Both BCNS and ICNS show similar trends in end-use energy demand, with differences of around 2%. During this period, the growth in electricity demand will be the primary driver of increases in end-use energy demand.
- **Electricity and hydrogen will become the emerging energy carriers in China's low-carbon end-use energy transformation.** During the 14th Five-Year Plan period, electricity will replace coal as the most dominant energy source of China's end-use energy demand. The share of electricity in end-use energy demand will increase from about 28% in 2023 to 44%-45% in 2040 and 59%-62% in 2060. Hydrogen's share is also expected to grow from today's roughly 0% to approximately 2% in 2040 and 12%-14% in 2060. By 2060, hydrogen will become the second-largest energy resource in China's end-use energy demand.
- Direct carbon emissions from end-use energy sectors will first rise and then decline, peaking before 2030, reaching net-zero by 2060 with carbon removal technologies. Among key sectors, the building sector will be the first to achieve net-zero emissions. In contrast, the industrial and transportation sectors are projected to reduce emissions by more than 90% by 2060 but are unlikely to fully achieve net-zero without relying on carbon removal technologies as a fallback solution.
- **The industrial sector's low-carbon transformation will follow four main pathways:** continuous adjusting industrial structure; promoting energy-saving and low-carbon processes and technologies; developing circular economy; and applying large-scale use of clean energy such as electricity and hydrogen. Industrial end-use energy demand is expected to peak around 2030 and decline by approximately 25% by 2060 compared to 2020 levels (with slightly higher demand in ICNS than BCNS). However, by 2060, China's industrial added value will be about four times that of 2020.
- **The building sector's low-carbon transformation will focus on five key pathways:** improving energy efficiency in new buildings; advancing energy retrofits for existing buildings; developing low-carbon and zero-carbon heating systems; increasing electrification rates; and accelerating the construction of green rural housing. The end-use energy demand in the building sector is expected to peak between 2030 and 2035, at 15–18% higher than 2020 levels (with the BCNS peaking later and at a higher level than the ICNS). By 2060, end-use energy demand in the building sector would decrease by about 11% from its peak. The electrification rate in buildings is projected to reach 84–87% by 2060, with the remaining energy needs met by zero-carbon heat

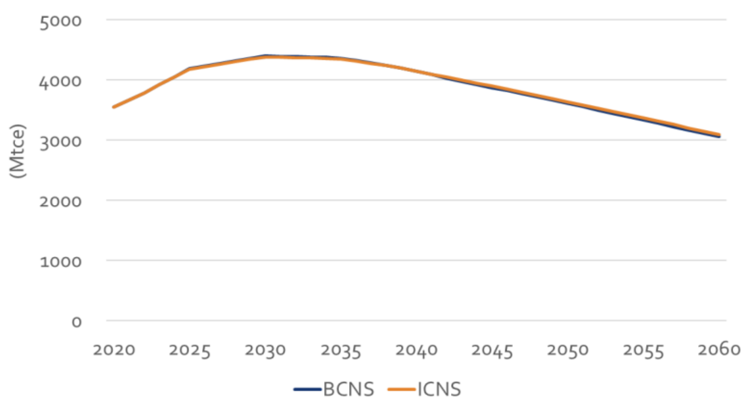
and biomass energy. Power demand from data centres would experience explosive growth, with electricity consumption in 2060 projected to be approximately ten times that of 2020.

- **The transportation sector's low-carbon transformation will focus on three main pathways:** optimizing the transportation structure; promoting the adoption of electric vehicles; and facilitating the transition to low-carbon and zero-carbon fuels. End-use energy demand in the transportation sector is expected to peak around 2030. By 2060, energy demand for transportation will return to levels near those in 2020, with minimal differences between the ICNS and BCNS scenarios. By 2035, the penetration rate of new energy vehicles (including electric, hybrid, and fuel cell vehicles) for passenger cars will exceed 95%. By 2060, the total number of electric vehicles is projected to reach 480–540 million.
- **End-use sector energy demand management will be an important part of the energy transformation.** In industries such as non-ferrous metals, chemicals, light industry and other industries will retrofit their electrical equipment, which can match fluctuating power sources to a certain extent. In the building sector, technologies such as virtual power plants, technologies for intelligent public building groups, and flexible household energy management can reduce peak power loads and balance load fluctuations. In the transportation sector, smart charging and vehicle-to-grid (V2G) technologies will enable vehicles to charge and discharge based on power system dispatch needs. End-use energy technologies will increasingly provide flexible resources, interacting with the energy supply system to reduce the need for additional power generation capacity while offering ancillary services to support the safe and efficient operation of the grid.

4.2 Overall trends in end-use energy demand

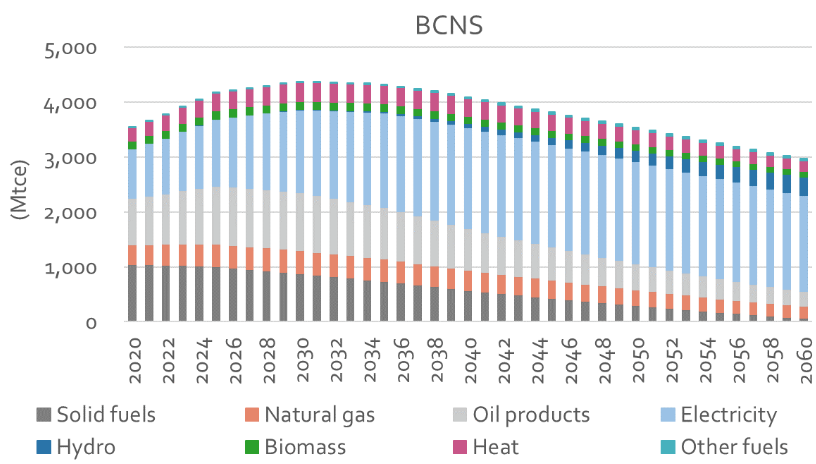
Under both scenarios, the trends in end-use energy demand are similar (as shown in Figure 4-1). End-use energy demand is expected to peak around 2030 and then gradually decline due to changes in market demand, improved energy efficiency, and deep electrification. By 2060, end-use energy demand will decrease to 3,060 Mtce in BCNS and 3,090 Mtce in ICNS.

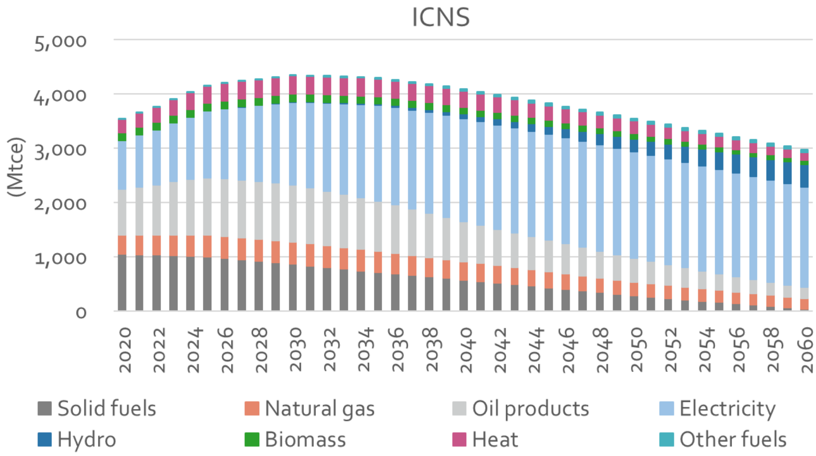
Figure 4-1 End-use energy demand for two scenarios



The share of clean energy in end-use energy demand will steadily increase under both scenarios. In BCNS, coal's share of end-use energy demand decreases from 29.6% in 2020 to 2.3% by 2060, while in ICNS, it drops further to 1.5% by 2060. Similarly, the share of oil demand declines from 23.8% in 2020 to 9.0% in BCNS and 6.5% in ICNS by 2060. For natural gas, its share falls from 10.0% in 2020 to 7.0% in BCNS and 6.4% in ICNS by 2060 (as shown in Figure 4-2).

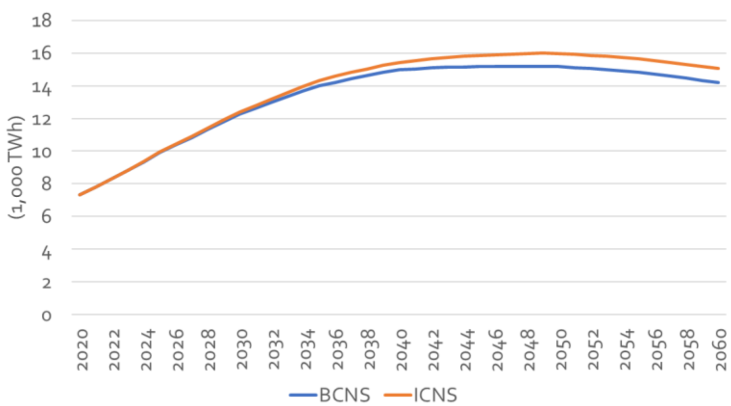
Figure 4-2 Structure of end-use energy demand in the two scenarios





In both scenarios, end-use electricity demand continues to rise until around 2050, where it peaks, followed by a slight decline (as shown in Figure 4-3). By 2060, end-use electricity demand reaches 14,200 TWh in BCNS and 15,100 TWh in ICNS. Electrification rates increase steadily under both scenarios. In BCNS, the share of direct electricity consumption in end-use energy demand rises from 25.4% in 2020 to 39.4% in 2035 and 57.0% in 2060. In ICNS, electricity's share in end-use energy demand reaches 40.4% in 2035 and 60.5% in 2060.

Figure 4-3 Two scenarios end-use electricity demand



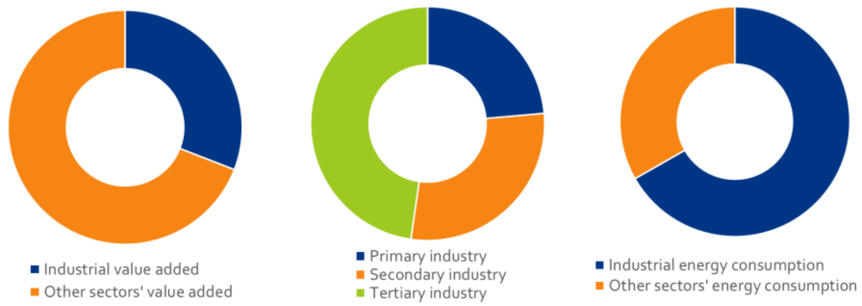
4.3 Industrial sector

Industrial end-use energy demand is expected to peak by 2030

Low-carbon development in the industrial sector is critical to achieving China's carbon peak and carbon neutrality goals. Industry has long been the cornerstone of China's economy, contributing over 30% of GDP and supporting significant social employment while driving steady economic growth. At the same time, it is the primary source of energy consumption and carbon emissions, making it essential to the nation's decarbonization objectives.

The deep decarbonization of the industrial sector will be a strategic and systematic transformation requiring sustained, innovative efforts. This complex, long-term endeavour demands breakthroughs in concepts, technologies, business models, and pathways. Success will depend on coordinated advancements in areas such as industrial upgrading, demand reduction, energy efficiency improvements, and energy substitution (as illustrated in Figure 4-4).

Figure 4-4 Share of value added, employment and energy consumption in the industrial sector, 2020

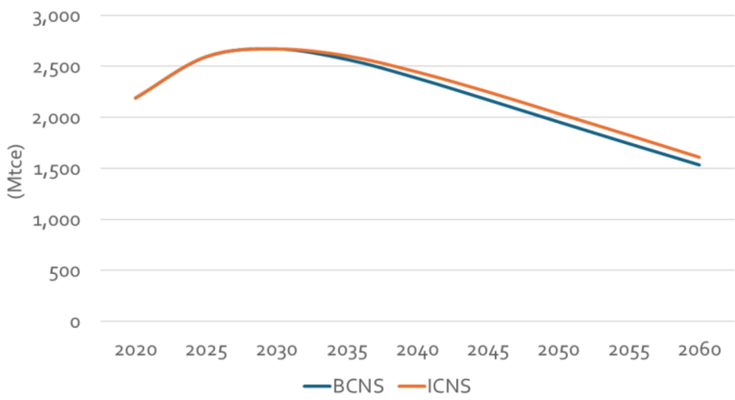


Source: China Statistical Yearbook

In BCNS, industrial energy demand increases from 2,190 Mtce in 2020 to a peak of approximately 2,700 Mtce by 2030. It then gradually declines to 1,530 Mtce by 2060. In ICNS, industrial energy demand also peaks around 2030 at a similar level to the BCNS but declines more slowly, reaching 1,610 Mtce by 2060.

The slightly higher energy demand in ICNS reflects a more favourable international environment that allows China to better leverage its comparative advantages in the industrial sector (as shown in Figure 4-5).

Figure 4-5 Projection for end-use energy demand in the industrial sector



Low-carbon industrial development will reshape China's industrial landscape and productivity distribution. The transition to low-carbon industrial development will redefine production functions and factor supply conditions, restructuring regional comparative advantages and development patterns. Under the combined pressures of industrial iteration, rising factor costs, and stricter environmental and carbon emission constraints, carbon-intensive industries will accelerate the transformation.

The abundant renewable energy resources in China's central and western regions will become a key comparative advantage in the carbon-neutral era, positioning these areas as critical hubs for resource- and capital-intensive industries. By 2060, over 50% of electric arc furnace steel production, 60% of electrolytic aluminium production, and more than 70% of synthetic ammonia and other chemical production are expected to be concentrated in these renewable energy-rich regions. This will enable localized use of green electricity and green hydrogen, supporting deep decarbonization of industrial products while fostering sustainable development and low-carbon growth in these areas.

Four pathways to achieving carbon neutrality in the industrial sector

Industry restructures towards to advanced, high value-added, and service-oriented

Over the past decade, China's industrial system has successfully passed "stress tests" such as international trade disputes and the impact of the COVID-19 pandemic, establishing a "China model" for high-quality industrial development. Looking ahead, China will further optimize its industrial structure by emphasizing high-end, intensive, and service-oriented growth.

By 2060, the share of high-value-added industries, including pharmaceuticals, machinery manufacturing, and electronics, will increase from less than 35% in 2020 to over 50% (as shown in Figure 4-6). Meanwhile, the share of traditional energy-intensive industries—such as steel, cement, petrochemicals, and non-ferrous metals—will decline from nearly 40% in 2020 to less than 30%. Production volumes for these energy-intensive products are expected to peak during the 14th Five-Year Plan period, with 2060 output levels decreasing by 30–50% compared to 2020 (as shown in Figure 4-7 and Figure 4-8).

Figure 4-6 Industrial Value-added Structure by Sector in 2020 and 2060

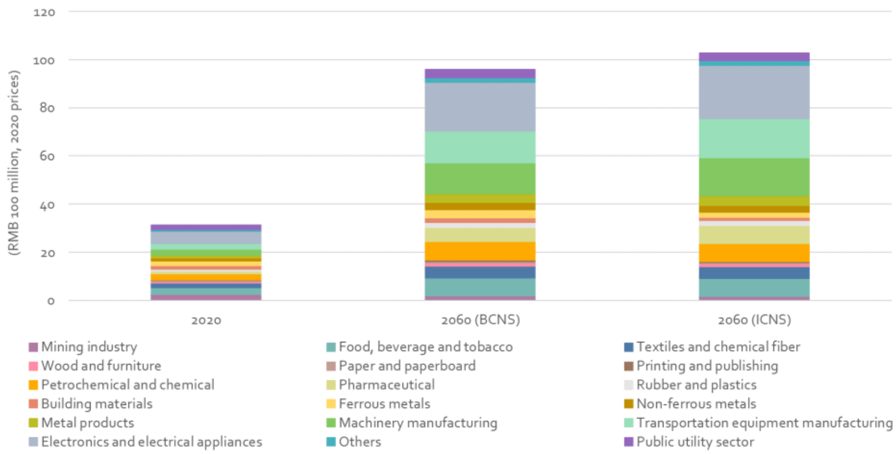


Figure 4-7 Change in crude steel production from 2020 to 2060 (by process)

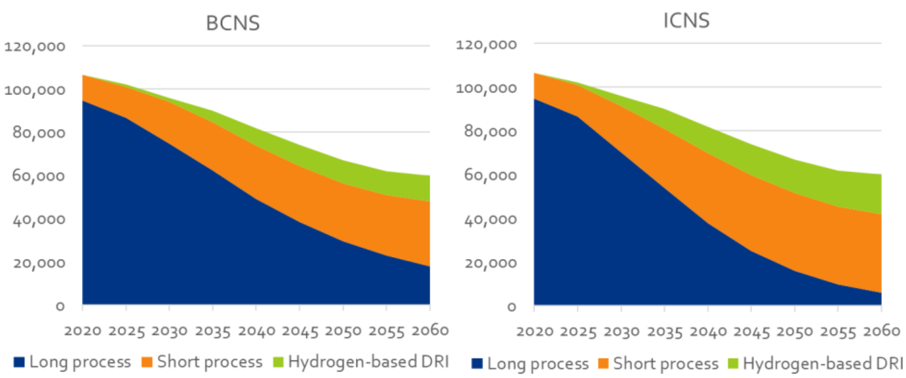
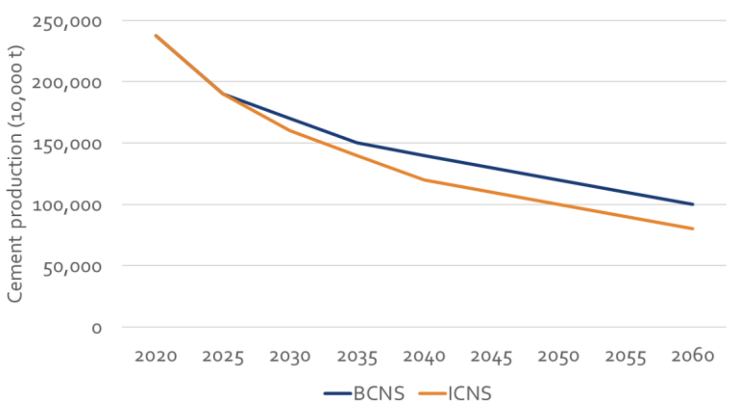


Figure 4-8 Change in cement production from 2020 to 2060

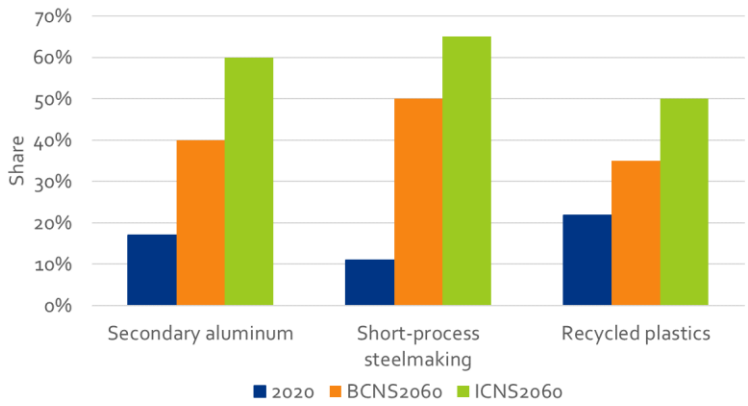


Circular integration will define the new industrial development model and drive process transformation.

China's circular industrial development system has already taken shape. In 2020, recycled aluminium, electric arc furnace (EAF) steel, and recycled plastic accounted for 17%, 11%, and 22% of their respective total production. During the 13th Five-Year Plan period, the circular economy contributed 25% to overall carbon reduction efforts. As a new economic growth model based on the principles of "reduction, reuse, and recycling," the circular economy will become a cornerstone of China's industrial transformation. It will drive a shift in processes from reliance on primary resources to the adoption of secondary, recycled materials.

By 2060, in BCNS, the share of recycled aluminium, EAF steel, and recycled plastic in total production will increase to approximately 40%, 50%, and 35%, respectively. In ICNS, with more robust low-carbon policies, these shares will rise further to 60%, 65%, and 50% (as shown in Figure 4-9).

Figure 4-9 Major product recycling process production shares in 2020 and 2060

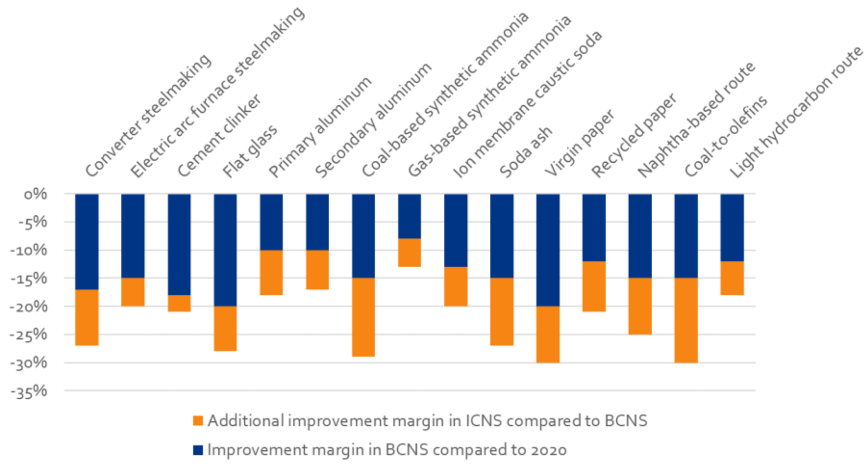


AI and advanced technologies would boost Energy Efficiency

Significant progress has been made in improving energy efficiency within China's industrial sector, with notable advancements in energy performance for major energy-intensive products. Amid the wave of a new industrial revolution characterized by intelligence, digitization, and networking, industrial energy efficiency is poised to improve further.

In BCNS, energy efficiency for key products is expected to improve by 15–25% by 2060 compared to 2020 levels. In ICNS, the deep application of AI, advanced technologies, and innovative business models—particularly driven by digital upgrades—will unlock substantial additional efficiency gains. By 2060, energy efficiency for key products is projected to improve a further 10–15% compared to BCNS. At this point, China is expected to establish a number of world-class energy-efficient factories, positioning itself as a global leader in industrial energy efficiency (as shown in Figure 4-10).

Figure 4-10 Decline in energy consumption per unit of major products in 2060

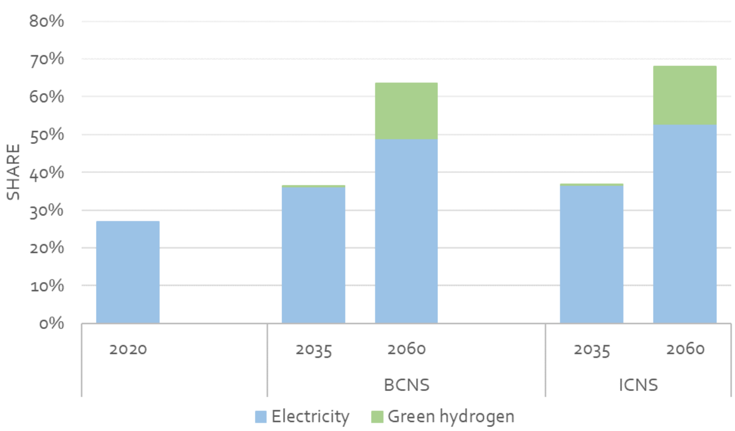


Energy end use system transits towards high share of electricity and hydrogen

In recent years, the energy consumption structure of China's industrial sector has steadily improved, with coal's share in the energy mix declining to 56% in 2021. This trend will continue, with coal usage shifting toward cleaner, more efficient, and low-carbon applications. Electrification and hydrogen energy—specifically green hydrogen—will play leading roles in transforming industrial energy consumption.

In BCNS by 2060, the electrification rate will reach 49.0%, and hydrogen will account for 14.5% of industrial energy consumption. In ICNS, driven by large-scale adoption of electric heating technologies and significant reductions in green hydrogen costs, the electrification rate will rise to 52.9%, and hydrogen's share will increase to 15.1% (as shown in Figure 4-11).

Figure 4-11 Share of electricity and hydrogen energy demand in the industrial sector, 2020 to 2060



4.4 Building sector

End-use energy demand in the building sector will first increase and then decrease

The building sector is one of China's major contributors to energy consumption and carbon emissions. Economic growth, urbanization, and improving building service levels will drive further increases in energy demand. Conversely, enhanced energy efficiency standards, wider adoption and continuously upgrading of energy-saving technologies and products, will enable higher-quality services with lower energy inputs. As a result, the building sector energy demand will rise in the near to medium term and gradually decline in the medium to long term.

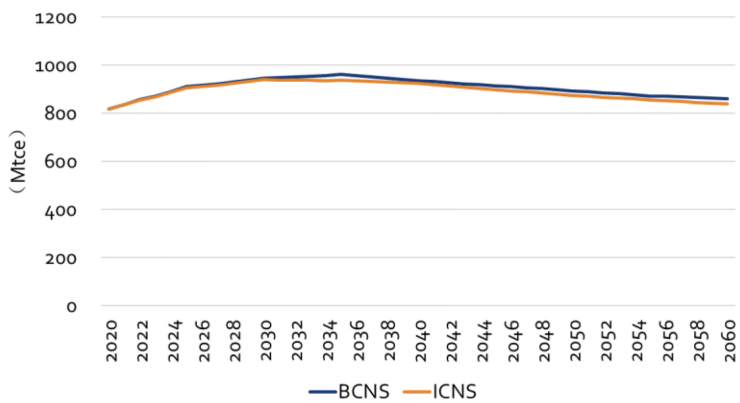
In 2020, based on the current national energy consumption accounting standards (including only commercialized energy), the building sector's end-use energy demand was approximately 700 Mtce, accounting for about 20% of total end-use energy consumption of China. Additionally, rural areas consumed around 120 Mtce of non-commercialized biomass energy, bringing the total to approximately 820 Mtce.

Looking ahead, as biomass energy consumption becomes increasingly commercialized and included in energy statistics, this analysis of building sector energy demand and consumption structure incorporates all forms of biomass energy.

End-use energy demand in the building sector

Under both scenarios, end-use energy demand in the building sector follows a pattern of initial growth followed by a decline. The demand peaks at different times: 2035 for BCNS and 2030 for ICNS, with respective peak values of 960 Mtce and 940 Mtce. By 2060, the building sector's energy demand is projected to decrease to 860 Mtce in BCNS and 840 Mtce in ICNS. This represents a 2.5% lower demand in 2060 for ICNS than BCNS (as shown in Figure 4-12).

Figure 4-12 End-use energy demand in the building sector for different scenarios

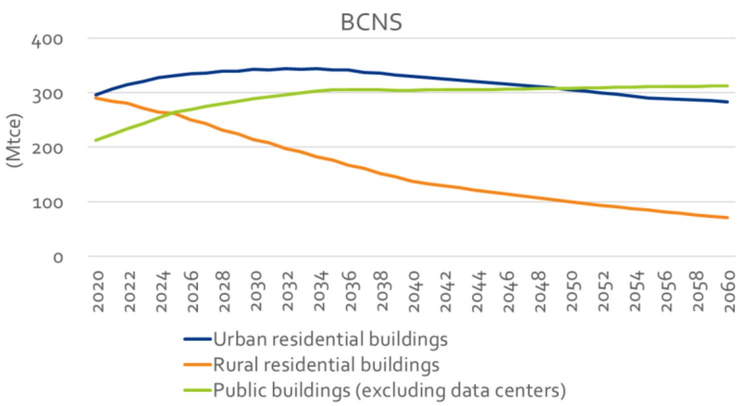


End-use energy demand by building type

Driven by changes in building area and energy intensity trends, end-use energy demand varies across building types. In BCNS, urban residential energy demand initially grows and stabilizes between 2030 and 2035, peaking at approximately 340 Mtce. Afterward, it gradually declines to 280 Mtce by 2060, slightly below 2020 levels. Rural residential energy demand shows a continuous decline, dropping to 70 Mtce by 2060, only one-fourth of the 2020 level. Commercial and public buildings (excluding data centres) experience steady energy demand growth, increasing rapidly to reach 300 Mtce by 2035, then stabilizing with a slow rise to 310 Mtce by 2060.

In ICNS, enhanced international cooperation and cost reductions in energy-saving and low-carbon technologies lead to higher adoption rates of advanced technologies. This scenario also supports the development of more diverse and high-end energy products and services. By 2060, urban and rural residential energy demand in ICNS is slightly lower than BCNS, while demand for commercial and public buildings (excluding data centres) is marginally higher. Overall, combined energy demand for these three building types decreases by 3.2% compared to BCNS (as shown in Figure 4-13).

Figure 4-13 End-use energy demand outlook for various building types in BCNS

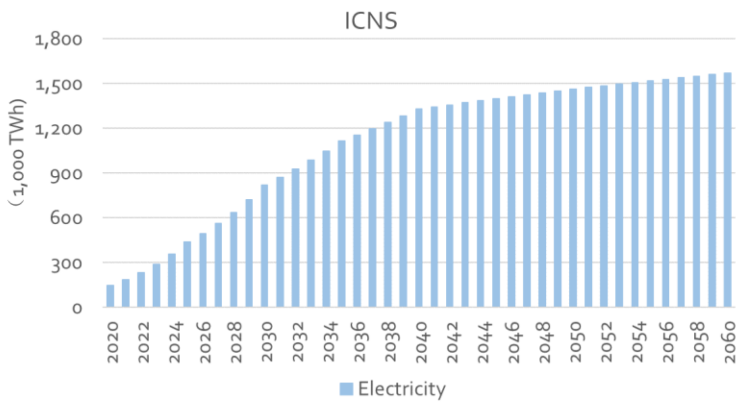


Energy demand in data centres

Energy demand in data centres is expected to grow explosively. On one hand, advances in artificial intelligence and big data analytics will drive exponential increases in computing power requirements, rapidly escalating energy demand. On the other hand, breakthroughs in hardware technology and improvements in deep learning algorithms will enhance computational performance while reducing energy use per unit of computing power. Additionally, the Power Usage Effectiveness (PUE) metric for data centres still has room for significant improvement, further enhancing energy efficiency.

In the long term, both the growth in computing power and advancements in computational efficiency carry substantial uncertainty, making energy demand forecasts challenging. While ICNS may involve higher computing power requirements compared to BCNS it also assumes greater energy efficiency for IT equipment and data centres. For this reason, this study does not differentiate data centre energy demand between the two scenarios. By 2060, electricity demand from China's data centres is projected to reach approximately 1,600 TWh, nearly ten times the 2020 level (as shown in Figure 4-14).

Figure 4-14 Data eentre power demand outlook

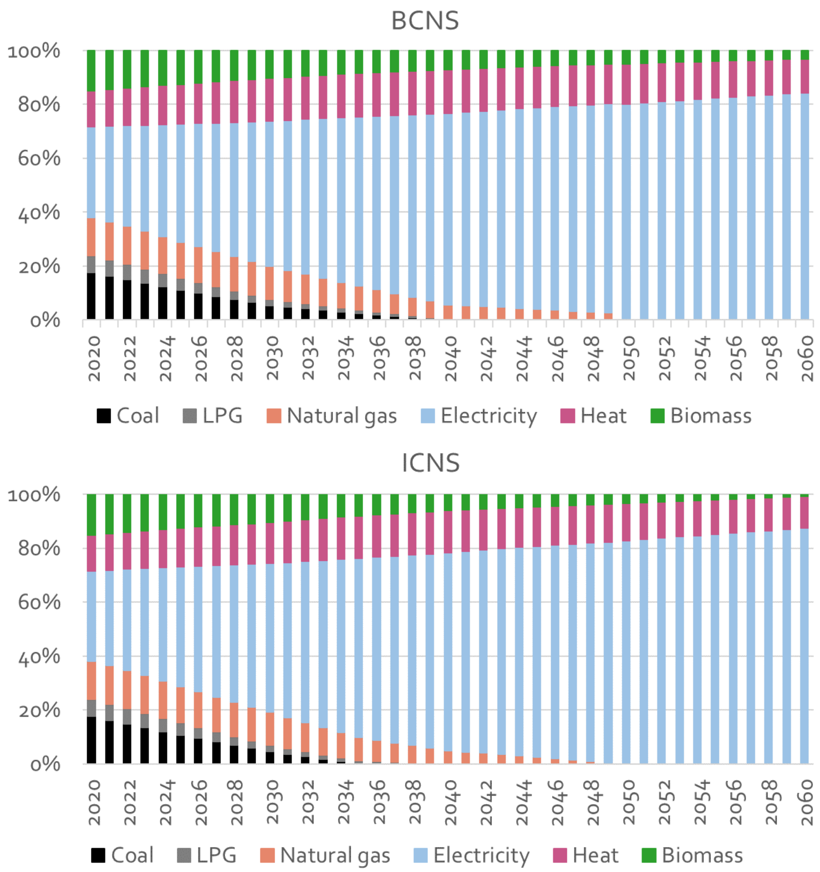


End-use energy demand by energy type

Increasing electrification rate and replacing coal, natural gas, and other fossil fuels with green electricity are crucial for achieving low-carbon transformation in the building sector. Heating, as the most fossil-fuel-intensive area in the building sector, is a key focus for decarbonization, making the adoption of low-carbon and zero-carbon heating solutions particularly important.

Under both BCNS and ICNS, the share of fossil and biomass energy consumption in the building sector steadily declines. Coal, oil, and natural gas consumption are gradually phased out. The share of electricity consumption continues to rise, while the share of heat consumption is overall stable with increase at first and decline then. In ICNS the reduction in fossil energy use occurs more rapidly. By 2060, most of the building sector's end-use energy demand will be met by renewable electricity, with the remainder supplied by zero-carbon heat and biomass energy (as shown in Figure 4-15).

Figure 4-15 End-use energy mix in the building sector under the two scenarios



End-use energy demand in the building sector is driven by multiple factors

Total building area will continue to grow, with the growth rate gradually slowing

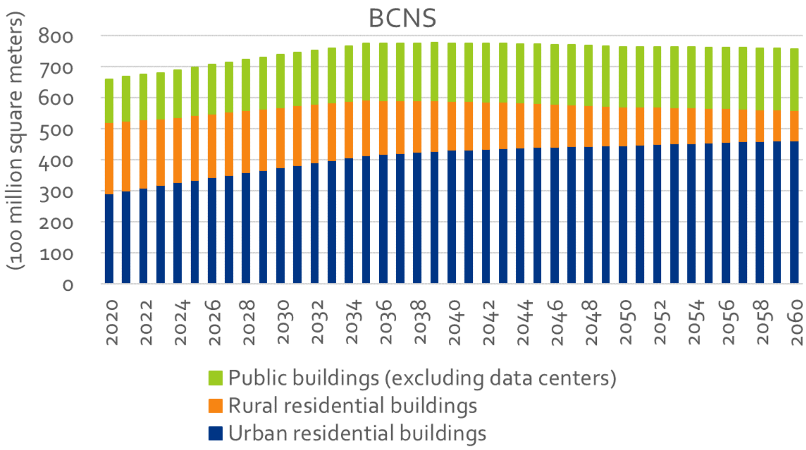
In 2023, China's urbanization rate was 66.16%, leaving room for further growth compared to developed countries. By 2060, urbanization is expected to exceed 80%, driving increased demand for urban residential buildings, while rural residential demand will decline. Additionally, the continued expansion of the service sector will further boost the demand for public buildings.

From a per capita perspective, urban residential area per capita in China currently approaches the lower end of levels in developed countries and is expected to grow moderately in the future. Rural residential area per capita is already comparable to the mid-levels in developed countries and is projected to remain stable, slightly exceeding current levels by 2060. Commercial and public building area per capita still lags significantly behind developed countries, particularly for buildings such as hospitals and schools, which are expected to experience substantial growth.

Projections indicate that total floor area for civil buildings in China will continue to grow rapidly until 2035, after which the growth rate will slow, peaking around 2040. Beyond 2040, total building area will stabilize with a slight downward trend. In ICNS, more frequent international exchange and cooperation will modestly increase demand for hotel buildings, leading to slightly higher commercial and public building area compared to BCNS.

At peak, total building area is projected to reach 77.7 billion m² in BCNS and 77.8 billion m² in ICNS. By 2060, total building area is expected to decrease to 75.8 billion m² in BCNS and 76.4 billion m² in ICNS (as shown in Figure 4-16).

Figure 4-16 Building area projections by type in BCNS



Demand for a better quality of life drives improvements in building services

As living standards rise and the functionality and quality of services in the service sector improve, consumers will increasingly prioritize building quality, demanding enhanced features and indoor environments. This shift will drive the energy intensity of various building end-uses to continue rising. By 2060, energy demand for appliances in urban residential buildings is projected to increase to approximately 6.5 times the 2020 level per unit of floor area. Similarly, energy demand for hot water in commercial and public buildings is expected to grow to about 2.5 times the 2020 level per unit of floor area.

Pathways for low-carbon transformation in the building sector

Expanding energy-efficient buildings to reduce energy intensity

Energy-efficient buildings are designed with enclosures that offer superior thermal performance, effectively reducing energy demand on space heating and cooling service. Some energy-efficient designs also enhance natural lighting, which lowers lighting energy requirements. Currently, one-third of urban buildings in China are non-energy-efficient, and the majority of rural buildings remain non-energy-efficient.

In the future, promoting the construction and retrofitting of energy-efficient buildings to increase their share will be a critical strategy for reducing energy demand and carbon emissions in the building sector.

Improving energy efficiency standards for new urban buildings

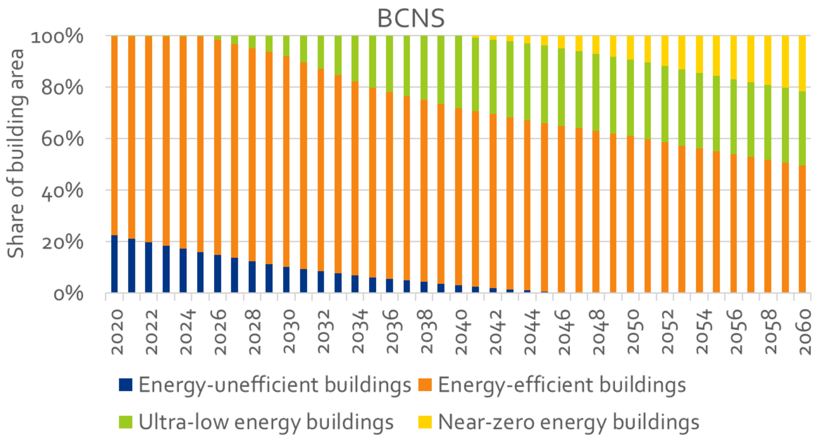
China plans to further enhance energy efficiency standards for new buildings and accelerate the adoption of ultra-low energy and near-zero energy building standards. According to the *Carbon Peaking Implementation Plan for Urban and Rural Construction*, by 2030, new residential buildings in severely cold and cold regions would be required to meet 83% energy efficiency standards, while those in other regions should achieve 75%. New commercial and public buildings are expected to meet 78% energy efficiency standards. Both BCNS and ICNS are based on these targets.

In BCNS, northern urban residential buildings, other regional residential buildings, and commercial and public buildings are projected to fully adopt ultra-low energy building standards by 2030, 2045, and 2040, respectively. Near-zero energy building standards would be fully implemented by 2045, 2055, and 2050. In ICNS, more effective international cooperation and technology sharing accelerate these transitions, which standards would be fully implemented almost five years earlier than in BCNS respectively.

In both scenarios, the share of non-energy-efficient buildings in residential and public sectors would decline until it reaches zero. The proportion of near-zero energy buildings would steadily increase, while the shares of energy-efficient and ultra-low energy buildings would first rise and then decline. By 2060, in ICNS, the share of near-zero energy buildings would be higher, while the shares of energy-efficient and ultra-low energy buildings would be lower compared to BCNS.

For example, in northern urban residential buildings by 2060, the share of ultra-low energy and near-zero energy buildings increases from nearly zero in 2020 to 28.9% and 21.4%, respectively, in BCNS, with energy-efficient buildings decreasing to 49.7%. In ICNS, the shares of ultra-low energy and near-zero energy buildings rise to 22.0% and 28.4%, respectively, with energy-efficient buildings declining to 49.6% (as shown in Figure 4-17).

Figure 4-17 Distribution of buildings with different energy efficiency ratings in urban residential buildings in the northern region in BCNS



Advancing deep energy retrofitting of existing buildings

Deep energy retrofitting of existing buildings, when technically and economically feasible, has the potential to achieve over 20% energy savings. Enhancing the retrofitting of existing buildings will be a critical measure to reduce energy intensity in the building sector. The model prioritizes retrofitting non-energy-efficient buildings, followed by older energy-efficient buildings that need updates to meet current standards.

The ICNS envisions more extensive retrofitting efforts compared to BCNS, resulting in a larger cumulative retrofitted area. Since the difference in retrofitting intensity between the two scenarios primarily emerges after 2030, the ICNS assumes a retrofit rate 5 %-points higher than the BCNS in each Five-year Planning period. However, this difference in retrofitting intensity does not significantly impact the overall share of energy-efficient buildings between the two scenarios.

Advancing the construction of green rural houses

China's rural areas currently lack mandatory building energy efficiency standards, resulting in most rural buildings not being energy efficient. This leads to higher energy demand per unit area for heating and cooling and generally poor indoor thermal conditions. Moving forward, accelerating the construction of green rural housing is essential. Efforts should focus on improving the thermal performance of building enclosures, enforcing energy-efficient design standards for new rural buildings, and integrating energy retrofits for existing rural buildings into clean heating initiatives. These measures will significantly increase the share of energy-efficient rural buildings, with near-zero energy rural housing being promoted in suitable regions.

The share of non-energy-efficient rural buildings is expected to decline rapidly in the coming years. In ICNS, stronger promotion of energy-efficient, ultra-low energy, and near-zero energy rural housing would result in higher adoption rates than BCNS. By 2060, in northern rural residential areas under the ICNS, the share of ultra-low energy and near-zero energy buildings is projected to reach 25%.

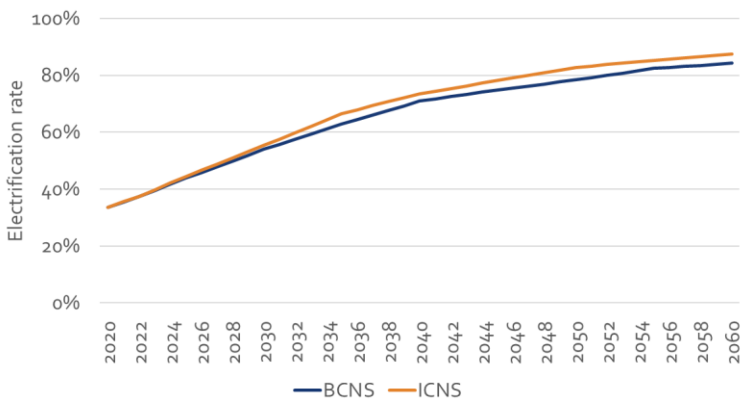
Accelerating the optimization of building energy structures to achieve low-carbon transformation

Promoting electricity substitution

Electrification is a critical pathway for replacing direct fossil fuel use in the building sector and a fundamental prerequisite for achieving low-carbon development. Currently, the level of electrification in China's building sector falls short of low-carbon development requirements. Moving forward, the adoption of technologies such as heat pumps, electric water heaters, and electric cooking appliances should be promoted based on regional conditions to replace fossil fuel-based equipment and continuously increase electrification rates in the building sector.

In BCNS, the electrification rate in the building sector is projected to rise to 84.2% by 2060. In ICNS, greater innovation in electricity substitution technologies, combined with lower costs and higher adoption rates, is expected to increase the electrification rate to 87.4% by 2060 (as shown in Figure 4-18).

Figure 4-18 Electrification rates in the building sector under the two scenarios



Promotion of low-carbon and zero-carbon heat supply

Heating accounts for over 30% of energy consumption in the building sector and more than 70% of the sector's coal consumption. Therefore, low-carbon heating transformation is critical for decarbonizing the building sector. Future efforts should adopt differentiated strategies for various climate zones and building types to advance low-carbon heating.

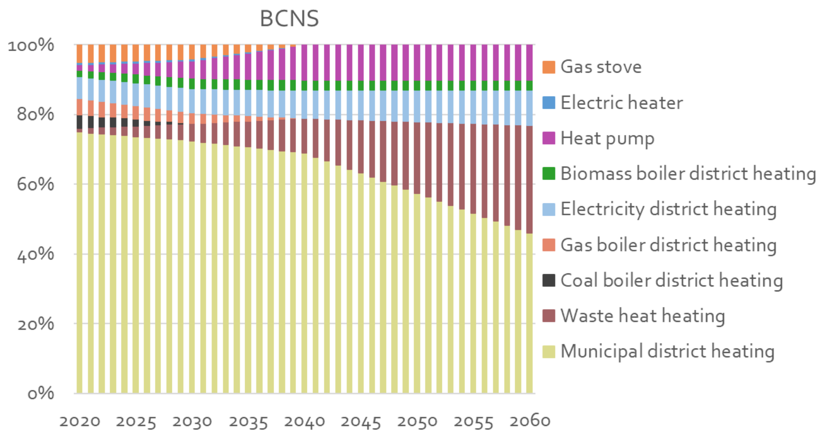
In northern urban areas, existing district heating networks should be optimized by prioritizing and fully utilizing surplus heat from power plants, industrial facilities, and data centres and so on to replace fossil fuels-based heating. The remaining heating demand may be met with zero-carbon heat sources such as renewable electricity and biomass. For areas not covered by district heating or for ultra-low and near-zero energy buildings, localized heating solutions such as individual heat pumps (air-source, ground-source, water-source, and wastewater-source), medium- and deep-layer geothermal, solar energy, and biomass heating technologies should be promoted.

Under both scenarios, the share of surplus heat in heating northern urban residential buildings (excluding ultra-low and near-zero energy buildings) is expected to rise from less than 2% in 2020 to 31% and 33%, respectively, by 2060.

In hot-summer and cold-winter regions, heat pumps should be the preferred heating option, gradually replacing coal and gas for heating. Residential buildings are better suited for decentralized heating systems, while public buildings would adopt centralized heating at the building level.

In rural areas, energy retrofits for buildings should be prioritized, with air-source heat pumps promoted for decentralized heating. In regions where heat pumps are unsuitable, such as in severely cold climates zone, alternative heating solutions like electric boilers, electric heaters, and biomass stoves would be considered (as shown in Figure 4-19).

Figure 4-19 The distribution of heating technologies in northern urban residential buildings in BCNS



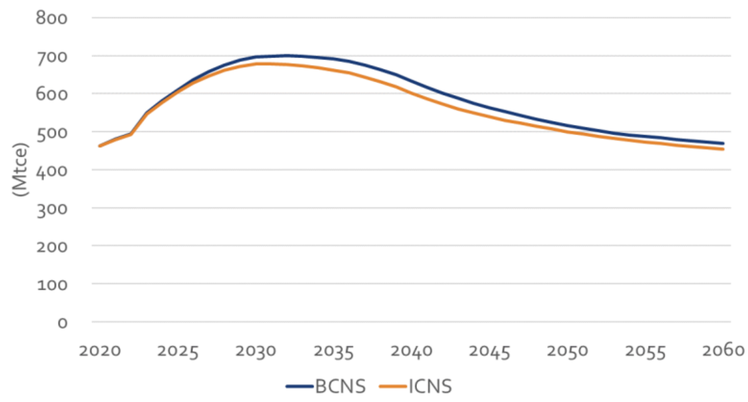
4.5 Transport sector

Energy demand for transportation will see peaking around year 2030 and then steadily decline

End-use energy demand in the transport sector

In terms of total end-use energy demand, the transportation sector is projected to peak at 699 Mtce in BCNS, subsequently declining to 470 Mtce by 2060. In ICNS, the peaking value is slightly lower at 678 Mtce, with demand falling to 455 Mtce by 2060 (as shown in Figure 4-20).

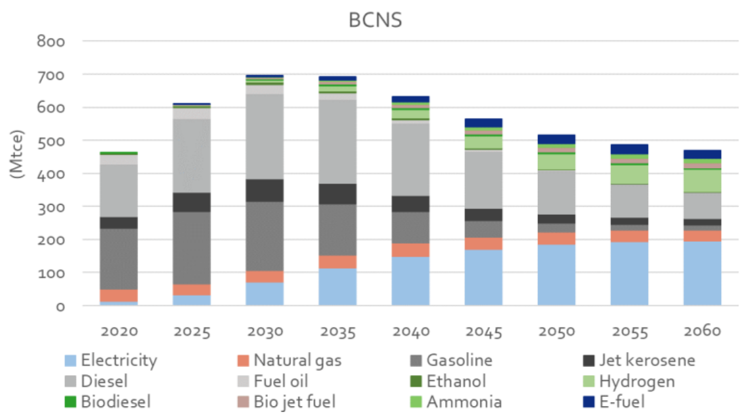
Figure 4-20 Transport end-use energy demand, 2020-2060

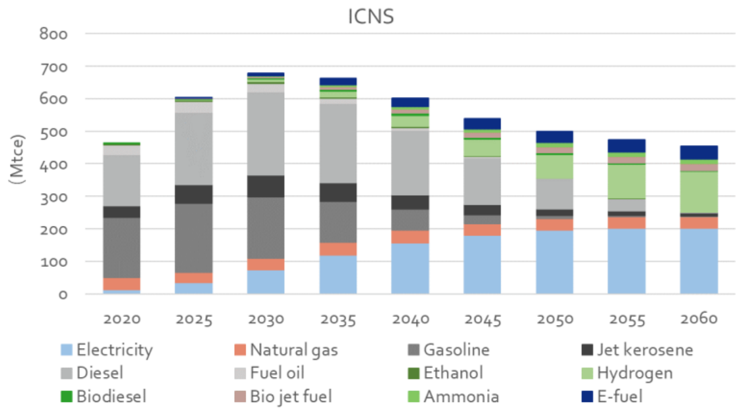


End-use energy demand by energy type

After 2045, electricity is expected to become the dominant energy source in the energy mix for transportation sector (as shown in Figure 4-21). In BCNS, by 2060, electricity will account for 41.5% in the energy mix, while hydrogen will rise to 14.5%. In contrast, the ICNS projects a higher share of electricity at 44.6% and a significantly stronger role for hydrogen, with its share reaching 27.9% in year 2060. Additionally, in ICNS, the share of oil products will decline to 2.9%, while biofuels will increase to 4.9%, and other P-t-X fuels will account for 8.8% in the energy mix.

Figure 4-21 Structure of transport end-use energy demand, 2020-2060



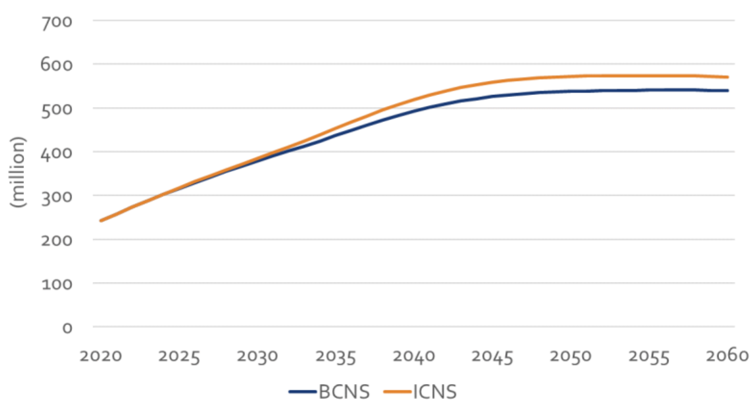


End-use energy demand in the transport sector is driven by multiple factors

Growth in vehicle ownership

With increasing travel demand and a thriving automobile industry, China's vehicle ownership is expected to grow significantly. Under both scenarios, passenger vehicle ownership (including private cars and taxis) shows a trend of initial growth followed by stabilization (as shown in Figure 4-22). By 2060, passenger vehicle ownership is projected to reach 540 million vehicles in BCNS and 570 million vehicles in ICNS.

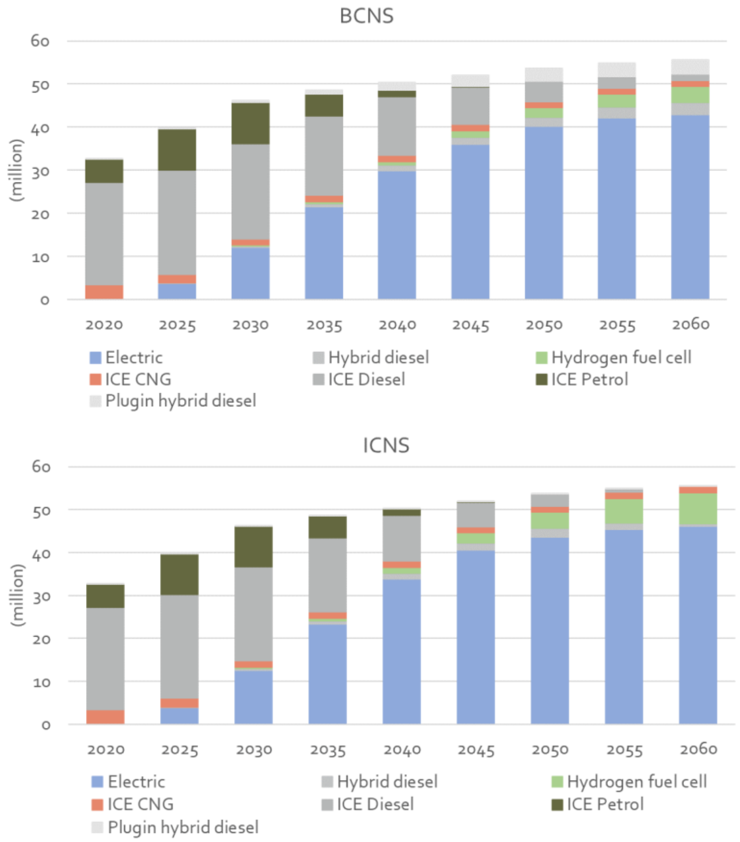
Figure 4-22 Changes in passenger car ownership



From the perspective of truck ownership, a steady upward trend is observed in both scenarios. In 2020, the ownership number of trucks was 32.61 million, increasing to 46.12 million by 2030 and reaching 55.55 million by 2060.

The fuel split between trucks features significant differences between scenarios. In 2020, diesel trucks accounted for 73%. By 2060, the share of diesel trucks has dropped to 2.7% in BCNS and just 0.1% in ICNS. Meanwhile, the share of electric trucks rises significantly, reaching 77% in BCNS and 83% in ICNS (as shown in Figure 4-23).

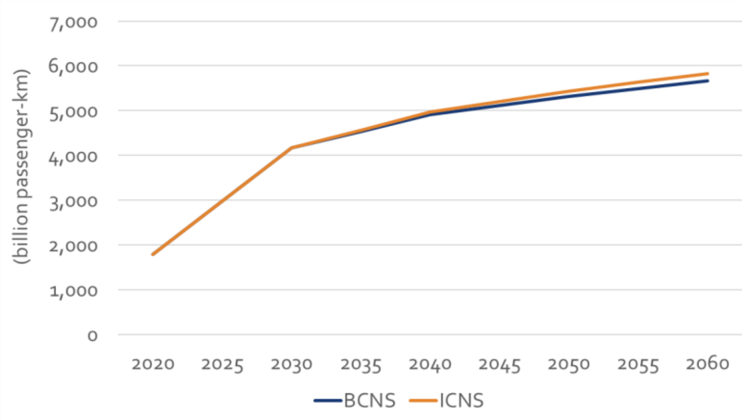
Figure 4-23 Ownership distribution of trucks



Increase in passenger transport volume

Passenger transport volume in non-road modes is projected to increase throughout the forecast period. By 2060, intercity passenger transport turnover is expected to grow from 1.8 trillion passenger-kilometres in 2020 to 5.7 trillion passenger-kilometres in BCNS and 5.8 trillion passenger-kilometres in ICNS (as shown in Figure 4-24).

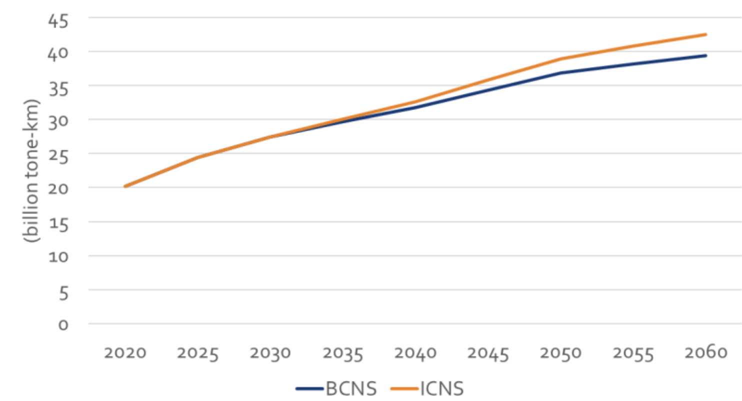
Figure 4-24 Passenger volume outlook



Increase in freight transport volume

Driven by economic growth, freight volume is expected to rise significantly. By 2060, it is projected to reach 39.3 trillion tonne-kilometres in BCNS and 42.5 trillion tonne-kilometres in ICNS (as shown in Figure 4-25).

Figure 4-25 Freight volume forecast

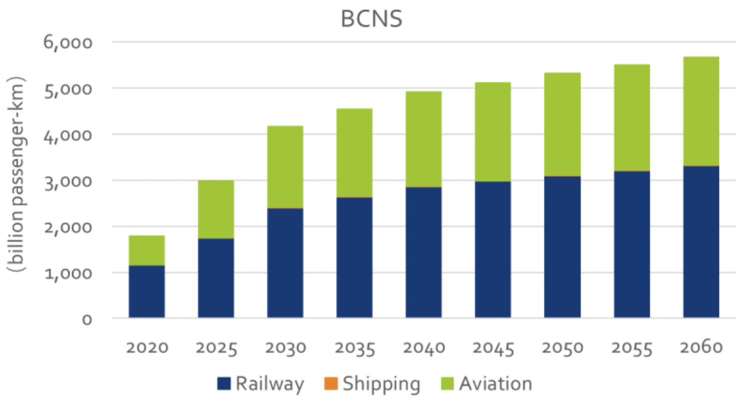


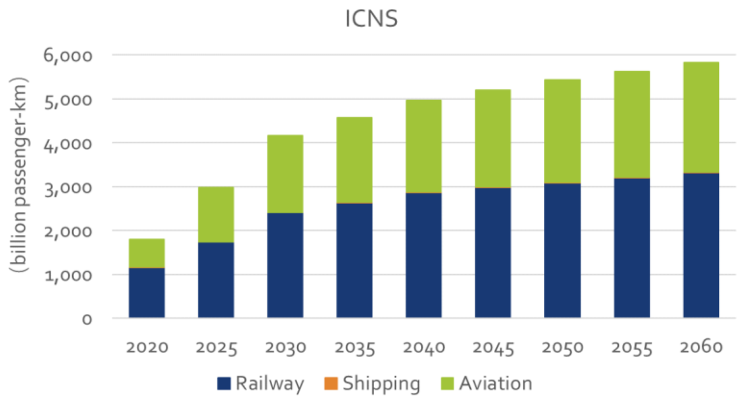
Three pathways for low-carbon transformation in the transportation sector

Optimising the transportation structure

With increased demand for international exchanges and advancements in aviation technology, air passenger transport is expected to grow steadily. By 2060, air passenger volume is projected to rise to 2.3 trillion passenger-kilometres in BCNS and 2.5 trillion passenger-kilometres in ICNS (as shown in Figure 4-26). In addition, with proper infrastructure and planning, high-speed rail can offer advantages such as convenience and greater luggage capacity, making it competitive with air travel for journeys of approximately 800 kilometres. High-speed rail is expected to play an increasingly significant role in intercity passenger transport. By 2060, high-speed rail passenger volume is projected to exceed 3.3 trillion passenger-kilometres.

Figure 4-26 Future passenger transport structure

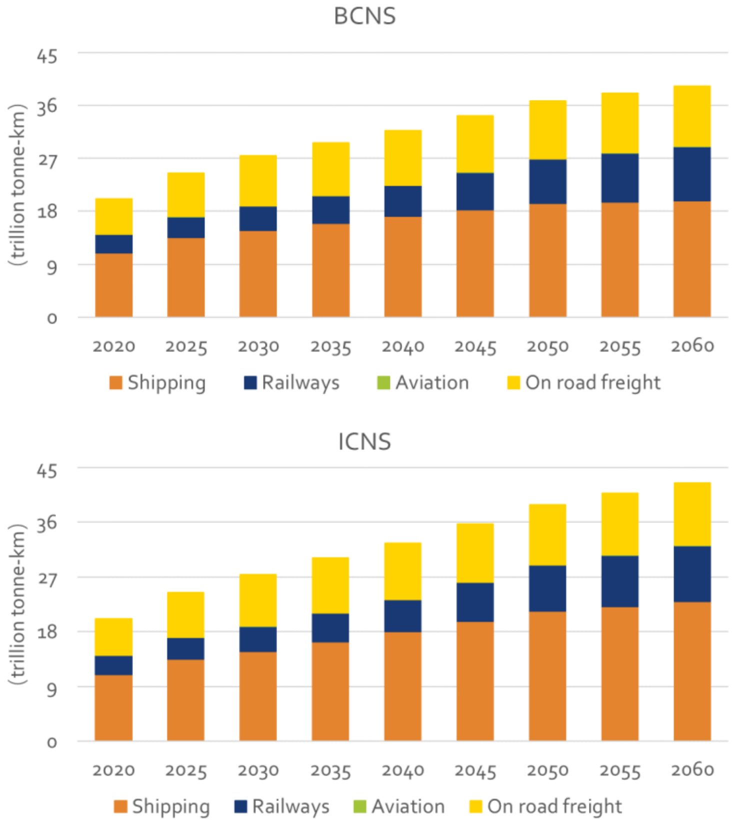




For the freight transportation, waterway and railway transport will continue to benefit from their energy-efficient advantages, gradually replacing road freight as the dominant modes of transport. By 2060, freight volume via waterways and railways is expected to increase steadily. In BCNS, waterway freight volume will reach 20 trillion tonne-kilometres, while ICNS projects 23 trillion tonne-kilometres. Waterway freight will account for over 50% of total freight volume, maintaining its position as the primary freight mode. Railway freight volume will grow to account for approximately 25% of total freight volume.

Compared to 2020, by 2060, waterway freight volume is projected to increase by 78% in BCNS and 102% in ICNS, while railway freight volume will grow by 167% (as shown in Figure 4-27). After 2030, the growth rate of road freight volume will slow year by year, with its share gradually declining.

Figure 4-27 Future freight transport structure

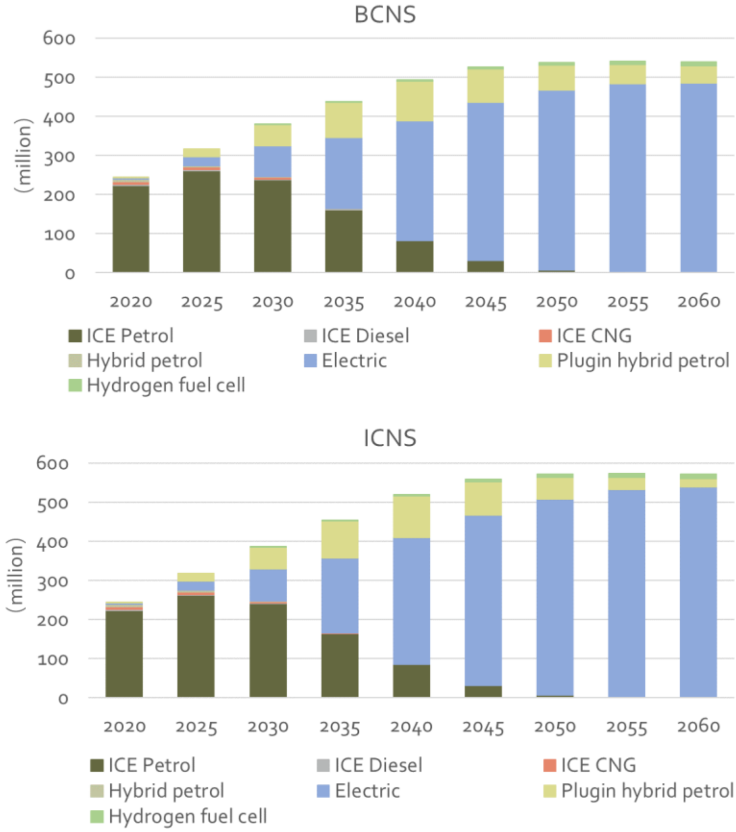


Widespread adoption of new energy vehicles (NEVs)

With rapid advancements in NEV technology and continued policy support, the scale of NEVs, led by electric vehicles (EVs), will continue to expand. The market penetration rate of NEVs in passenger vehicles is accelerating, reaching 53.9% by August 2024. By 2035, NEVs (including EVs, hybrid vehicles, and fuel cell vehicles) are expected to exceed 95% of passenger vehicle sales in China.

By 2060, EVs will dominate the NEV market. In terms of ownership, EVs will account for 89.9% of passenger vehicles in BCNS and 94.3% in ICNS. The share of plugin hybrid vehicles will decline to 8.2% and 3.7%, respectively, while fuel cell vehicles will constitute 1.9–2.0% of passenger vehicles. Petrol and diesel engine vehicles will be completely phased out by 2060 (as shown in Figure 4-28).

Figure 4-28 Future power train structure of passenger cars



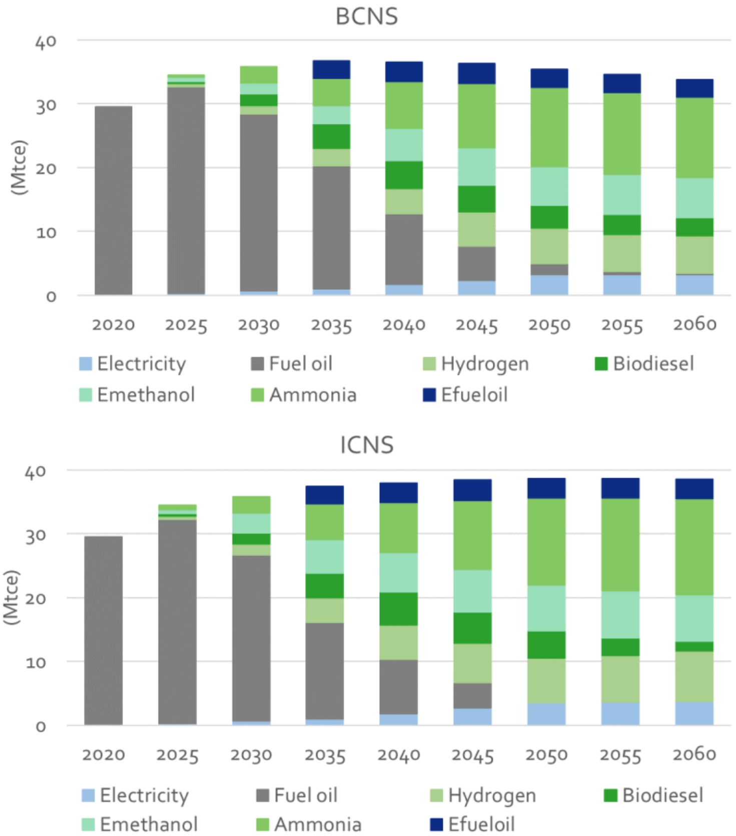
Accelerating the adoption of low-carbon and zero-carbon fuels

With increased international cooperation in technology, the penetration of low-carbon technologies across sectors is accelerating.

In aviation sector, liquid alternative fuels are projected to advance rapidly. By 2060, electricity-based synthetic fuels are projected to account for 23–29% of aviation fuel consumption, while biofuels will contribute 23–28%. The share of conventional aviation kerosene will decrease to below 30%.

In shipping sector, ammonia as a fuel will begin to see a notable increase in adoption after 2030. Other fuels, such as electricity-based methanol, hydrogen, and biodiesel, will also grow. By 2060, ammonia accounts for 37% of shipping energy demand in BCNS and 39% in ICNS. Hydrogen's share will rise to 17.4% in BCNS and 20.5% in ICNS. These fuels will play a critical role in reducing carbon emissions in the transport sector (as shown in Figure 4-29).

Figure 4-29 Future energy mix for the water transport sector



5 Transformation of the power sector

5.1 Main findings

- **Accelerating the development of a new power system which meets rising electricity demand across society.** By 2060, total electricity consumption in China is projected to rise to 20,000–22,200 TWh. Processing and conversion sectors, including hydrogen production, synthetic fuel generation, and electric heating, will become significant growth drivers, collectively accounting for approximately 25% of total electricity consumption. Accelerating the development of a clean, low-carbon, safe, abundant, cost-effective, demand-responsive, and flexible intelligent power system will be essential for achieving net-zero emissions in the energy sector. This transformation will ensure the growing electricity demand across society is met sustainably and efficiently.

- **Power generation capacity will continue to grow, enabling a comprehensive clean energy transformation of the power system.** By 2060, China's total installed power generation capacity is expected to reach 10,530–11,820 GW, with renewable energy accounting for approximately 96% of this capacity. Renewable energy will contribute 93–94% of the total electricity generation, marking a significant shift towards a clean and sustainable power system.

- **Wind and solar power installations will grow significantly, with distributed solar holding enormous potential.** By 2060, China's combined wind and solar power capacity will need to reach 9,320–10,700 GW. Of this, wind power installations will account for 2,950–3,460 GW, while solar power installations will reach 6,370–7,240 GW. Solar installations will represent approximately two-thirds of the total wind and solar capacity, with distributed solar making up 70% of total solar capacity.

- **By 2060, a flexible and secure new power system will be established.** China's demand for power system flexibility resources is projected to reach 5,280–5,870 GW by 2060. New flexibility resources, such as advanced energy storage, hydrogen production, and synthetic fuel generation, will dominate this capacity. Among these, hydrogen production and synthetic fuel generation will require capacities of 3,110–3,560 GW. Vehicle-to-grid interaction provided by electric vehicles will contribute 810–900 GW, while electrochemical energy storage capacity will reach 240–280 GW. As these flexibility resources expand, the reliance on coal-fired power for system balancing will decrease significantly, enabling a cleaner and more adaptable power system.

- **Cross-regional power exchange capacity will increase significantly, optimizing the national power grid structure.** By 2035, China will establish a power grid structure characterized by "west-to-east power transmission, north-to-south power transmission, and regional interconnections," enabling the grid to flexibly respond to regional power supply and demand fluctuations, much like a "sponge." By 2060, the combined power exports from the Northwest, Northeast, and North China regions are expected to increase by 140–150% compared to 2022 levels.

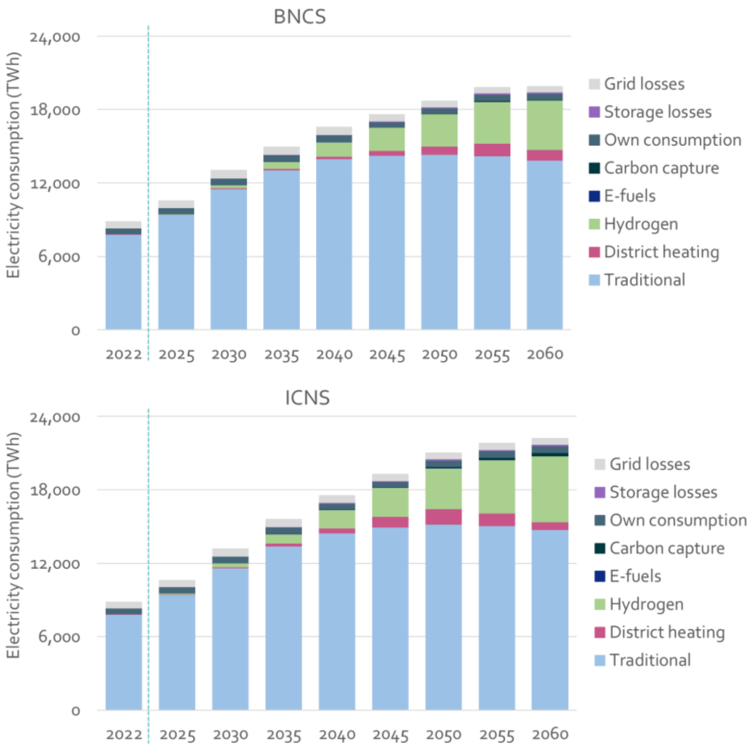
5.2 Structure of electricity supply and demand

Continued increase in electricity consumption by society as a whole

Total electricity consumption across society is expected to grow steadily until 2060. This increase is driven by accelerated end-use electrification, large-scale growth in new electricity demands such as data centres, advancements in EV-V2G and demand-side response, as well as the integration of electricity into hydrogen production, synthetic fuel generation, and electric heating. The adoption of long-term negative-carbon technologies will also contribute to this upward trend.

In BCNS, total electricity consumption will reach 16,500 TWh by 2040 and further rise to 20,000 TWh by 2060. In ICNS, electricity consumption will grow to 17,500 TWh by 2040 and 22,200 TWh by 2060 (as shown in Figure 5-1).

Figure 5-1 Demand and structure of electricity consumption in society as a whole, 2022-2060

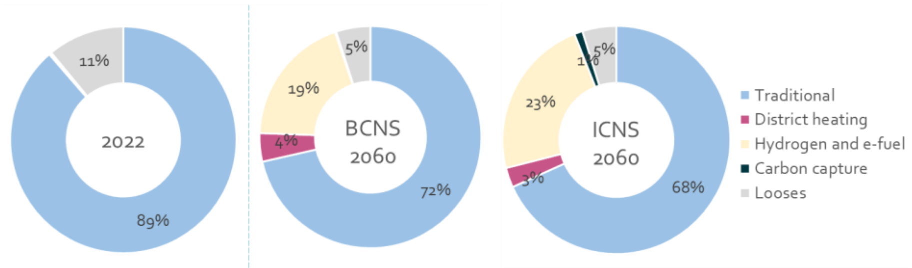


The share of electricity demand from processing and conversion sectors will continue to rise. As a high-proportion renewable energy system is gradually established, the variability and intermittency of wind and solar power become increasingly evident, significantly raising the demand for system flexibility. The rapid growth of new energy storage systems and demand-side response resources, while not increasing overall electricity consumption, supports load balancing by smoothing peaks and valleys in electricity usage.

Low-cost, large-scale applications of green electricity for hydrogen production, synthetic fuel generation, and electric heating—classified as processing and conversion electricity demand—will become the primary drivers of increased electricity consumption. With the improvement of a unified national electricity market, the coordinated operation of spot markets, ancillary service markets, and capacity mechanisms will enhance the adoption of electric boilers and heat pumps, further boosting electricity demand for heating.

By 2060, in BCNS, electricity demand for hydrogen production and synthetic fuel generation is projected to reach 4,100 TWh, accounting for 19% of total electricity consumption, while electric heating will consume 870 TWh, contributing 4%. In ICNS, these figures rise to 5,400 TWh (23% of total demand) for hydrogen and synthetic fuels and 660 TWh (3%) for electric heating (as shown in Figure 5-2).

Figure 5-2 Comparison of the structure of society-wide electricity demand in 2022 and 2060



Renewable energy will dominate installed capacity and electricity generation

Accelerating the development of a clean, low-carbon, safe, abundant, cost-effective, demand-responsive, and intelligent power system is a key measure for achieving net-zero emissions in the energy sector. By 2040, total installed power capacity is projected to reach 7,690 GW in BCNS and 9,370 GW in ICNS, with renewable energy accounting for 82% and 86% of installed capacity, respectively. Renewable energy will also account for 69% of electricity generation in BCNS and 77% in ICNS. At this stage, renewable energy will become the dominant source of both capacity and generation, while coal-fired power transitions to a backup and role.

By 2060, total installed capacity is expected to increase to 10,530 GW in BCNS and 11,820 GW in ICNS, approximately four times the capacity of 2022 (as shown in Figure 5-3). Electricity generation will rise to 20,000 TWh in BCNS and 22,200 TWh in ICNS (as shown in Figure 5-4). Renewable energy's share of installed capacity is expected to reach 96%

under both scenarios by 2060 (as shown in Figure 5-5), while its share of electricity generation will reach 93% in BCNS and 94% in ICNS (as shown in Figure 5-6).

Regarding conventional power sources, coal and gas power plants will gradually transition to standby roles or be naturally retired by 2060. Nuclear power capacity is expected to reach 180 GW, and hydropower (excluding pumped storage) will reach 540 GW. BECCS is projected to reach 160 GW in BCNS and 120 GW in ICNS by 2060.

Figure 5-3 Installed power generation and structure, 2022-2060

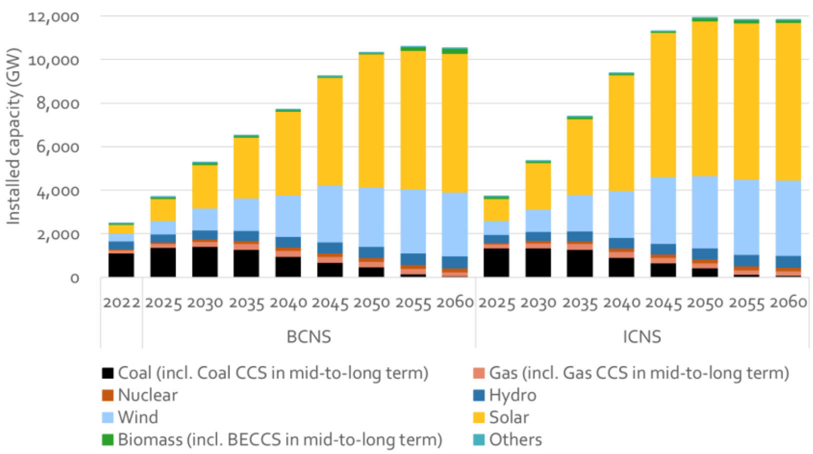


Figure 5-4 Electricity generation and structure from 2022 to 2060

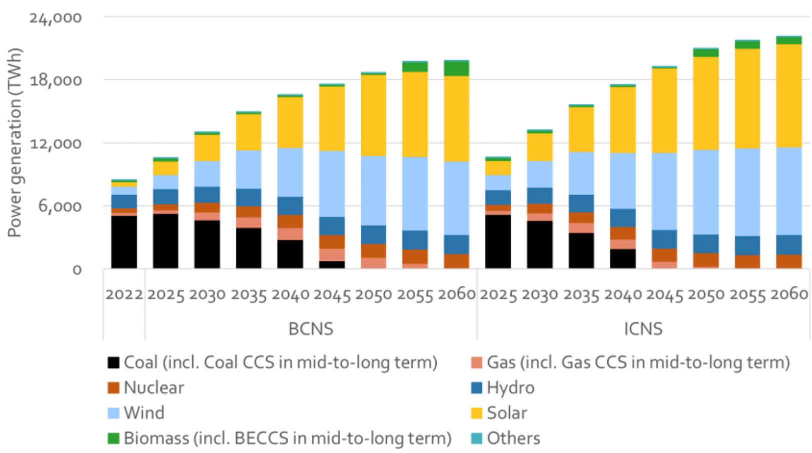


Figure 5-5 Comparison of installed power generation mix in 2022 and 2060

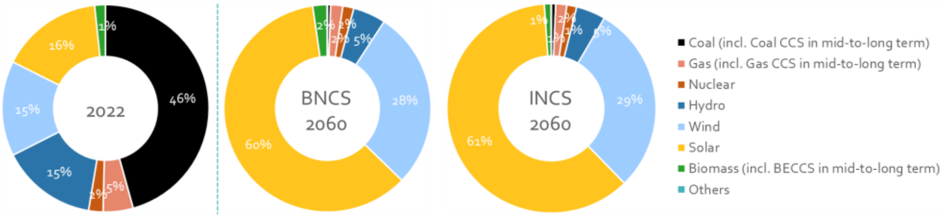
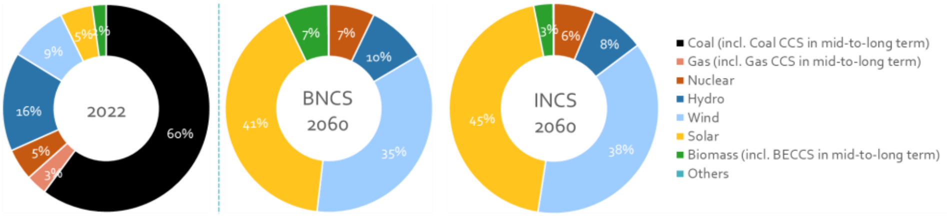


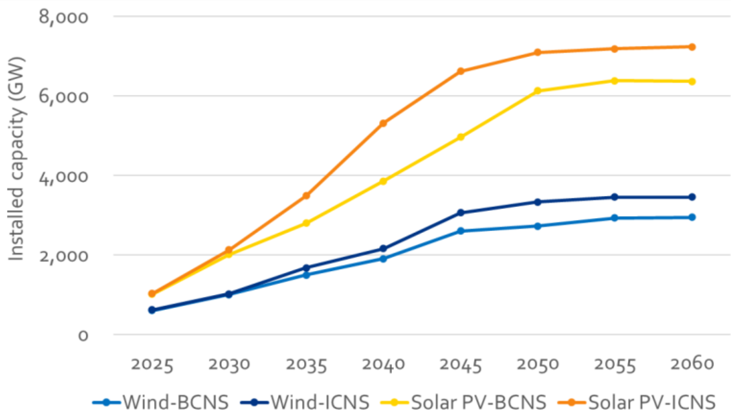
Figure 5-6 Comparison of generation mix in 2022 and 2060



5.3 Wind-based electricity supply

Driven by the investment costs of renewable energy projects and industry development trends, the additional installed capacity of wind power and photovoltaics will maintain a relatively fast growth rate and the newly installed capacity will further increase under both scenarios. The combined installed capacity of wind power and PV power generation in 2040 will reach 5,760-7,480 GW. After 2050, the development of wind power and PV enters a peak plateau period. By 2060, under the two scenarios, the combined wind and PV installations reach 9,320-10,700 GW (as shown in Figure 5-7), with PV accounting for about two-thirds of the installed capacity.

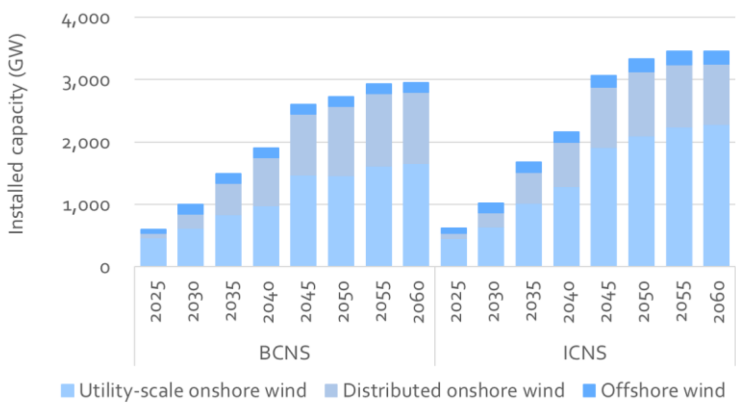
Figure 5-7 Installed wind and photovoltaic power size, 2025-2060



Onshore wind is the dominant force in wind power development

In BCNS and ICNS scenarios, from 2023 to 2040, the total installed capacity of wind power will increase from 440 GW to 1,900 -2,160 GW. By 2040, the share of onshore wind power reaches 92% and 93%, and the installed offshore wind power reaches about 160 GW. Thereafter, as the technology of low-wind-speed wind turbines further matures, the cost of onshore wind power will continue to decline, and new installations will continue to accelerate. As offshore wind power moves further out to sea, the distance increases, leading to higher construction costs. After 2045, the pace of wind power installation will slow down. By 2060, the total installed wind power capacity will reach 2,950-3,460 GW, respectively, under the two scenarios. (as shown in Figure 5-8).

Figure 5-8 Installed wind power size by technology, 2025-2060



In terms of regional distribution, the 'Three Norths' (northwest, north, northeast) have abundant wind and land resources, and are suitable for the concentrated deployment of large-scale onshore wind power. Under the BCNS and ICNS scenarios, 61%-65% of onshore wind power installed capacity will be concentrated in the 'Three Norths' in 2040, with this proportion further increasing to 70%-75% by 2060 (as shown in Figure 5-9).

Taking into account factors such as sea wind resources and seabed conditions, it is more cost-effective to build offshore wind projects in East China and South China. Under the BCNS and ICNS scenarios, in 2040, the combined share of offshore wind in East China and South China reaches 84-85%, with a small number of installations in North China and Northeast China. By 2060, the installed capacity of offshore wind power in the East China and South China will grow further, with their combined share rising to 83% and 89%, respectively. (as shown in Figure 5-10).

Figure 5-9 Regional deployment of installed onshore wind power in 2060

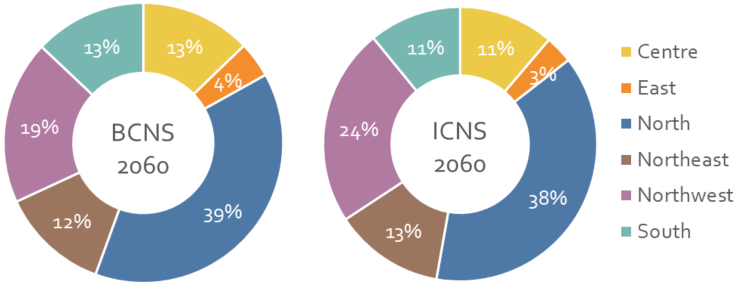
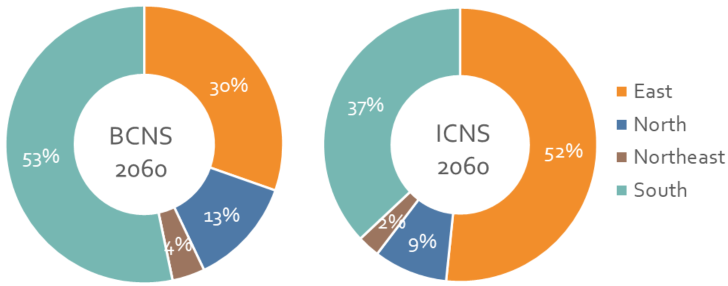


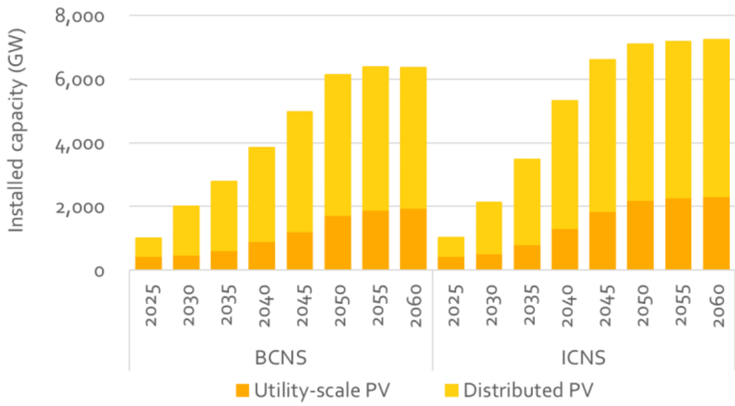
Figure 5-10 Regional deployment of installed offshore wind power in 2060



Distributed PV is the leading force in PV development

China has abundant solar photovoltaic resources, and over the medium to long term, installation costs are expected to decline further. Especially, there is significant potential for developing photovoltaics on building rooftops and façades. Under the BCNS and ICNS scenarios, from 2023 to 2040, installed PV power generation capacity will increase from 610 GW to 3860-5320 GW. Among these, distributed photovoltaic power generation will gradually become the mainstay of installed photovoltaic power generation capacity growth. By 2040, distributed PV installations will significantly exceed centralized PV installations, with distributed PV accounting for over 75% under both scenarios. Until 2050, the cost of PV continues to decline, and annual new installations remain relatively large. Afterward, the pace of photovoltaic installation slows, primarily focusing on replacing existing photovoltaic power plants that are naturally retired on a large scale. By 2060, photovoltaic installations will reach 6370-7240 GW, respectively, with distributed photovoltaics accounting for 70% and playing a dominant role (as shown in Figure 5-11).

Figure 5-11 Installed PV size by technology from 2025 to 2060



From the regional distribution point of view, the "Three Norths" region has abundant solar irradiance, significant land resources, and better conditions for the construction of external transmission lines, so there are considerable cost advantages in building concentrated photovoltaic projects. Under the BCNS and ICNS scenarios, in 2040, concentrated photovoltaics in the Three Norths regions accounted for 78% and 75% of concentrated photovoltaic installations, respectively; by 2060, this proportion will further increase to 79% and 75% (as shown in Figure 5-12). Due to the limited rooftop resources in cities, the focus of distributed PV development is gradually shifting from the eastern load centres to the 'Three Norths' region.

By 2040, distributed PV installations in the Central, East, and South regions will account for over 60% of the total distributed PV capacity. By 2060, under the BCNS and ICNS scenarios, this proportion will slightly decrease to 57% and 60%, respectively, resulting in a more balanced regional distribution of distributed PV (as shown in Figure 5-13).

Figure 5-12 Regional deployment of installed centralised PV in 2060

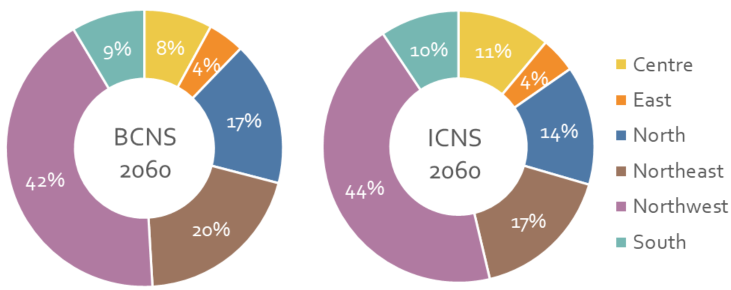
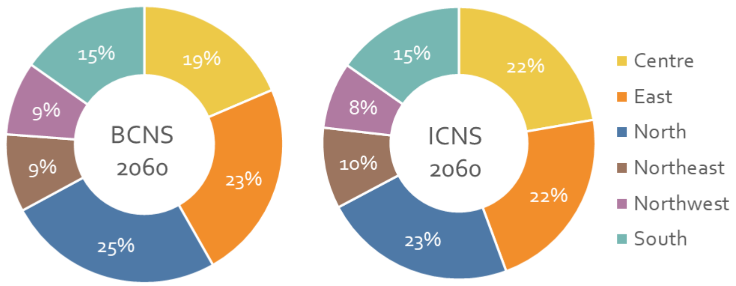


Figure 5-13 Regional deployment of installed distributed PV in 2060



5.4 Power system flexibility resources

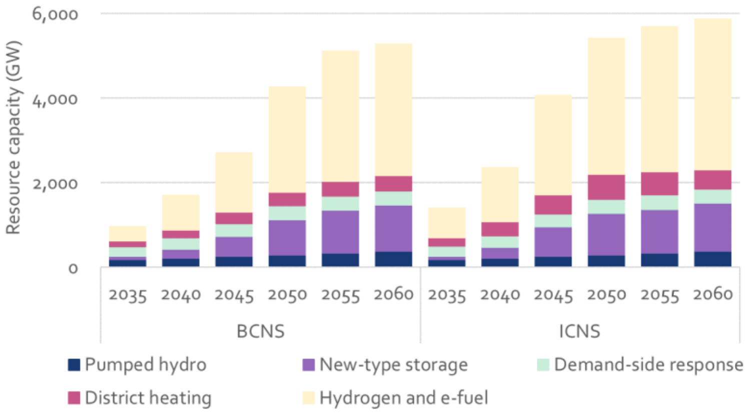
Rapid overall growth in flexibility resources

The modelling analysis shows that in 2060, the installed capacity and power generation of wind and PV will increase by 18% and 7% respectively compared to CETO2023, placing higher demands on the flexibility of the power system. In terms of scenario setting, in addition to considering the improvement of the real-time regulation capability of the power system, it is also necessary to consider the increase of cross-seasonal regulation capability. To achieve this, the group categorizes flexible resources into six types: coal-fired power units upgraded for flexibility, pumped storage, new energy storage (electrochemical energy storage systems and EV-V2G), demand-side response, electric heating (electric boilers and heat pumps), and electric production of hydrogen and synthetic fuels. Among these, new flexibility resources include energy storage systems (electrochemical plants and EV-V2G), demand-side response, electric heating, electric hydrogen production, and synthetic fuel production. These emerging resources will play a crucial role in ensuring the safe and stable operation of the new power system in the future.

Under the BCNS and ICNS scenarios, by 2040, China's pumped storage and new flexible resources combined will need to reach a total of 1,700 to 2,350 GW; and further increase to 5,280-5,870 GW by 2060 (as shown in Figure 5-14). In addition, flexible coal power will also need to play an important role- in real-time balancing. Electricity usage and storage, new energy storage technologies, electricity-based hydrogen, synthetic fuels and heat, will become the primary flexibility resources.

Throughout this process, the principle of 'establishing the new before abolishing the old' will be adhered to. With the expansion of new energy and renewable energy generation, the development of new flexibility resources, and the gradual improvement of the power system's control capabilities, coal-fired power generation will naturally be phased out, transitioning from serving as base load power to becoming a source of regulating and standby power.

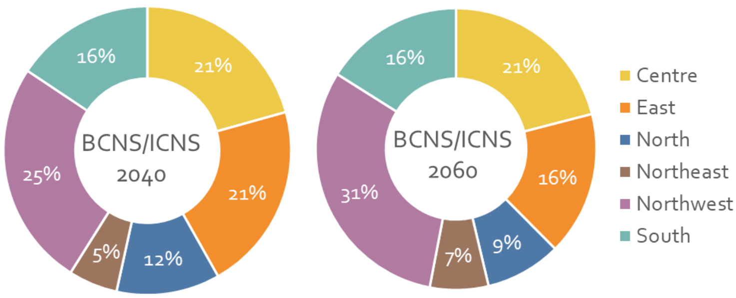
Figure 5-14 Pumped storage and new flexibility resources, 2035-2060 Scale of demand



Pumped storage continues to grow in scale

Pumped storage capacity will grow to 220 GW by 2040, considering factors like equipment capacity, design and construction capabilities, and construction timelines. Development will then slow down, with installed capacity reaching around 380 GW by 2060. Regionally, the focus of pumped-storage development will shift from east to west, roughly in line with China's regional deployment of large-scale clean energy bases. In BCNS and ICNS, by 2040, Central China, the South, and the Northwest will together account for approximately 62% of the nation's pumped storage total installed capacity. By 2060, this share is expected to increase further to about 68% (as shown in Figure 5-15).

Figure 5-15 Regional deployment of installed pumped storage capacity in 2040 and 2060



New flexibility resources accelerated development

By 2040, wind power and solar PV generation together account for more than 50% of total electricity generation, and green power becomes the mainstay of electricity. By that time, under the BCNS and ICNS scenarios, the installed capacity of traditional regulated power sources, such as thermal power, nuclear power, biomass power, and pumped storage, will account for 63% and 55% of the peak load, respectively. Meanwhile, the demand for new flexible resources, including electrochemical storage plants, EV-V2G, demand-side response, electric boilers, heat pumps, electric hydrogen production, and electric synthetic fuels, will account for 56% and 72% of the peak load. The roles and functions of traditional adjustable power sources and new flexible resources in the power system form an effective complement to each other, guaranteeing the safe and stable operation of the power system. From a technical perspective:

- Taking into account factors such as the construction and operating costs of electrochemical energy storage plants and the market willingness of electric vehicles to participate in V2G, the installed capacity of electrochemical energy storage and EV-V2G will reach a total of about 250 GW in 2040 under both scenarios.
- Under the two scenarios, the demand-side response capacity will reach about 270 GW in 2040.
- Abundant and cheap green electricity facilitates the large-scale development of electrolysis of hydrogen and electrolysis of synthetic fuels. From 2023 to 2040, the capacities of electrolysis of hydrogen and electrolysis of synthetic fuels will increase by 32% and 36%, reaching 810 GW and 1,270 GW in BCNS and ICNS, respectively.
- In terms of electricity-based heating, under the BCNS and ICNS scenarios, the demand for electric boilers will increase by 51% and 56%, respectively, from 2023 to 2040, reaching 190-320 GW.

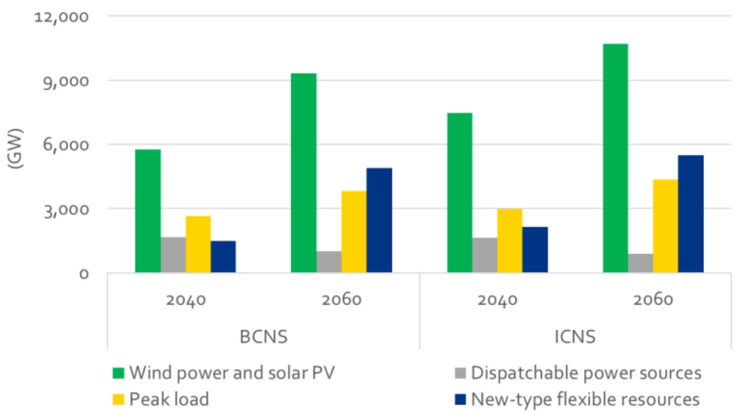
In 2060, under the BCNS and ICNS scenarios, the combined share of wind and photovoltaic power generation in total power generation will reach 76% and 84%, respectively, and the ability of flexible resources to support power system operation will be even more significant. By then, under the two scenarios, the demand for new flexible resources will reach 129% and 126% of peak load, respectively, replacing traditional adjustable power sources as the main regulating resources of the power system (as shown in Figure 5-16 and Figure 5-17).

In terms of sub-technologies:

- In 2060, under both scenarios, electrochemical energy storage plants will achieve flexible and widespread application in terms of source, grid and load, as construction costs continue to decrease. Electrochemical energy storage capacity will increase significantly to 280-240 GW. At the same time, the number of electric vehicles in use will surpass 500 million, and the willingness of electric vehicles to participate in the V2G market will grow substantially. As a result, EV-V2G capacity will reach 810-900 GW. Together with electrochemical storage, they will account for 23% and 20% of the demand for new flexible resources. In both scenarios, demand-side response capacity reaches about 340 GW.
- The installed capacity of electricity-based hydrogen production and electricity-based synthetic fuel production will increase to 3110 and 3560 GW in BCNS and ICNS, respectively, accounting for 63% and 65% of the demand for new flexible resources. These technologies will not only contribute to real-time power system balancing but also play a key role in inter-seasonal regulation.

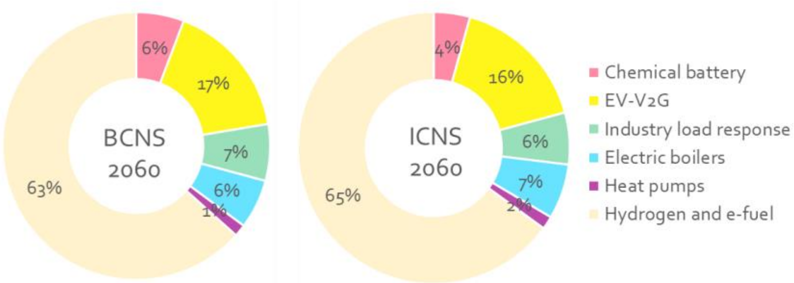
- Under both scenarios, by 2060, the demand for electric boilers will reach 290-360 GW, while the demand for heat pumps will reach 70-90 GW.

Figure 5-16 Total wind PV installations, peak load and various types of flexibility resources, 2040 to 2060



Note: Traditional adjustable power sources include thermal, nuclear, biomass and pumped storage, while new flexible resources include electrochemical storage plants, EV-V2G, demand-side response, electric boilers, heat pumps, electric hydrogen production and electric synthetic fuels.

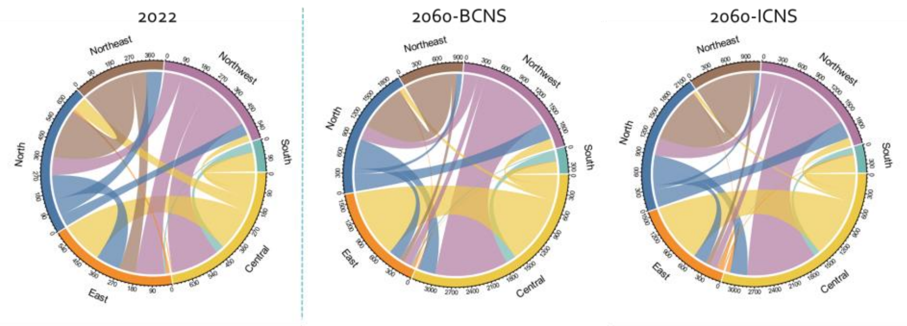
Figure 5-17 Structure of new flexibility resource requirements in 2060



5.5 A new “sponge-like” smart grid

The cross-regional interconnection capacity significantly improves, leading to further optimisation of China’s electricity grid. Over the next 30 years, China's electricity grid structure will gradually evolve, seizing opportunities for “backbone interconnection and local balance” development. By 2035, the deployment of the national backbone grid following the strategy of West-to-East and North-to-South power transmission with inter-regional mutual support will be complete. This will enable the power grid to balance power supply and demand across different regions, functioning as a flexibility resource. The grid will respond flexibly to changes in electricity supply and demand like a “sponge” by using digital and intelligent technologies. By 2060, the total scale of electricity exports from the Northwest, Northeast, and North China regions will increase by 140% to 150% compared to 2022 (as shown in Figure 5-18). To adapt to the large-scale development of distributed new energy, the distribution grids will be transformed from "passive" one-way radiation networks to "active" two-way interactive systems, focusing on the self-generation and self-consumption of renewable energy sources in the industry, agriculture, commercial, and residential sectors. Additionally, a massive zero-carbon distribution network will be formed, providing strong support for the development of more than 5,000 GW of distributed photovoltaic and decentralised wind power. Drawing on international cooperation experience, we will build a new form of energy network where synergies between electricity, hydrogen, heat, and transport are fully integrated.

Figure 5-18 Inter-regional electricity transfers in 2022 and 2060 (TWh)



5.6 Production-consumption simulation of new power systems

The production curves depict hourly-level power output and electricity load. These curves illustrate the dynamic balance between supply and demand in the power system (as shown in Figure 5-19, Figure 5-20 and Figure 5-21). In the figures, base load includes end-sector electricity consumption and grid losses. Flexibility resources include pumped hydro, chemical storage, EV-V2G, district heating, hydrogen and e-fuel production, as well as demand-side response.

During a typical week in summer 2022, coal, hydropower, nuclear power, and other power sources are stable, providing important support to meet the electricity demand (as shown in Figure 5-19). This shows a load-following capability of the power system. By 2060, under both scenarios, after solar and wind power become the main power sources, various types of energy storage and demand-side response resources, on multiple time scales, will replace the traditional dispatchable power sources. This provides important regulation support for the safe and stable operation of the new power system. At that time, the source-load interaction characteristics of the power system will undergo a significant transformation. For example, flexibility resources such as demand-side response and EV smart charging shift the electricity load from nighttime to daytime, thus making the electricity load curve more compatible with the output curve of volatile power sources such as PV power generation (the electricity load curve before the shift is shown as the black dotted line), as exemplified by a typical summer week and a typical winter week in BCNS:

- During the daytime in summer, when sunshine is abundant, solar power output rises rapidly and falls in the late afternoon. When the generation output exceeds the electricity load (as in Figure 5-20 Day 1), pumped hydro, chemical storage, hydrogen and e- fuel production, EVs, and industrial demand-side response resources kick in. These flexible loads account for 60% of the total load during the peak load hour.
- During summer nights, as solar output decreases to zero and wind output increases (as seen on the fifth day in Figure 5-20), the electricity consumption of hydrogen and e-fuel production increases, and their electricity load accounts for about 20% of the electricity load at that time. When wind power output is low (as on the sixth day in Figure 5-20), pumped hydro, chemical storage, and EV-V2G systems begin discharging extensively, with a combined storage output reaching around 32% of the total power output.
- During the winter months, the duration and maximum output of solar power decrease compared to the summer months, while wind power output increases. Although the overall electricity load decreases slightly in winter, the heating demand significantly raises in the electricity load for district heating. Consequently, the importance of thermal storage for maintaining the dynamic balance of the new power system increases (as shown in Figure 5-21).

Figure 5-19 Hourly power balance of the national power system for a week - Summer 2022

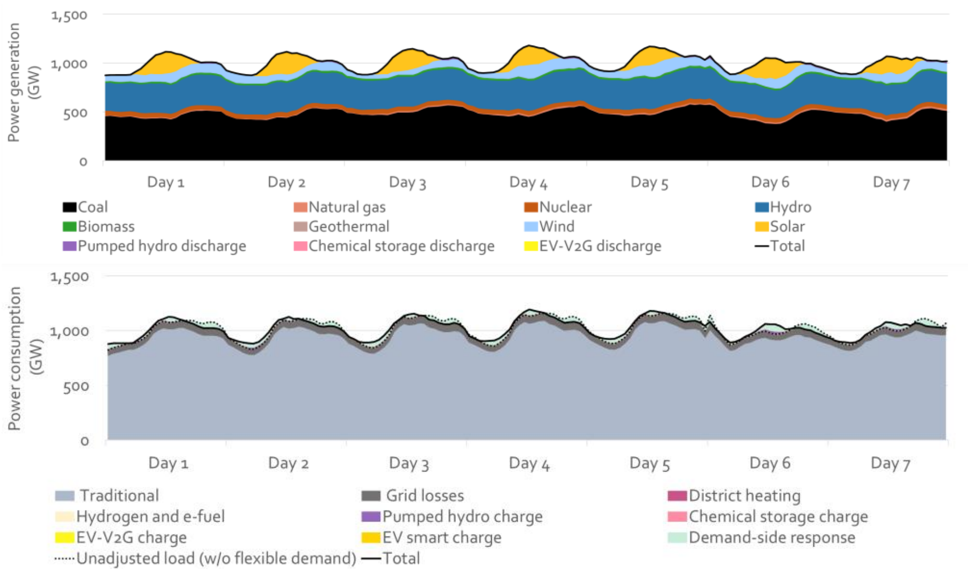


Figure 5-20 Hourly power balance of the national power system for a week in BCNS - Summer 2060

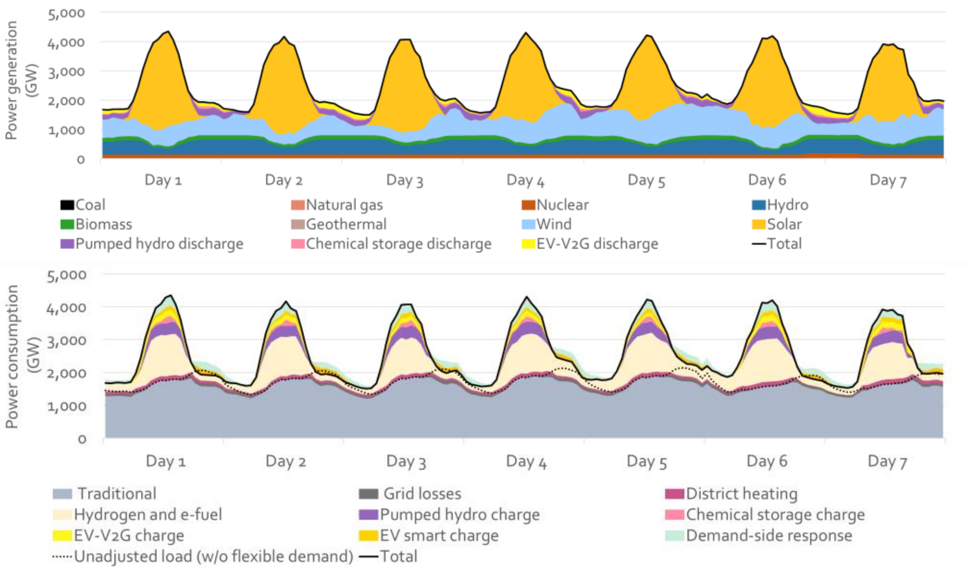
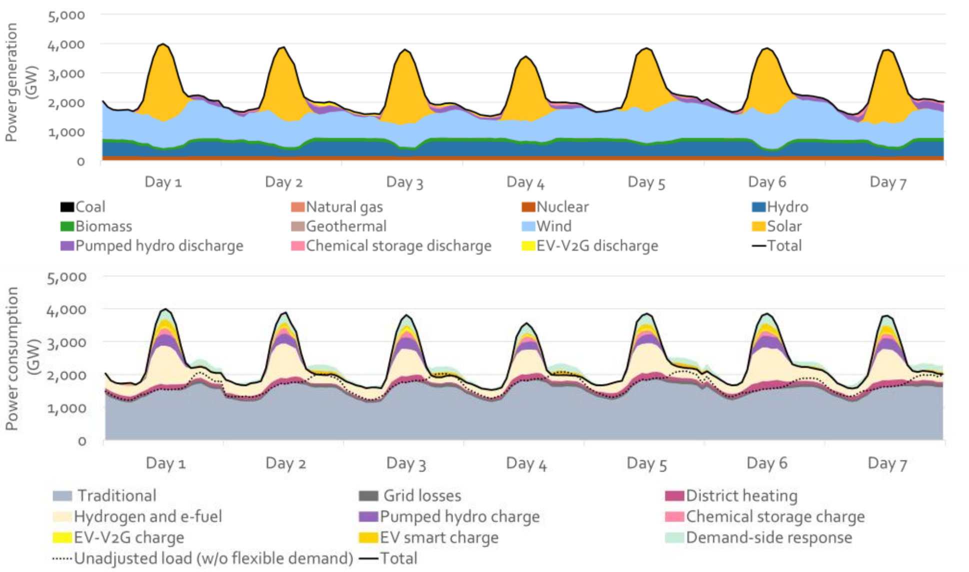


Figure 5-21 Hourly power balance of the national power system for a week in BCNS - Winter 2060

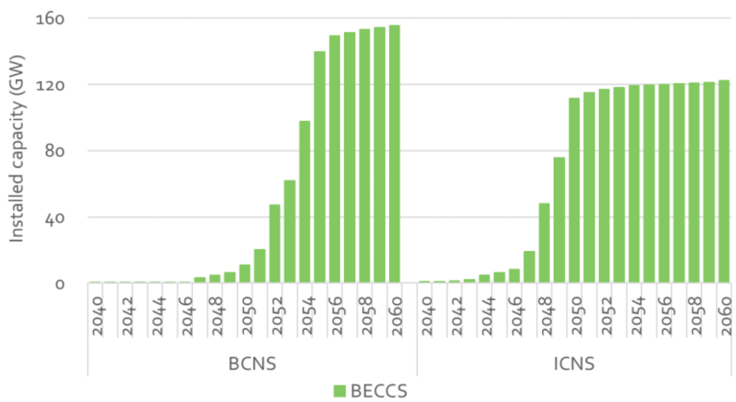


5.7 Carbon capture in the power sector

BECCS can provide negative carbon emissions for the power sector and energy system. The national biomass resources have been accounted for, with due consideration of resource caps for agriculture, forestry, municipal waste, and biogas. Considering the limited availability of biomass resources and their potential use across multiple sectors, biomass resources were allocated to the building, transport, and power sectors in order of lowest cost of use for the whole society. In the two scenarios, the amount of biomass used for heating in the building sector and the consumption of biomass-based aviation fuel differ. This results in variations in the amount of biomass resources available for the power sector including BECCS and the associated CO_2 capture capacity.

The power sector is expected to start deploying BECCS technology after 2030 to enable a carbon-negative power system. BECCS enters a rapid development phase starting in 2050 for the BCNS scenario and 2045 for the ICNS scenario. In 2060, the total installed capacity of BECCS reaches 160 and 120 GW for the two scenarios, respectively (as shown in Figure 5-22). In ICNS, the remaining CO_2 emissions are captured by the use of Direct Air Capture (DAC) technology.

Figure 5-22 Installed biomass power generation with the addition of carbon capture and storage equipment, 2040-2060



6 Socio-economic impacts of energy transformation

6.1 Main findings

- **China's energy transformation has promoted the green and low-carbon development of its economy.** While providing energy security for economic and social development, the large-scale and high-quality development of non-fossil energy sources, through the continued substitution of fossil energy gradually replacing fossil fuels, it can effectively reduce carbon emissions and environmental pollutants at source. This provides critical support for achieving the goals of a Beautiful China, carbon peaking, and carbon neutrality.

- **At the same time, the energy transformation has created new jobs in the energy sector,** with rising wages and increased social welfare, demonstrating that the transformation promotes social equity and supports a just transition for the energy sector as a whole.

- **International cooperation is beneficial for China in advancing its energy transformation and to achieve more opportunities for economic growth and better social development outcomes**. A comparison of the simulation results under the two energy transformation scenarios shows that, under the ICNS, China's energy transformation generates a higher positive socioeconomic impact compared to the BCNS. This highlights the promising outlook for China, in cooperation with the international community, to create the conditions necessary to follow an ideal path for the energy transformation

6.2 Improving the depiction of changes in industrial structure in dynamic computable general equilibrium models

Depicting changes in industrial structure is a challenge in dynamic computable general equilibrium modelling

In conducting policy evaluation using the dynamic Computable General Equilibrium (CGE), the accurate depiction of dynamic changes in the industrial structure of the macroeconomy is a significant challenge. Currently, both domestic and international research, as well as the China Energy Transformation Policy Assessment (CETPA) model utilise exogenous parameter settings to portray the dynamic changes in industrial structure, which introduces a degree of subjectivity.

To address this, the research team, based on China's economic development and industrial structural changes, studied and improved the methodology of the CETPA model to represent the changes in industrial and energy structures. This approach avoids the reliance on exogenous parameters for the dynamic changes of the industrial structure, further strengthening the integration of the CETPA model with the results of the research team's energy model scenario simulation, which provides technical support for a better evaluation of the socio-economic impacts of the energy transformation.

Improving the CETPA model representation of changes in China's industrial structure

Sectoral refinement has broadened the model's scope of application. The further subdivision of the secondary sector allows the model to be applied for further research, including the transformation and upgrading of heavy chemical industries, the development of high-end equipment manufacturing, the transformation and upgrading of the construction industry, the structural transformation of primary energy, the structural transformation and upgrading of the power sector, the development of renewable and new energy sources, and the development and utilisation of nuclear energy technology. The subdivision of the tertiary sector allows the model to be more widely used in studies on the transformation and development of the transport industry, the development of the retail and food industry, the development of the medical and healthcare industry, the development of the science and education industry, as well as tourism, cultural and public services.

Using endogenous sectoral economic growth rates for future time periods enhances the flexibility of the model and the accuracy of the simulation results. By using endogenous economic growth rates of different sectors in the future macroeconomy, the model automatically derives the corresponding data, i.e. from future energy transformation data, to determine the endogenous economic growth rates of these sectors. This enhances the efficiency and simplified application of the model. At the same time, exogenous variables are set, which can be directly introduced into the model in combination with the judgement on the macroeconomic and industrial development in different future years. This allows for a timely reflection on the changes in the economic and energy development, enhancing the flexible application of the model, and reducing the uncertainty of the simulation results.

6.3 Changes in China's industrial structure

Trends in industrial structure since reform and opening up

Since the reform and opening up, the evolution of China's industrial structure has shown obvious features of industrialisation and modernisation, which are mainly manifested in:

- The share of the primary sector has steadily declined, from 27.7% in 1978 to 7.0% in 2018, a decrease of 20.7 percentage points. Since 2018 it has fluctuated around 7%, reaching 7.7% in 2020 and 7.1% in 2023.
- The secondary sector has gone through three distinct stages. From 1978 to 1990 there was a decline in the proportion of the secondary sector. A development strategy prioritising heavy industry led to a high proportion of secondary sector, reaching 47.7% in 1978. After the reform and opening up, the light industry has been greatly developed and the industrial structure has been optimized. The proportion of the secondary sector dropped to 41.0% in 1990. The second stage, from 1991 to

2006, saw a steady increase in the proportion of the secondary sector. With the establishment and development of the socialist market economic system, the manufacturing industry grew rapidly. The proportion of industry gradually increased to 47.6% in 2006, forming a complete industrial system. The third stage began in 2007 and saw a decline due to severe overcapacity in the manufacturing sector and an industrial adjustment period. By 2016 the share of the secondary sector fell below 40% and further declined to 38.3% in 2023.

- The proportion of the tertiary sector has been rising. At the beginning of the reform and opening-up period, the tertiary sector accounted for only 24.6%. Since the reform and opening up, the tertiary sector has consistently developed. This development accelerated from 2008. In 2013, the tertiary sector surpassed the secondary sector, reaching 46.9% and by 2015 it had exceeded 50%. In 2023, the structure of the primary, secondary, and tertiary sectors was 7.1%, 38.3%, and 54.6%, respectively.

China's industrial structure has evolved significantly. Initially, it was dominated by agriculture. It then shifted to being dominated by industry. Finally, it has become dominated by services. This evolutionary path follows the general law of industrial structure evolution. In 1978, the industrial structure was characterized by the primary, secondary, and tertiary sectors having proportions of 27.7%, 47.7%, and 24.6%, respectively. By 1985 the tertiary sector had surpassed the primary sector for the first time, and the adjusting the proportions to 27.9%, 42.7%, and 29.4%. This marked a significant shift from a 'two, one, three' structure to a 'two, three, one' structure. In 2012, the scale of the tertiary sector once again exceeded that of the secondary sector and became a driving force for the development of the national economy. The structure of the three sectors made a historic shift from "two, three, one" to "three, two, one", with the proportions of the three sectors adjusted to 9.1%, 45.4%, and 45.5%, respectively. Currently, China's economic development has entered a new stage, characterized by strategic adjustments and transformation of the economic structure. By 2019, the proportions of the three sectors were 7.1%, 38.6%, and 54.3%, respectively. This further consolidated the "three-two-one" industrial pattern and will enhance the comprehensiveness, co-ordination, and sustainability of the economic development. In 2020, influenced by the COVID-19 pandemic, the proportions were 7.7%, 37.8%, and 54.3%, respectively. By 2023, the industrial structure continued to evolve, with the proportions of the three industries adjusting to 7.1%, 38.3%, and 54.6%, respectively, returning to the pre-pandemic trend.

Specifically, the proportion of GDP from the value added by the primary sector has continuously declined, from 27.7% in 1978 to 7.1% in 2023, a drop of 20.6 percentage points. The proportion of GDP from the secondary sector has followed an oscillating trajectory: it declined from 47.7% in 1978 to 41.0% in 1990, and then rose to 47.6% in 2006, followed by a gradual decline to 37.8% in 2023, a drop of 9.9 percentage points. With the implementation of the new round of open-door policies, it rose to 47.6% in 2006, and then declined gradually to 37.8% in 2020. It then rose to 38.3% in 2023. The share of value added by the tertiary sector in GDP has steadily increased from 24.6% in 1978 to 54.5% in 2020, a rise of 29.9 percentage points. The proportion of value added in the tertiary sector was affected by the COVID-19 pandemic, declining to 52.8% in 2022 before rising again to 54.6% in 2023, exceeding the pre-epidemic level.

While the structure of the three sectors has been upgraded, the internal structure of agriculture, industry, and services have also been continuously optimised during the adjustment process.

- The basic position of agriculture has become more consolidated, and agriculture, forestry, animal husbandry, and fisheries are developing in an all-round manner. At the beginning of the reform and opening-up period, agricultural development was dominated by planting, with a single product type and unbalanced development. With the continuous optimisation and adjustment of agricultural policies, the comprehensive production capacity of agriculture has steadily increased, and the modern agricultural system has been established and perfected. In terms of the total output value of agriculture, forestry, animal husbandry, and fisheries, the proportion of traditional agriculture has continued to decline, from 80% in 1978 to 54.1% in 2022. Meanwhile, the proportion of forestry, animal husbandry and fisheries has risen from 3.4%, 15%, and 1.6%, respectively to 4.4%, 26.0%, and 9.9% in 2022.
- Industrial development is moving towards the middle and high end, and a modern industrial system is gradually being established. At the beginning of the reform and opening-up period, China's industry was dominated by labour-intensive general processing and manufacturing. With the rapid development of industrialization, industrial restructuring has achieved significant results, gradually changing from a simple structure to a complete range of categories, and from labour-intensive industries to labour-, capital-, and technology-intensive industries. Currently, China is the only country with all the industrial categories listed in the United Nations Industrial Classification. It ranks first globally in the production of more than 200 types of industrial products. Additionally, the value added by its manufacturing sector has been the highest in the world since 2010.
- The level of the service sector is constantly rising, and modern and emerging service industries are developing rapidly. At the beginning of the reform and opening-up period, the development of China's service sector lagged. Traditional service industries, such as wholesale and retail, and transport were the main contributors to the sector. With the economic development and improvement of people's living standards, the demand for productive and living services is growing rapidly, and the modern service industry is booming and developing rapidly. From 2017 to 2022, the average annual growth rate of business income of strategic emerging service, for companies over a certain size, was 14.9%. This growth rate was significantly higher than the overall growth rate of business income for the service sector. In line with

the general trend of residents' consumption upgrading, the development of tourism, culture, sports, health, pension and other leisure industries are booming.

Characteristics of changes in industrial structure during the Fourteenth Five-Year Plan period

Since 2012, socialism with Chinese characteristics has entered a new era, and economic development has shifted from a phase of rapid growth to one of high-quality development. During the "14th Five-Year Plan" period, China not only faces a strategic opportunity for high-end and green transformation development but also takes on the responsibility of promoting change in quality, efficiency, and dynamics of economic development as well as improving overall productivity.

- The new generation of technological and industrial changes provides new opportunities for the high-end and green transformation of China's industries. At present, a new wave of technological and industrial revolution is flourishing globally, leading to profound historical changes in production methods, division of labour, and industrial organisation. Countries around the world are actively cultivating high-tech industries and striving to take the lead in the international market. China is seizing the opportunities presented by this new wave of technological and industrial changes by transforming and upgrading traditional industries using new-generation information technologies such as the internet, big data, cloud computing, the Internet of Things, and artificial intelligence to accelerate and upgrade green transformation of industries. By taking advantage of the initiative to build a strong manufacturing country and the "Internet Plus" action plan, focusing on advanced manufacturing, China has promoted the transformation and development of the industry towards being high-end, intelligent, efficient, and green.
- Innovation-driven development provides solid support for industrial high-end and green transformation. The key to successful transformation and upgrading of industries lies in innovation, which becomes the main driving force for development. In 2006, the State Council issued the *National Medium and Long-term Science and Technology Development Plan (2006-2020)*, which clearly defined the direction of the construction of the national innovation system. The 18th CPC National Congress formally established the innovation-driven development strategy in 2012, putting China on a new track of innovation-driven growth. Since the implementation of the innovation-driven development strategy, major innovations have emerged, substantial breakthroughs have been made in the reform of the science and technology system. The vitality and capacity of innovation subjects have been continuously enhanced, and the effectiveness of the national innovation system has been significantly improved. The Global Innovation Index Report 2020 shows that China's innovation capacity ranks 14th globally, ranking among the world's top 15 for two consecutive years, and positioning it as a leading innovative nation. China's research and development (R&D) expenditure accounted for 2.23% of its GDP in 2019, exceeding the average EU level. The number of R&D personnel remains the

highest in the world, forming the largest scientific and technological talent pool in the world. China also led the world in the number of patents granted for inventions ranks and ranked second in both the number of international scientific and technological papers and their citations. These innovation advantages have provided a new power source for industrial upgrading and green transformation.

- The pace of the green transformation of industries is accelerating under the dual carbon targets. There is an interactive relationship between carbon emissions and industrial structure. On the one hand, upgrading the industrial structure can reduce carbon emissions and improve carbon emission performance. On the other hand, policies aimed at controlling carbon emissions can also promote green transformation and upgrading of the industrial structure. Given China's status as the "world's factory" and a major manufacturing country, there is a close correlation between industrial restructuring, energy restructuring, and carbon emission control. Promoting the optimisation of industrial structure and technological advancement is crucial to achieving the carbon peak and carbon neutrality goals. During the "14th Five-Year Plan" period, it is necessary to strictly curb the blind development of high-energy-consuming and high-emission industries. This can be achieved by optimising the stock of production capacity through energy-saving and efficiency improvements, accelerating the low-carbon transformation of traditional industries, and at the same time accelerating the development of high-technology industries, advanced manufacturing industries, the digital economy, and other strategic emerging industries. It is important to vigorously develop a new type of green and low carbon economy, and push forward the structural adjustment and upgrading of industries to gradually realise the carbon neutrality goal.

6.4 Socio-economic impacts of China's energy transformation

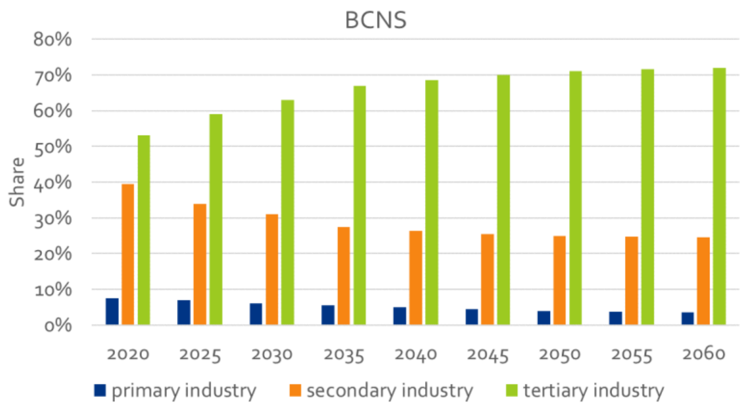
This chapter uses the improved CETPA model to assess the socio-economic impacts of China's energy transformation. The assessment includes the value of goods supplied by the energy sector, industrial structure, sectoral employment, sectoral investment, and the contribution rates to economic growth under different scenarios. Finally, the differences in socio-economic impacts between the two scenarios, such as the energy sector's contribution to economic growth, sectoral investment, and employment, are compared.

Analysis of BCNS scenario modelling results

Trends in industry structure in BCNS

Classifying the whole macroeconomy according to the three major sectors, the industrial structure of the three major sectors and their trends in BCNS are shown in Figure 6-1.

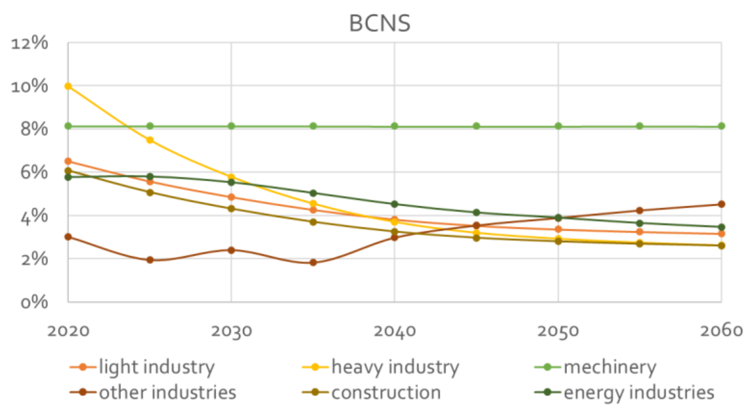
Figure 6-1 Structure of the three sectors and their trends in BCNS



Based on Figure 6-1, the proportion and trend of the three sectors in BCNS align with the expectation that the tertiary sector outperforms the secondary sector, and the secondary sector outperforms the primary sector. The primary sector has a small share, which decreases annually from 7.5% in 2020 to 3.5% in 2060. The secondary sector's share was 39.4% in 2020, then it gradually decreased to 31% in 2030 and 24.5% in 2060. The tertiary sector's share was 53.1% in 2020, then it increased annually to 63% in 2030 and 72% in 2060. Figure 6-1 shows that after 2035, the structural changes in the proportions of the three sectors slow down.

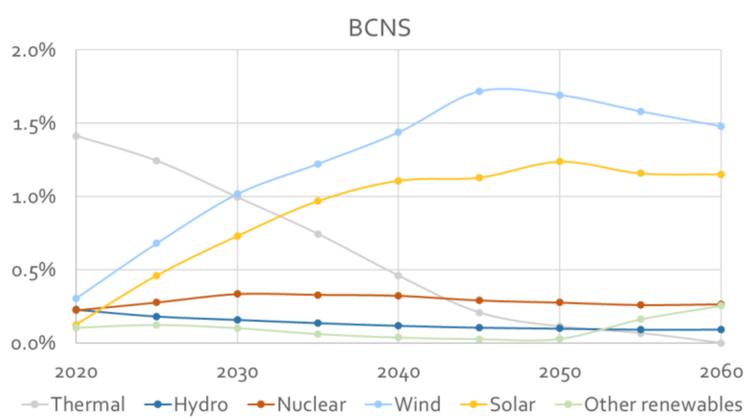
Figure 6-2 shows the GDP share of output of various economic sector in the secondary sector in different years and their trends. The share of GDP from equipment manufacturing in the secondary sector remains stable, which indicates that the equipment manufacturing industry has the same growth rate as the overall economy. As the GDP share of the secondary sector decreases over time, the GDP share of sectors within the secondary sector also declines yearly. The fastest decline is in heavy industry, followed by light industry and construction. The GDP share of the energy sector also declines year by year, but at an overall slower rate. This is mainly because of the relatively smooth overall change in energy sector, which mask the trends in the GDP shares of the individual energy sectors.

Figure 6-2 GDP share of output by sector in the secondary sector and its evolution



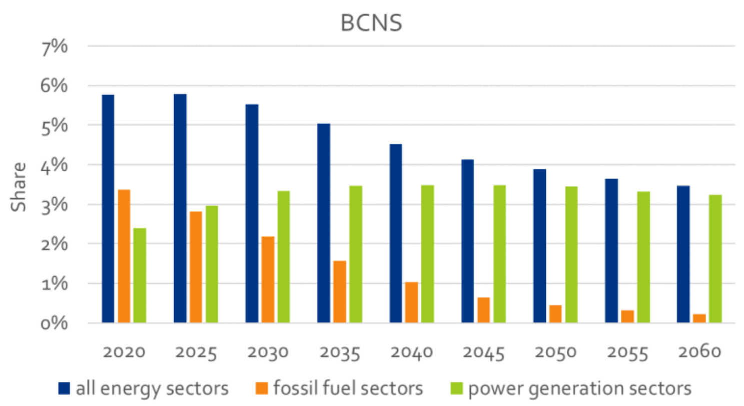
The GDP share of each power sector and its trend are shown in Figure 6-3. The GDP share of thermal power declines rapidly from 2020 until 2055 and then declines slowly. The GDP shares of wind power and solar power increase rapidly, and the share of wind power is larger than the share of solar power. The share of wind power rises to a peak of 1.72% in 2045 and then declines slowly, whereas solar power reaches a peak of 1.24% in 2050 and then declines slowly.

Figure 6-3 Structural trends in the power industry in BCNS



Dividing the energy sector into fossil energy and electricity, Figure 6-4 shows the GDP shares and trends of the energy sector, the fossil energy sector, and the power sector. From Figure 6-4 it can be seen that the GDP share of the energy sector is generally on a downward trend. However, the GDP share of the fossil energy sector declines rapidly, while the GDP share of the power sector increases.

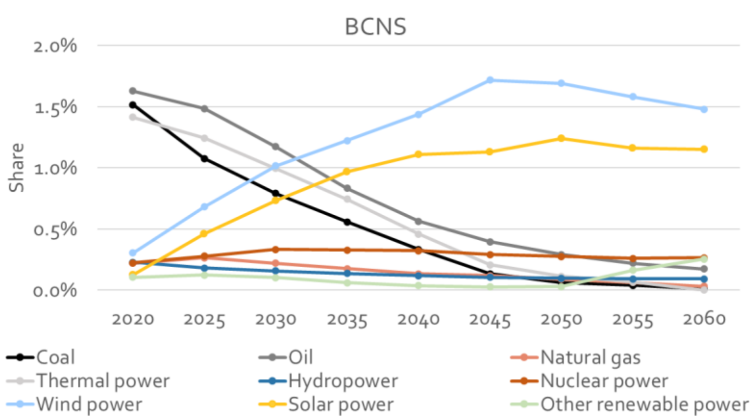
Figure 6-4 Changes in the growth contribution of the energy sector in BCNS



The proportion of supply value of the energy sector in BCNS

The value of products produced by each industry in the overall economy in BCNS reflects the supply value of domestic production, mainly for the supply of goods in the domestic market and foreign exports. The structure of the supply value of energy products in BCNS is shown in Figure 6-5.

Figure 6-5 Product supply value structure of the energy industry in BCNS



The meaning of the value volume structure of product supply in the energy industry is the proportion of the value volume of a particular energy product supply to the total value volume of commodity supply in the economy. From Figure 6-5 it can be seen that the supply value of coal, oil, and thermal power is gradually decline over time. From 2020 to 2040 the supply value of these products declines rapidly. This trend continues between 2040 and 2060, but at a slower pace. The supply value of wind and solar power shows a rapid upward trend, and the growth rate slows down after 2050. Although the absolute supply of wind power and solar power products continues to rise due to the large total value of goods produced in the economy, the growth rate of their value proportion slows down. Put another way, this change is more intuitively illustrated by the trend in each sector's value added relative to itself. As shown in Figure 6-6, solar power and wind power are the two sectors with the most significant growth relative to the 2020 level of value added by sector, with value added in 2060 reaching 31 and 16 times the 2020 level, respectively.

Figure 6-6 Trends in energy sector value added in BCNS

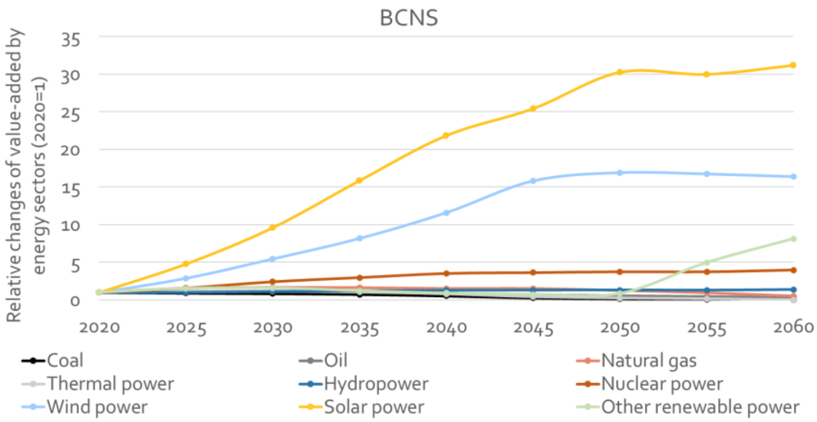
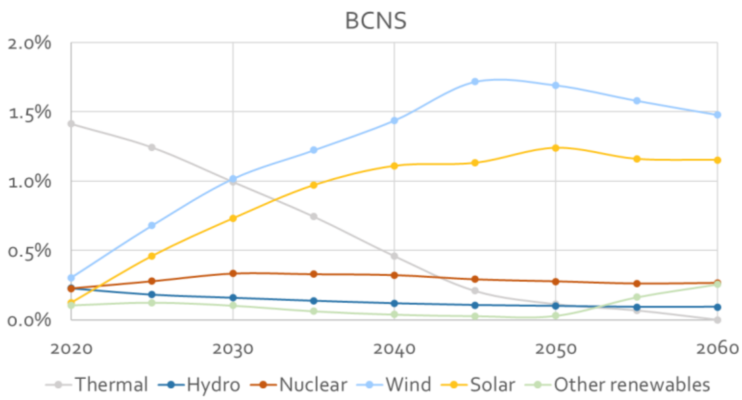


Figure 6-7 shows the trend in the proportion of the supply value of commodities in different power sectors in BCNS. The supply value-volume share of thermal and hydropower gradually declines after 2020, while the supply value-volume shares of wind, solar power and nuclear power generally show an increasing trend.

Figure 6-7 Trend in value share of power industry supply in BCNS



Employment trends in BCNS

The amount of employment in each sector of the economy in BCNS and its trends are shown in Figure 6-8. Employment in the energy sector is relatively small, and the sectors with significant employment are mainly the tertiary sector, the secondary sector excluding energy, and the primary sector. Employment in the agricultural sector has been declining over time, as well as in light industry, heavy industry, and construction. Employment in equipment manufacturing, other industry, transportation, commerce and food service, health care, education and technology, and other services shows a trend of increasing and then decreasing, with the peak occurring around 2035.

Figure 6-8 Volume of employment and its trend by sector of the economy in BCNS

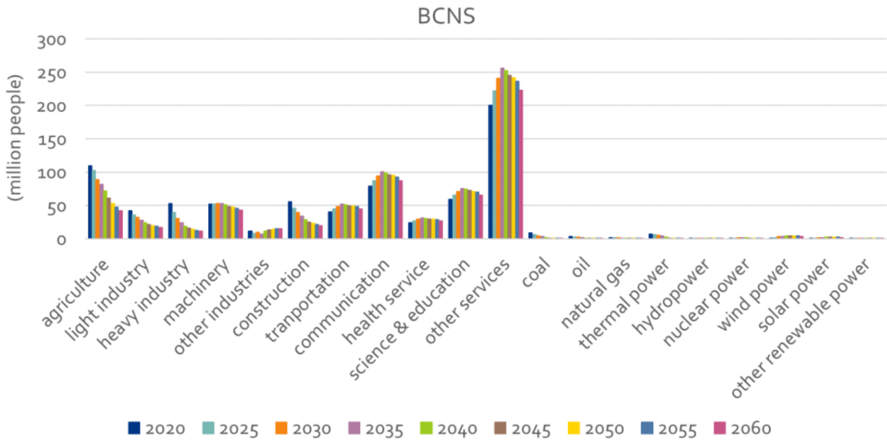


Figure 6-9 Energy sector employment volume and its trends in BCNS

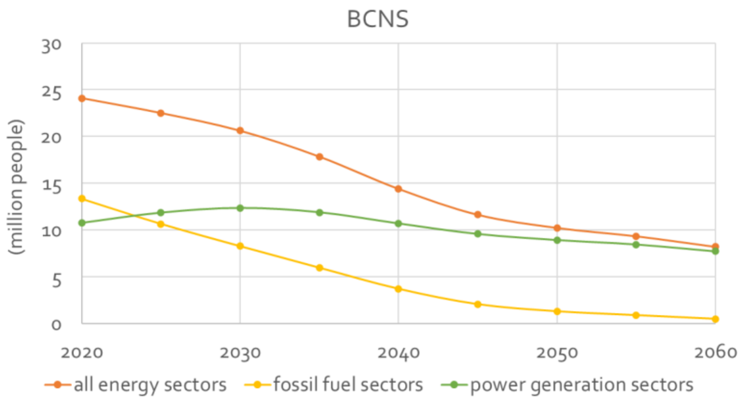
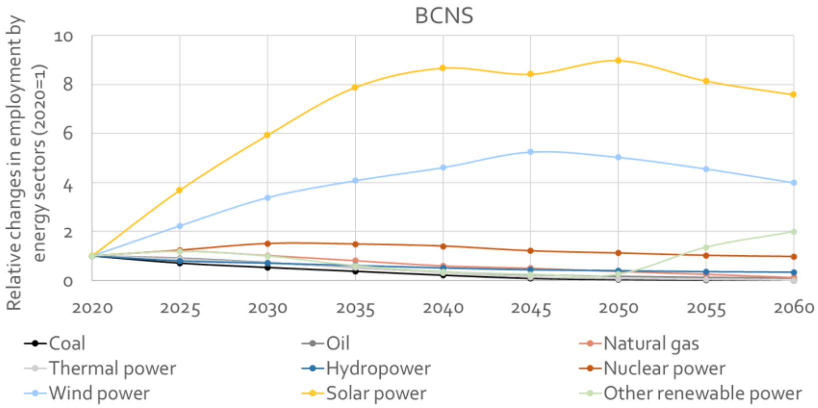


Figure 6-9 and Figure 6-10 show the employment levels and trends in the energy sector in BCNS. Figure 6-9 illustrates the overall employment levels and trends in the energy sector, the fossil energy sector, and the power sector. This shows a downward trend in overall energy sector employment over time. Looking at the trends in employment for specific energy sectors, solar power and wind power employment provide the most new employment. Employment in these two energy sectors reach eight and four times their 2020 levels, respectively, by 2060, as shown in Figure 6-11.

Figure 6-10 Trends in employment in the energy sector in BCNS



Trends in investment in BCNS

The BCNS return of investment (ROI) for each energy sector and their trends are shown in Figure 6-11. The changes in the ROI of each energy sector show different trends over time. The ROI of coal, oil, natural gas, thermal power, and hydropower show a decreasing trend, while the ROI of nuclear power, wind power, and solar power increase and then decrease.

Figure 6-11 Energy sector ROI and trends in BCNS

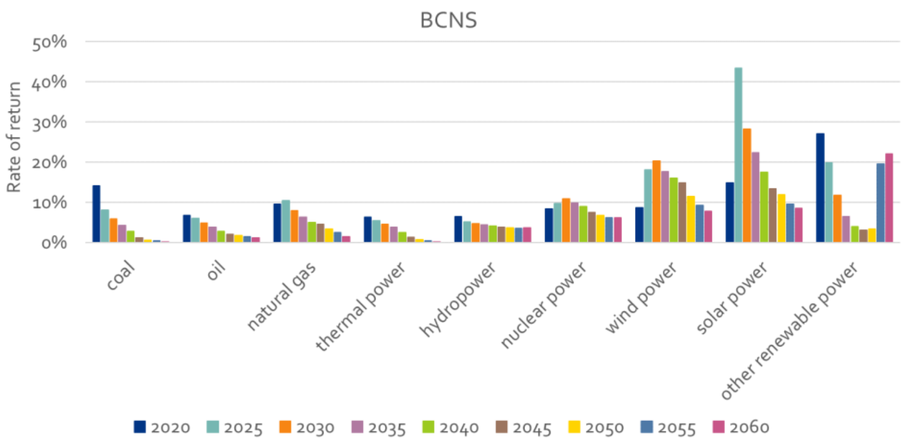


Figure 6-12 Investments amounts and trends in the energy sector in BCNS

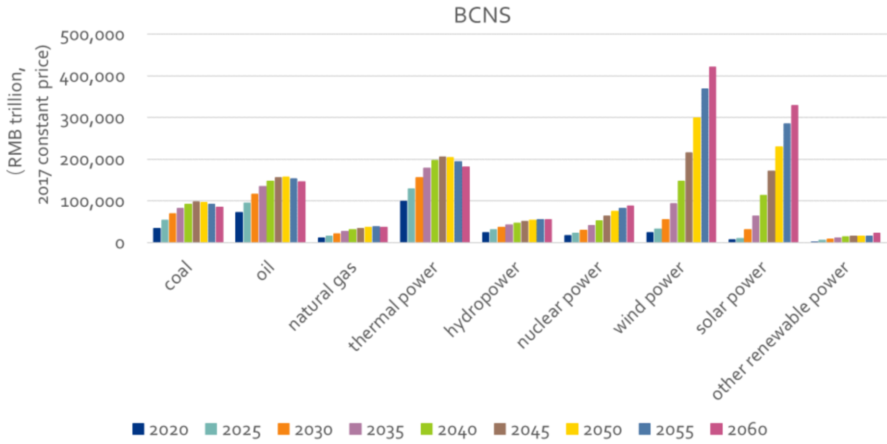
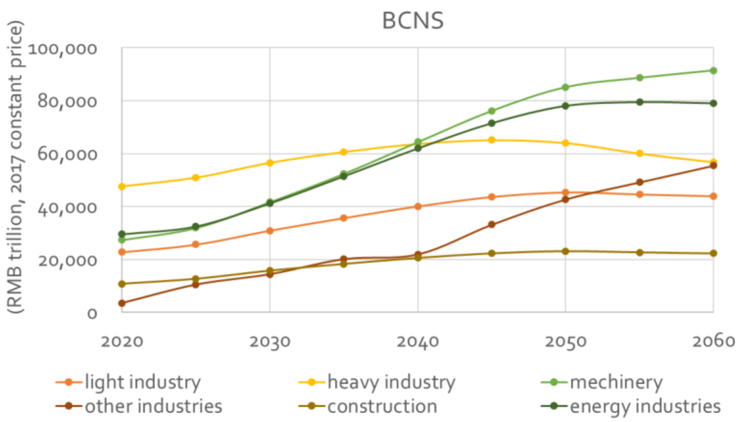


Figure 6-12 shows the energy sector investment volume and trends in BCNS. The amount of investment in the coal, oil, natural gas, and thermal power sectors rises gradually over time, peaks, and then declines rapidly. The amount of investment in the hydropower and nuclear power sectors also gradually increases over time, peaks, and then declines slowly. In contrast, the investments in the wind and solar power sectors shows a continuous upward trend.

Figure 6-13 Trends in investment by sector in the secondary sector in BCNS

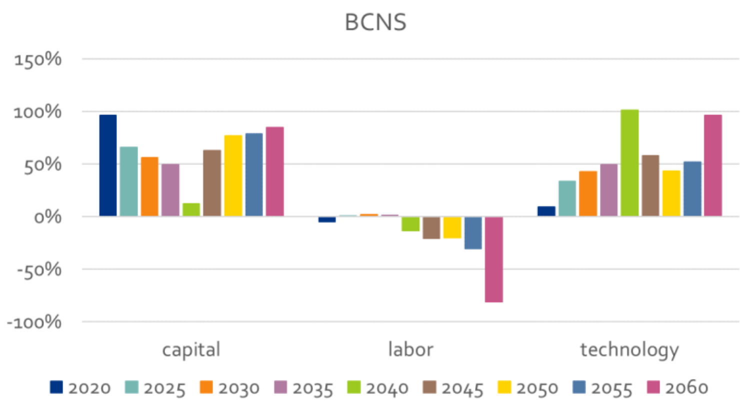


The amount of investment in each sector of the secondary sector in BCNS and trends are shown in Figure 6-13. The overall trend of investment in each sector of the secondary industry is upward, with slower growth in construction and light industry, faster growth in equipment manufacturing, the energy sector, and other industries, and a shift from upward to downward investment in heavy industry in the middle and late stages.

Factor contribution to growth in BCNS

The contributions rates and trends of economic growth factors in BCNS are shown in Figure 6-14. In BCNS, capital and technological progress have high contribution rates to economic growth, while labour has a low, or even negative, contribution rate. Over time, the contribution rates of capital, labour, and technological progress change. From a macroeconomic perspective, future economic growth will mainly depend on technological progress and capital investment. The contribution of labour to growth is small and gradually turning negative due to the overall downward trend in population and employment.

Figure 6-14 Factor contributions to economic growth and trends in BCNS



Analysis modelling results in ICNS

Trends in industrial structure in ICNS

Classifying the whole macroeconomy according to the three sectors, the structure of the three sectors and their trends in ICNS are shown in Figure 6-15. The primary sector in ICNS scenario accounts for a relatively small proportion, and the proportion decreases year by year; the proportion of the secondary sector also decreases, while the proportion of the tertiary sector is the largest and continuous to increase.

The GDP share of output of each economic sector of the secondary sector in different years and its trends are shown in Figure 6-16. The output share of the equipment manufacturing sector in the secondary sector remains stable, indicating that the equipment manufacturing sector will maintain the same growth rate as the macroeconomy in the future. As the GDP output share of the secondary sector is decreasing annually, the output share of other sectors in the secondary sector also decreases year by year. The fastest declining sector is heavy industry, followed by light industry and construction. The energy sector's share of GDP has also been declining annually, but at an overall slower rate. This is because the energy sector remains relatively stable, masking the trends in the GDP shares of the individual energy industries.

Figure 6-15 The structure and trends of the three major sectors in ICNS

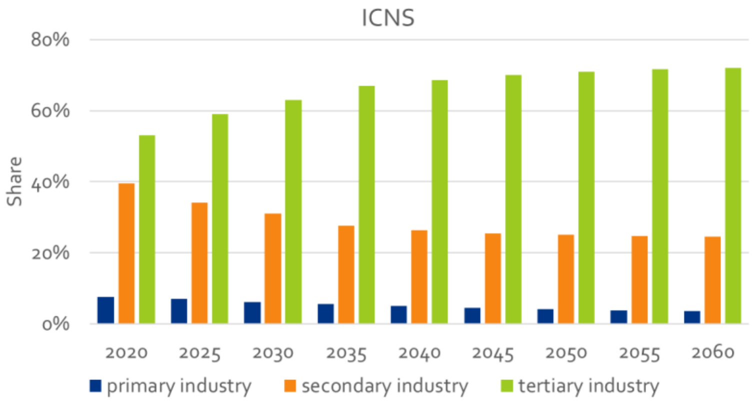
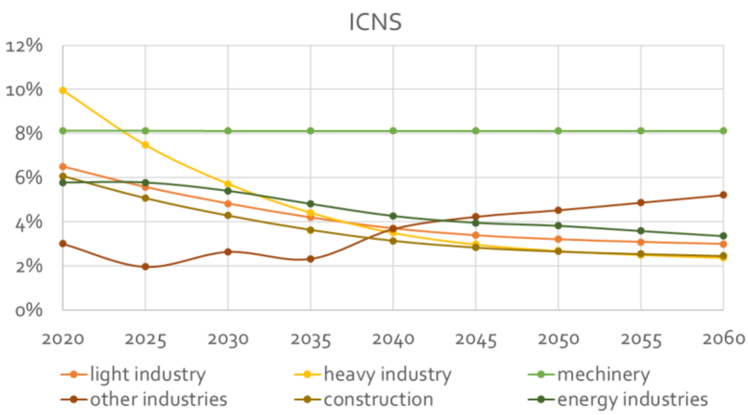


Figure 6-16 The GDP output share and changes in the secondary sector



The supply value share of energy sector supply in ICNS

The value of the product produced by each industry of the macroeconomy in ICNS reflects the supply value of domestic production, mainly used for the supply of goods in the domestic market and the export of goods. The structure of the value of the product produced by the energy industry in ICNS is shown in Figure 6-17. The value of product supply of coal, oil, and thermal power is gradually declining over time. Between 2020 and 2050, the share of product supply value declines rapidly. From 2050 to 2060 the share continues to declining, but at a slower rate. The supply of wind and solar power products shows a rapid upward trend. Put another way, this change is more intuitively illustrated by the trend in each sector's value added relative to itself, as shown in Figure 6-18. Compared to 2020 levels, solar and wind power are the two sectors with the most significant growth, with value added in 2060 reaching 35 and 18 times the 2020 level, respectively.

Figure 6-17 Product supply value structure of the energy industry in ICNS

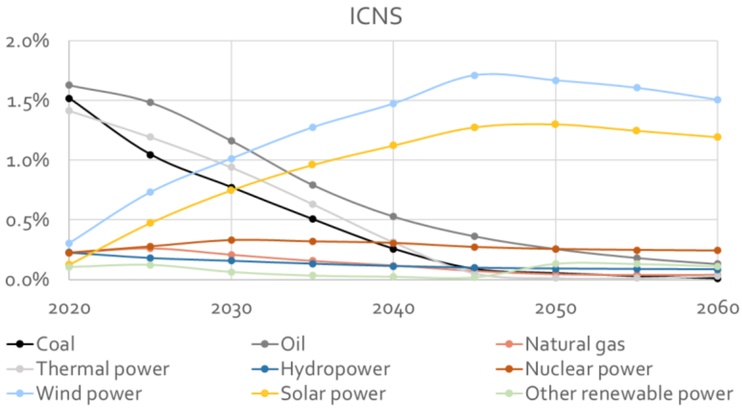
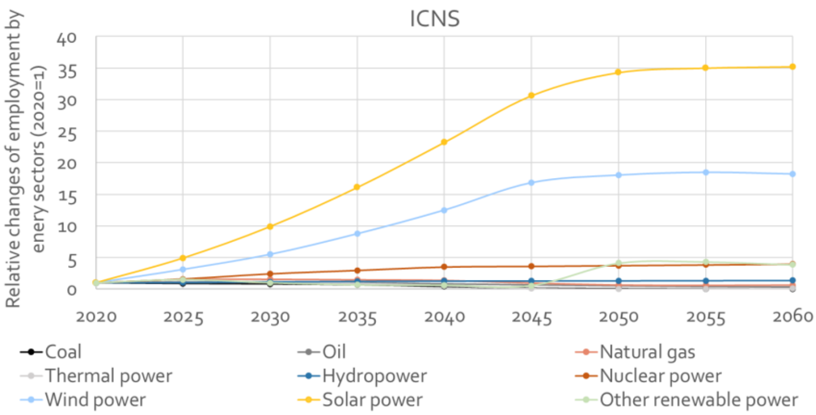


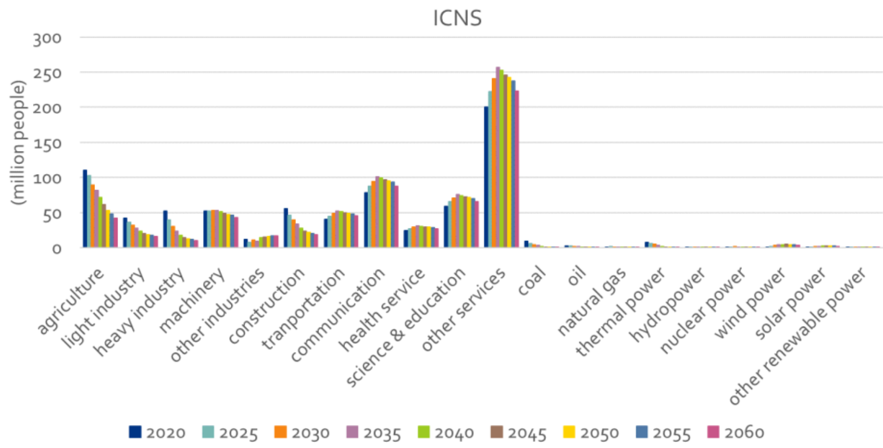
Figure 6-18 Trends in the value-volume share of power industry supply in ICNS



Trends in employment volume in ICNS

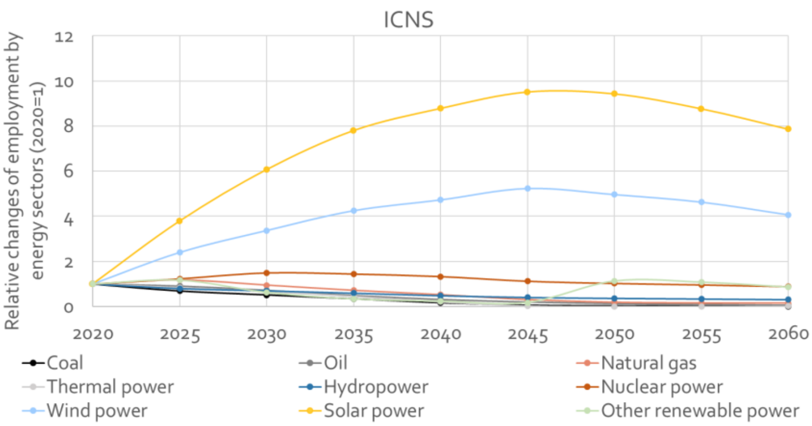
The amount of employment in each sector of the economy in ICNS and its trends are shown in Figure 6-19. Employment in the energy sector is relatively small. The sectors with significant employment are mainly the tertiary sector, non-energy industries in the secondary sector, and the agricultural sector. Employment in the agricultural sector has been declining over time, as well as in light industry, heavy industry, and construction. Employment in equipment manufacturing, other industry, transport, commerce and catering, healthcare, education and technology, and other services first increases and then decreases.

Figure 6-19 Volume of employment and its trend in each sector of the economy in ICNS



The fluctuations in employment levels in the energy sector are shown in Figure 6-20. Over time, employment in coal, oil, thermal power, and hydropower declines steadily. Solar and wind power provide the most new employment. Compared to 2020 levels, employment in these two new energy sectors are eight and four times the 2020 level, respectively, by 2060, as shown in Figure 6-20.

Figure 6-20 Trends in the employment in the energy sector in ICNS



Investment trends in ICNS

The ICNS scenario investment return rates and trends for each energy sector are shown in Figure 6-21. Over time, the changes in the ROI of each energy sector show different trends. The ROIs of coal, oil, natural gas, and thermal power show a decreasing trend. The return on investment for nuclear, wind, and solar power is first rising and then falling.

Figure 6-21 Investment returns rates and trends in energy industries ICNS

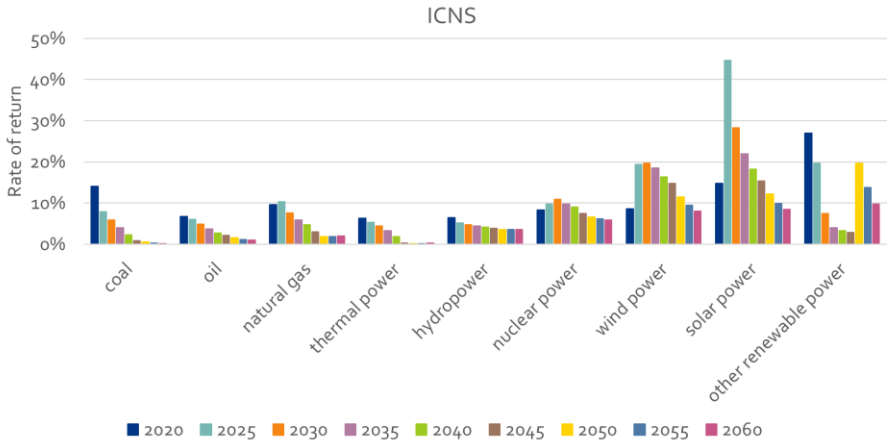
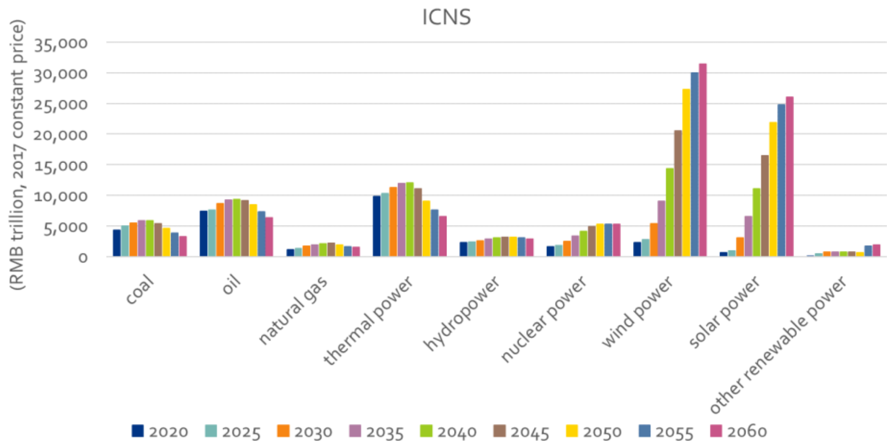


Figure 6-22 Amount and trend of investments in the energy sector in ICNS

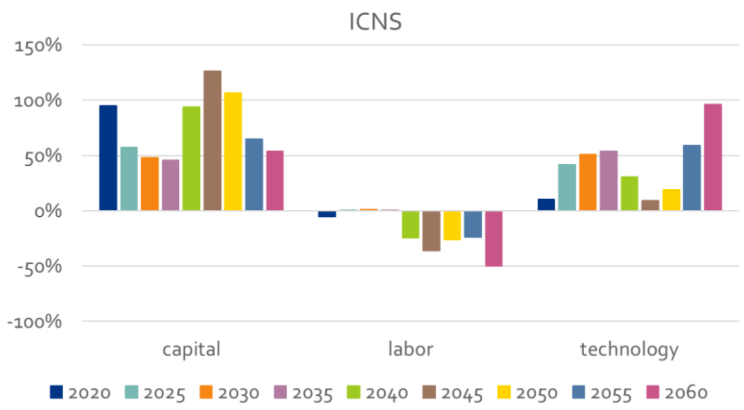


Amount of capital investment in the energy sector and trends in ICNS are shown in Figure 6-22, the investments in the coal, oil, natural gas, thermal power, hydropower, and nuclear power sectors first increase and then decrease over time. In contrast, the amount of investment in the wind and solar power sectors shows a continuous upward trend.

Factor contribution to growth in ICNS

The contribution rates and trends of economic growth in ICNS are shown in Figure 6-23. In the economic growth of the ICNS scenario, the contribution rate of capital and technological progress is larger, and the contribution rate of labour is smaller, or even negative. Over time, the contribution rates of capital, labour, and technological progress are changing. From a macroeconomic perspective, future economic growth will depend mainly on technological progress and capital investment. The contribution of labour to growth is small and gradually turns negative due to the decline in population and employment.

Figure 6-23 Factor contributions to economic growth and trends in ICNS



Main findings

The above results of the socio-economic impact evaluation of China's energy transformation using the CETPA model show that, under both scenarios, China's energy transformation promotes green and low-carbon economic development. While providing energy security for economic and social development, the large-scale and high-quality development of non-fossil energy sources, through the continued substitution of fossil energy gradually replacing fossil fuels, it can effectively reduce carbon emissions and environmental pollutants at source. This provides critical support for achieving the goals of a Beautiful China, carbon peaking, and carbon neutrality. At the same time, the energy transformation has created new jobs in the energy sector, with rising wages and increased social welfare, demonstrating that the transformation promotes social equity and supports a just transition for the energy sector as a whole.

Furthermore, as illustrated in Figure 6-24 and Figure 6-25, a comparison of the simulation results under the two energy transformation scenarios shows that, in ICNS, China's energy transformation generates a higher positive socioeconomic impact compared to the BCNS scenario. This highlights the promising outlook for China, in cooperation with the international community, to create the conditions necessary to follow an ideal path for the energy transformation.

Figure 6-24 Employment generated by wind and solar power in two scenarios

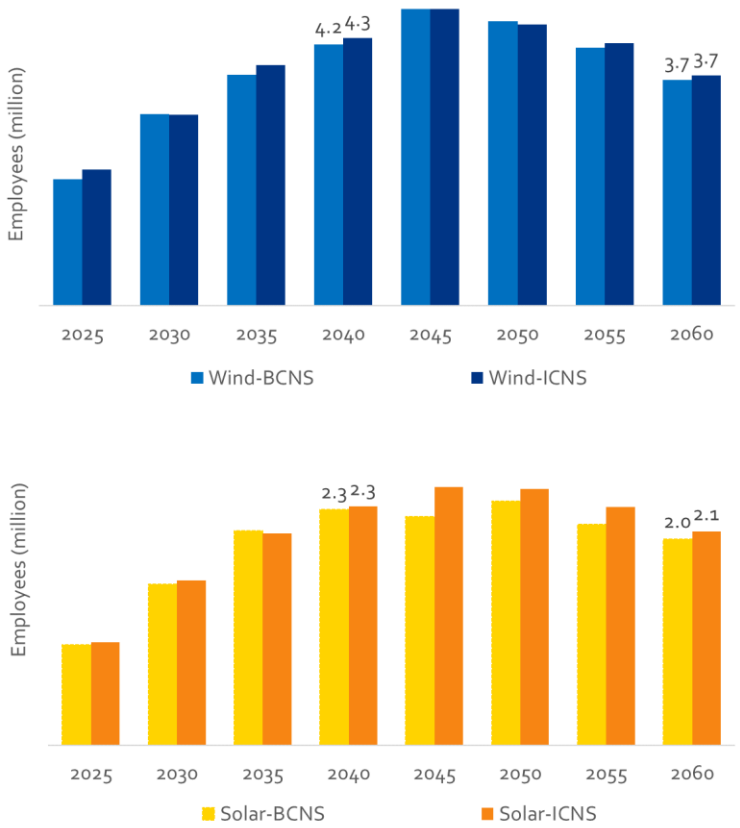
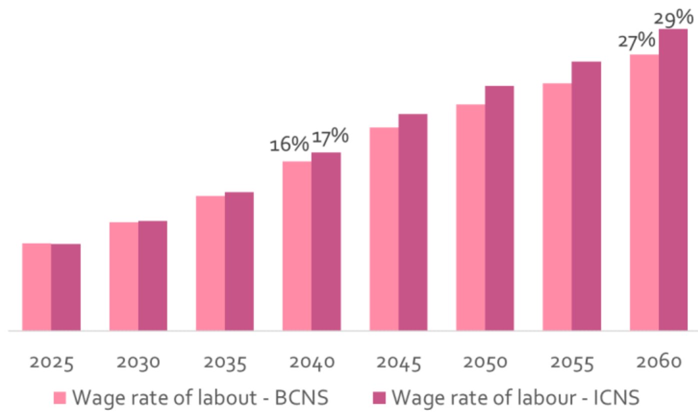


Figure 6-25 Trends in labour wage rate growth in two scenarios

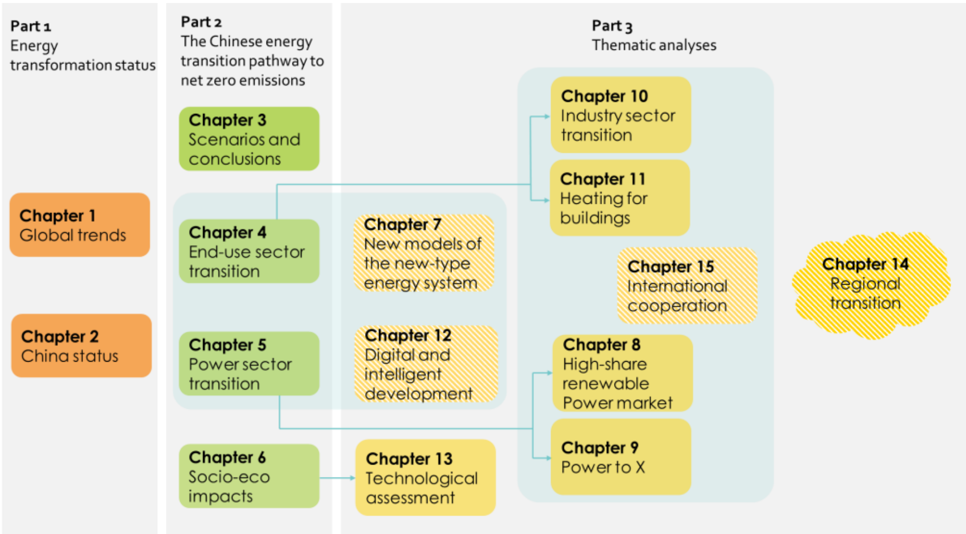


Part III Thematic analysis

Part III Thematic analyses

The third part of the CETO 2024 report consists of nine thematic analysis chapters on new models and new business models for a new energy system, building an electricity market adapted to a high proportion of renewable energy sources, synthetic fuels made from electricity, the low-carbon transformation of the industrial sector, the low-carbon transformation of building heating, and the development of digital intelligence in energy. The nine thematic analysis chapters mutually support the model analysis in Part II (as shown in Figure 5). The main conclusions of the chapters in Part III are presented below.

Figure 5 Relationships between the chapters of China Energy Transformation Outlook 2024



7 New models of the new-type energy system

The fundamental requirement of a new energy system is to achieve a higher level of unity in energy that is green, secure, and economically efficient. It is essential to balance development and security, ensuring a sequential approach that builds the new system before dismantling the old or advancing both simultaneously. This requires accelerating the planning and construction of a new energy system and driving systematic changes in energy consumption, supply, industry, markets, and governance. The goal is to enhance collaboration, interaction, and integration between various energy sources, as well as among energy producers, service providers, and consumers, fostering the development of new industry forms.

In the future, the energy industry must transition from being primarily resource-driven to being primarily technology-driven, fostering new productive forces through the development of new energy technologies, models, and business forms. The clean energy supply should evolve from a focus on centralised development and large-scale unified transmission and distribution to a balance between regional self-balancing and cross-regional optimisation. The transformation of end-use energy consumption should begin with electricity replacing coal, gradually expanding to a diversified clean energy mix, including electricity, hydrogen, and ammonia, turning major energy-consuming sectors into key drivers of the energy transformation.

Four key areas that need to be focussed on:

1. **Integrated development of new and traditional energy sources**. Accelerate the integrated development of hydropower, wind, and solar energy bases, implement coordinated dispatch of cascade hydropower stations, and run complementary hydropower and wind-solar systems. Upgrade hydropower bases into comprehensive renewable energy bases. Using underground coal mine subsidence areas for new energy generation, geothermal energy, and advanced energy storage. Integrate new energy with oil and gas fields by developing wind, solar, geothermal, and thermal utilisation projects in and around the fields while replacing energy consumption in oil and gas exploration with clean electricity and heat.
2. **Coupling of electricity, heat, hydrogen, and carbon**. Use low-cost renewable energy to drive electricity-heat coupling centred on energy storage, improving the ability of northern cities and industrial parks to absorb renewable energy and adjust power systems. Promote integrated production of wind, solar, hydrogen, ammonia, and methanol to localise green electricity utilisation in western regions, creating comprehensive energy-chemical bases. Foster price signal coordination between the electricity market and carbon emissions trading market to support a society-wide green and low-carbon transformation.

3. **Integration of Energy Production and Consumers:** Develop distributed solar energy systems for urban and rural residents, leveraging new characteristics of photovoltaic panels—such as lightness, flexibility, and transparency—to accelerate integrated applications like Building-Integrated Photovoltaics (BIPV) and PEDF building. Drawing from European and American experiences, better utilise market mechanisms to develop community-shared solar energy and virtual power plants and explore rural energy cooperatives for wind power in rural areas. Expand green industrial microgrids by creating comprehensive energy systems for electricity, heat, cooling, and hydrogen that efficiently complement each other based on the energy needs of enterprises and industrial parks. Promote integrated energy stations offering solar, storage, and charging/switching services, providing clean power for electric vehicles while also offering auxiliary services like peak-shaving and valley-filling for the electricity grid. While constructing floating offshore wind farms in deep-sea areas, efforts should also focus on developing "wind power + aquaculture" marine farms and offshore energy bases that integrate wind power with the production of hydrogen, ammonia, and methanol.

4. **New technologies support the development of new business models and industries**. To facilitate the energy industry's transition from resource-driven to technology-driven development, focus on key technological areas such as offshore wind power, next-generation solar cells, green hydrogen, and long-duration energy storage, with the goal of achieving large-scale application within the next 5–10 years. Breakthroughs are needed in critical materials, core components, and system integration. By integrating diverse application and consumption scenarios, new technologies will drive the expansion of new markets, enhance economic viability, and enable iterative upgrades of commercial and development models. This will foster the development of new models and business forms, cultivating and advancing new productive forces across upstream and downstream industries.

8 High-share renewable power market

With the gradual transfer of the electricity spot market to formal operation in many provinces and the implementation of the *Basic Rules for Electricity Spot Markets*, China has established an electricity market with the framework of "medium- and long-term contracts + spot market + auxiliary services". The next step in building an electricity market adapted to a high proportion of renewable energy is to focus on the following aspects:

Firstly, the construction of a unified national electricity market system. Promote the integrated design and joint operation of medium- to long-term, spot, and ancillary services markets. Eliminate barriers between provinces and advance the development of regional power markets, ensuring that cross-provincial electricity trading is not restricted. Improve the design of retail market mechanisms to ensure the effective transmission of wholesale market prices to end users.

Secondly, gradually integrating renewable energy into the power market. Establish a medium- to long-term electricity trading mechanism suited to the characteristics of renewable energy, encouraging supply and demand parties to sign longer-term contracts. Explore the use of government-authorized contracts for difference (CfD) to provide stable revenue streams for renewable energy, integrate existing guaranteed renewable energy into the market, and continue supporting the application of advanced renewable generation technologies.

Third, establishing a price formation mechanism for distributed new energy to participate in the electricity market. Support new market participants such as energy storage companies, virtual power plants, and load aggregators. Gradually implement time-of-use pricing for distributed renewable energy or allow it to participate in the spot market. Improve the allocation method for transmission and distribution costs, determining additional charges for distributed renewable energy based on distribution voltage levels.

Fourth, improving the capacity tariff mechanism. Incorporate flexible resources into the capacity market, with a focus on supporting the procurement of flexible ramping capacity. Shift procurement priorities from peak load periods to times of ramping constraints. Refine the time-period classification in the capacity market and expand settlement periods from annual to quarterly.

9 Power to X

9.1 Main findings

- Producing synthetic fuels such as hydrogen, ammonia, and methanol using electrolysis is an essential technological pathway towards global carbon neutrality. These fuels are new energy carriers for future energy transformation.
- Several countries are actively planning the development of synthetic fuels produced through electrolysis and are strengthening low-carbon standards. The United States has formulated the "National Clean Hydrogen Strategy and Roadmap," Germany has developed a new hydrogen strategy, and Japan has introduced the 2023 version of its hydrogen development strategy. At the same time, countries continuously enhance the low-carbon and zero-carbon standards for electrolysis-produced fuels.
- Domestic policies for synthetic fuels produced through electrolysis are continuously being evolved, and production capacity is rapidly increasing. In 2023, large green hydrogen projects were constructed in Hebei, Guangdong, and Inner Mongolia. In terms of green methanol and green ammonia, China has completed and is constructing 11 green low-carbon methanol projects.
- The synthetic fuel industry using electrolysis is beginning to take shape, and costs are continuously decreasing. In 2023, China's alkaline electrolyser technology entered a new iteration stage. There is significant room for improvement regarding the economic viability of synthetic fuel production with cost reductions in photovoltaic/wind power generation, hydrogen production power sources, and electrolysers.
- The economic viability of synthetic fuel development needs to be improved and still faces multiple challenges. Currently, the costs of green hydrogen, green ammonia, and green alcohol produced through electrolysis are about twice those of similar fossil fuel production costs. The mismatch between supply and demand further increases the difficulty of utilising synthetic fuels. The next stage involves building an industry ecosystem for preparation, storage, transportation, and utilisation to promote sustainable development.

9.2 Exploration and progress in e-fuels in China

In recent years, as the concepts of carbon peaking and carbon neutrality have deepened, electrically produced hydrogen, ammonia, and methanol have emerged as critical tools for achieving carbon neutrality. They are set to play an increasingly important role in the low-carbon energy transformation. However, due to significant technical and economic challenges, efforts in China and globally have primarily focused on hydrogen production.

Policies related to e-fuels in China

Electrically produced fuels span across power, chemical, transportation, and construction industries, involving long and complex industrial chains. In March 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the *Hydrogen Energy Industry Development Medium- and Long-Term Plan (2021-2035)*. This document outlined fundamental principles, phased targets, and key measures for hydrogen energy development, providing a clear direction for high-quality growth in China's hydrogen energy industry. In terms of industrial positioning, hydrogen is formally identified as an energy source and an integral component of the future energy system. Key segments of the hydrogen industrial chain are included in national strategic emerging industries. In terms of development goals, by 2025 the plan aims for 50,000 hydrogen fuel cell vehicles and for green hydrogen production to be between 100,000 and 200,000 tonnes. The plan emphasizes four main areas for decarbonization: transportation, energy storage, distributed energy, and industrial sectors, with a focus on creating innovative demonstration projects.

In 2023, under the guidance of top-level policies, China's hydrogen industry made strides toward becoming more comprehensive and refined. At the national level, six agencies, including the State Administration for Market Regulation and the NDRC, jointly issued the *Hydrogen Industry Standards Framework (2023 Edition)*, establishing a systematic standardization framework for hydrogen production, storage, transportation, and utilization. At the regional level, over 30 provinces and cities incorporated hydrogen energy into their 14th Five-Year Plans, with regions such as Beijing, Hebei, Sichuan, and Inner Mongolia issuing detailed implementation plans for hydrogen energy development.

Specifically for fuel cell vehicles, the Ministry of Finance, the Ministry of Industry and Information Technology, the Ministry of Science and Technology, the NDRC, and the NEA approved the first batch of city pilot clusters for fuel cell vehicle demonstration projects, including Beijing-Tianjin-Hebei, Shanghai, and Guangdong in 2021. In early 2022, two additional clusters were approved: Henan (led by Zhengzhou) and Hebei (led by Zhangjiakou). Deployment targets for these clusters include 5,300 vehicles for Beijing-Tianjin-Hebei, 10,000 for Guangdong, 7,710 for Hebei, and 5,000 for Henan.

In May 2024, the Ministry of Finance issued a budget notification allocating RMB 1.142 billion for the first-year subsidy for fuel cell vehicle demonstration projects across 23 cities.

The potential application of green hydrogen and ammonia as electrically produced fuels in power systems is receiving increasing attention, with corresponding national policies being continuously introduced.

In January 2022, the NDRC and the NEA issued the *14th Five-Year Plan for New Energy Storage Development Implementation*. The plan aims to achieve breakthroughs in long-duration storage technologies, including hydrogen storage and thermal (cold) storage, by 2025. It promotes the construction of projects involving long-duration electrical storage, hydrogen storage, and thermal (cold) storage and encourages demonstration applications of renewable energy-based hydrogen/ammonia production and hydrogen-electric coupling.

In 2023, policies targeting long-duration and hydrogen storage were further refined. **At the national level,** in January 2023, the Ministry of Industry and Information Technology (MIIT) and five other agencies issued the Guiding Opinions on Promoting the Energy Electronics Industry, emphasizing the prioritization of renewable energy development and the acceleration of research into new technologies such as solid-state batteries, sodium-ion batteries, and hydrogen storage/fuel cells. In September 2023, the NDRC and NEA jointly issued the Guidance on Strengthening Power System Stability Under New Conditions, calling for the effective use of hydrogen storage and other new storage technologies to create integrated and diversified storage solutions tailored to specific applications, enhancing system safety and overall efficiency.

At the regional level, seven provinces in central and western China with abundant wind resources have actively supported hydrogen storage industry development. Initiatives such as "wind power + hydrogen storage," "offshore wind power + hydrogen storage," and "solar PV + hydrogen storage" are increasingly being incorporated into local policies. Across the nation, more than 20 provinces have included "hydrogen storage" in their development plans.

Current status of the development of e-fuels in China

In recent years, China has made important breakthroughs in key technologies and equipment manufacturing in hydrogen production including electrolytic water and hydrogen fuel cells and has built a more complete hydrogen industry chain for hydrogen production, storage and transportation, refuelling and application.

In terms of hydrogen technology, the country has achieved wide-ranging technological advancement and innovation, with key performance indicators on par with international standards. Domestic alkaline electrolysers have entered the technology iteration stage, with about 10 models of 2000 Nm^3/h single-tank hydrogen production electrolysers launched in 2023, with the maximum single-tank hydrogen production reaching 3000 Nm3 /h. The supply chain of PEM electrolyser components is forming gradually, and domestic proton exchange membrane and catalyst technologies are gradually realising mass production. China has developed the preparation techniques and processes for key components such as catalyst, proton exchange membrane, carbon paper, membrane electrode module, and bipolar plates. China has mastered the design and manufacturing technology of hydrogen fuel cell stacks and established a fuel cell vehicle power system technology platform with independent intellectual property rights.

Similarly, green fuel production took large strides in 2023, as China added 37,000 tonnes/year of hydrogen production capacity from electrolysis 37,000 tonnes/year, making the cumulative capacity about 72,000 tonnes/year as of the end of 2023, with 63%

of the capacity concentrated in the provinces of Xinjiang and Ningxia, and 80% of the capacity will be produced by using PV. These large-scale green hydrogen projects will be mainly grid-connected. The cost of hydrogen production from electrolysis is decreasing steadily, and with the use of PV directly connected to hydrogen production, the cost of green hydrogen is marginally above 20 RMB/kgH2 . As for green methanol, 11 low-carbon methanol projects have been completed or are under construction in China as of 2023, with a low-carbon methanol capacity of about 366,000 tonnes/year. Regarding green ammonia, 13 projects have been started, corresponding to a disclosed green ammonia capacity of about 790,000 tonnes/year, most of which are planned to be completed in 2024 and 2025.

At present, China's hydrogen storage and transport is mainly based on 20 MPa for transport via long-tube trailers. Meanwhile, the development of pure hydrogen pipeline transmission and hydrogen blending in natural gas pipelines is being developed. The scale of hydrogen liquefaction has exceeded 10 tonnes/day, and liquid hydrogen for civil use has achieved a significant improvement. In the refuelling segment, more than 350 hydrogen refuelling stations have been built nationwide, accounting for about 40% of the global total and ranking first in the world, and breakthroughs have been made in 35MPa technologies for fast hydrogen refuelling and 70MPa integrated mobile hydrogen refuelling stations.

In the end-use segment, hydrogen-powered transport is developing rapidly, with the competitiveness of domestically-produced equipment improving significantly. In terms of transport, the number of hydrogen fuel cell vehicles has surpassed 10,000, and China's hydrogen fuel cell commercial vehicle production and application market has become the largest in the world. As for industry, hydrogen-based chemical industry is operational at pilot scale, and hydrogen metallurgy technology demonstration projects have been opened. As for energy, the pilot demonstration of key technologies in power generation and cogeneration has been completed. On the building side, the first "hydrogen into 10,000 homes" intelligent energy demonstration community project was established in Foshan.

Challenges facing China's e-fuels

First, production costs remain high. The economics of green hydrogen, green ammonia and green methanol, along with actual downstream demand are critical challenges. The current production cost of green hydrogen in China's western regions, rich in renewable energy resources, is about 20 RMB/kg, which is significantly higher than that of coal hydrogen production of 10 RMB/kg. The cost of green ammonia and green methanol is more than twice the price of conventional products in the market, for example, the domestic price of green methanol is about between 5,000 and 6,000 RMB/tonne, while the market price of conventional methanol is only about 2,500 RMB/tonne.

Secondly, there is a spatial mismatch between supply and demand. There is a natural mismatch in the spatial distribution of domestic production and use of electric fuels, as renewable energy is concentrated in the Northwest, Northeast and other regions, while the projected demands are mostly concentrated in the Southeast. The mismatch between supply and demand further enhances the cost of using electric fuels due to transport costs. At present, stationary hydrogen storage and road transport of hydrogen is still mainly 20 MPa, and the amount of hydrogen transported by a single vehicle is 260-460 kg, with high storage and transport costs and low efficiency. Currently, the domestic liquefaction scale of 10 tonnes/day has been achieved, but there is still a significant gap from the 100 tonnes/day hydrogen liquefaction plant in the United States. At present, the total length of domestic hydrogen pipeline is only a few hundred kilometres, and the pipeline construction mainly relies on Sinopec and other state-owned enterprises, lacking top-level design and regional planning. Considering the low efficiency of storage and long-distance transport of hydrogen, it still requires further efforts from all parties to expand hydrogen supply according to local conditions. Efforts are needed to promote the implementation of integrated projects such as hydrogen-electricity coupling and hydrogen chemical industry in Northwest China and realise the large-scale production and local consumption of green hydrogen.

Thirdly, the application still needs policy incentives. In recent years, local administrations have actively introduced policies to support the hydrogen energy industry, but at present, requirements regarding the management of hazardous chemicals still apply to hydrogen in many places, which creates certain difficulties for the construction of hydrogen production and refuelling stations, hydrogen transportation and application. In terms of administrative approval, the construction of hydrogen energy projects often requires cross-departmental collaboration, with different local authorities responsible in various regions. Provinces such as Hebei, Guangdong, Liaoning, Anhui, Guangdong, and Xinjiang have successively liberalized the access to electrolysers and integrated hydrogen production and refuelling stations outside chemical parks. Regions like Ordos in Inner Mongolia, Karamay in Xinjiang, and Shenzhen in Guangdong have given production subsidies or electricity tariffs reductions for wind-hydrogen production integration projects and electrolyser and refuelling integrated stations. Coordination with regards to the responsibilities and rights of different departments at the national level and the simplification of the approval process still needs to improve, both via policy and technical standards. In addition, wind energy and hydrogen storage integration projects often need to be matched with a certain amount of grid power, the price of electricity is the most important factor affecting the marginal cost of electric fuels, so the introduction of special support policies to give the above projects certain tariff concessions has also become an important issue to promote the development of the electric fuel industry.

9.3 Global practical experience and prospects for the production of e-fuels

Overview of global development of e-fuels

Setting more aggressive development goals

Under the dual requirements of actively responding to climate change and the energy crisis, major countries and regions have raised their targets for the development of electricity-based fuels, and the targets before and after the adjustments are shown in Table 9-1. For the EU, in order to fill the gas supply gap and promote renewable energy consumption, the European Commission proposed in REPowerEU to achieve 10 million tonnes of renewable hydrogen local production and 10 million tonnes of renewable hydrogen imports by 2030, which is equivalent to 20 million tonnes of renewable hydrogen energy demand in the EU in 2030, doubling the target set out in the 2020 European Hydrogen Energy Strategy.

For Japan, in June 2023, the Ministry of Economy, Trade and Industry (METI) released the *Basic Strategy for Hydrogen Energy (Revised Edition)*, which significantly increased the medium- and long-term hydrogen energy development targets, adjusting them from 5-10 million tonnes to 12 million tonnes (including ammonia) by 2040 and 20 million tonnes (including ammonia) by 2050.

For Germany, the new version of the *National Hydrogen Strategy (2023)* raises the 2030 target for domestic hydrogen production capacity from electrolysers to at least 10 GW from 5 GW in the 2020 version, and hydrogen demand from 90 to 110 TWh to 95 to 130 TWh.

For the United States, the *U.S. National Clean Hydrogen Strategy and Roadmap* released in June 2023 sets out near-, mid-, and long-term hydrogen development targets, with clean hydrogen demand reaching 10 million tonnes, 20 million tonnes, and 50 million tonnes in 2030, 2040, and 2050, respectively. The Hydrogen Energy Plan released in 2020 had previously set out a target for future U.S. domestic hydrogen demand of 41 million tonnes by 2050.

Table 9-1 Adjustment of hydrogen energy development targets in major countries and regions

	Previous	Adjusted
Japan	3 million tonnes by 2030 and 10 million tonnes by 2050	3 million tonnes, 12 million tonnes and 20 million tonnes in 2030, 2040 and 2050 respectively (all including ammonia)
United States of America	Estimated local hydrogen demand of 41 million tonnes in 2050	Clean hydrogen demand reaches 10 million tonnes, 20 million tonnes and 50 million tonnes in 2030, 2040 and 2050 respectively

EU	By 2030, install at least 40 GW of renewable energy electrolysers to reach 10 million tonnes per year of hydrogen production from renewable energy sources	EU renewable hydrogen production of 10 million tonnes by 2030 and renewable hydrogen imports of 10 million tonnes. 42% of industrial hydrogen should come from renewable fuels from non-biological sources (RFNBOs) by 2030, rising to 60% by 2035; and 1.2% green hydrogen synthetic fuel for aviation fuel by 2030.
Germany	Domestic hydrogen production capacity from electrolysed water targeted at 5 GW in 2030; hydrogen demand at 90-110 TWh	Domestic hydrogen production capacity from electrolytic water target raised to at least 10 GW in 2030; hydrogen demand is 95-130 TWh
United Kingdom of Great Britain and Northern Ireland	5 GW of low-carbon hydrogen capacity by 2030	Plans to increase low-carbon hydrogen production capacity to 10 GW by 2030, half of which will be fully greened
South Korea (Republic of Korea)	By 2040, the annual supply of hydrogen will reach 5.26 million tonnes	Annual renewable hydrogen production of 1 million tonnes and 5 million tonnes by 2030 and 2050, respectively, and increase hydrogen self-sufficiency to 50%

Focusing on enhancing the low-carbon attributes of fuels produced from electricity

Major countries and regions are focusing on strengthening the low-carbon attributes of electric fuels and accelerating the formulation and release of carbon emission standards for different types of these fuels. Japan's Hydrogen Energy Basic Strategy released in 2017 was widely criticised for failing to take into account the low-carbon attributes of hydrogen energy, and the 2023 version of the Hydrogen Energy Basic Strategy not only stipulates that the carbon emissions of clean hydrogen should be less than 3.4 kg CO_2/kg H_2, but also stipulates that the carbon emissions of clean ammonia should be less than 0.84 kg CO_2/kg NH_3.

The U.S. *National Clean Hydrogen Strategy and Roadmap (2023)* specifies that clean hydrogen carbon emissions should be less than 4.0kg CO_2 /kg H_2. In August 2022, the U.S. *Inflation Reduction Act (IRA)* proposed to provide a tax credit for green hydrogen, which would be available to hydrogen plants that emit less than 4 kg of carbon dioxide per kg of hydrogen output. Depending on carbon emissions (0.45 to 4 kg CO_2 e/kg H_2), the tax credits range from $0.12 to $0.6 /kg H_2, and for hydrogen production projects starting construction before 2033, the tax credits will be five times as high for the first 10 years of operation, i.e., from $0.6 to $3 /kg H_2.

The European Union, while setting aggressive targets for renewable hydrogen, has set clean hydrogen thresholds in the EU's Renewable Energy Directive II. The EU Renewable Energy Directive II also sets a clean hydrogen threshold of 3.38 kg CO_2/kg H_2 and requires renewable hydrogen to be produced from electricity generated by new renewable energy power plants.

The criteria for recognising clean and renewable hydrogen in different countries and regions are shown in Table 9-2. In general, countries and regions that have issued low-carbon hydrogen standards are "on the same path", all of them are below 4.0 kg CO2 e/kg H2. With the current technology, only hydrogen produced from renewable energy sources by electrolysis and fossil energy sources equipped with CCS can meet the requirements of the low-carbon hydrogen standard.

Table 9-2 Carbon Emission Requirements for Clean Hydrogen in Major Countries and Regions

	Publishing organisation	Document Title	Clean Hydrogen Standard $kgCO_2e/kg\ H_2$
United States of America	US Department of Energy (DOE)	National Clean Hydrogen Strategy and Roadmap	4.0
Japan	Ministry of Economy, Trade and Industry (MOEC) of Japan	Basic Strategy for Hydrogen Energy (revised)	3.4
EU	Commission of European Union	EU Renewable Energy Directive II	3.38

Expanding more diversified application scenarios

In order to promote the deep decarbonisation of "difficult-to-reduce areas", major countries and regions are re-designing the development path of hydrogen energy around the goal of achieving carbon neutrality and expanding more diversified hydrogen energy application scenarios. The 2017 version of Japan's hydrogen development strategy particularly highlights the application of hydrogen in the field of transport and power generation and proposes to promote 800,000 fuel cell passenger cars and 5.3 million cogeneration systems by 2030. This essentially represents the integration and extension of Japan's expertise in the hydrogen fuel cell equipment manufacturing industry and the automobile industry and does not put hydrogen energy under the goal of carbon neutrality and overall planning. The 2023 version of the Hydrogen Energy Development Strategy combines the development path with the goal of achieving carbon neutrality, expanding the application of hydrogen energy to "hard-to-emit fields" such as steel, chemicals, and aviation, and actively promoting the application of hydrogen-ammonia fuels in the field of coal power generation.

Similar to Japan, South Korea's *Hydrogen Economy Roadmap (2019)* proposes the promotion of 6.2 million fuel cell vehicles, 15 GW of industrial fuel cell power generation, and 2.1GW of household fuel cells by 2040; it has already been expanded to include steel and chemicals, which are key carbon-emitting sectors.

Although the 2020 version of Germany's hydrogen energy strategy has initially constructed multiple application scenarios, including industry and transport, the focus in the transport sector is on heavy goods vehicles. The new version of the hydrogen energy strategy extends the application of hydrogen energy in the transport sector to aviation and maritime transport, using hydrogen and hydrogen-rich fuels (ammonia, methanol, etc.) as sustainable fuels to promote deep decarbonisation in aviation and maritime transport.

The U.S. National Clean Hydrogen Strategy and Roadmap anticipates diversified clean hydrogen demand in the future, such as industry (6 to 1,100 million tonnes), transportation (5 to 8 million tonnes), power (4 to 8 million tonnes), and bio/synthetic fuels (2 to 6 million tonnes). In contrast, the previously released Hydrogen Energy Plan focuses on transport, followed by bio/synthetic fuels, and petroleum refining.

Table 9-3 Focus Areas of Support for Hydrogen Energy Development in Major Countries and Regions

	Previous	Adjusted
Japan	Transport, power generation applications	Expanding to steel, chemical and aviation, and promoting the application of hydrogen-ammonia fuels in the coal power sector
South Korea (Republic of Korea)	Transport, power generation applications	Expansion into steel, chemicals
Germany	Focus on heavy goods vehicles	Expansion to air and sea freight
United States of America	Transport, bio/synthetic fuels, petroleum refining	Expansion into industry, transport, power, synthetic fuels and many other areas

Building more resilient supply chains

With the current composition of risks in the global energy supply chain, major countries and regions are paying extra attention to the security of hydrogen supply and building a more resilient hydrogen supply chain. For example, the European Union has adopted an internal and external approach. On the one hand focusing on enhancing the local renewable hydrogen production capacity and plans to deploy 40 GW of electrolysers, and introducing initiatives such as the "Green Deal Industrial Plan" and the "Net Zero Industry Act" and is using trade support means to enhance the production capacity of electrolysis capacity in the European Union. On the other hand, the EU is focusing on enhancing the capacity of hydrogen imports, plans to deploy 40GW electrolysers in North Africa, Ukraine, and other regions. The European Commission has issued a proposal for a law on hydrogen blending of natural gas and a European Hydrogen Bank scheme, which allows the blending of up to 20% of low-carbon hydrogen in the natural gas network and guides and encourages the blending of hydrogen in natural gas pipelines and the cross-border transport of pure hydrogen by pipeline.

For further example, Japan has adopted a "gas not in one place" approach to actively develop international hydrogen trade, importing hydrogen or ammonia from Australia, Saudi Arabia, Brunei and other countries through liquid hydrogen, liquid ammonia, organic hydrogen storage and other means, in order to decentralise hydrogen import channels to enhance the security of hydrogen energy supply. In addition, the Republic of Korea has also clearly set the goal of increasing the self-sufficiency rate of hydrogen energy to 50% by 2050.

Experience and insights from major countries' production of e-fuels

Major developed countries around the world attach great importance to the development of the electric fuel industry, with key core technologies maturing, infrastructure construction speeding up , scale increasing , regional supply networks taking shape, and fuel cell shipments growing rapidly and costs continuing to fall. Driven by energy security and climate change, countries around the world are accelerating the development of the electric fuel industry, and 26 countries, including the United States, Germany, France and Japan, have introduced hydrogen energy plans, with the above countries accounting for more than 60% of the world's total economic output, and have clearly defined the positioning of hydrogen energy development based on their respective national conditions.

Although the role of electricity-based fuels in achieving carbon neutrality and enhancing the ability of the energy system to provide security of supply is significant, countries have different reasons for choosing electricity-based fuels to promote their own energy transformation. The European Union has taken the development of electric fuels as an important tool for economic recovery, security of energy supply and deep decarbonisation, and has vigorously promoted the application of electric fuels in the industrial and building sectors, while paying great attention to the investment in research and development of basic and common technologies. The United States, as the earliest country to propose the development of hydrogen energy, will initially take the development of hydrogen energy as an important guarantee of energy security, and later take the development of advanced hydrogen energy technology as a strategic investment in order to maintain its competitiveness in the international market and leading position in technology. Japan will build a "hydrogen society" as the ultimate development goal, to ensure energy security as the driving force, vigorously develop the hydrogen energy industry, and promote the application of hydrogen energy in various fields. South Korea is committed to developing its hydrogen industry into the fourth pillar industry, after the display, semiconductor and automobile pillars, and driving economic growth through the export of fuel cell technology. Overall, countries are paying more and more attention to the development of electric fuels, have formulated relevant development plans and introduced a series of related industrial policies, highlighting the growing importance of electric fuels.

Different policy thrusts

The EU seeks long-term decarbonisation and energy self-reliance, with plans such as the EU Hydrogen Strategy, REpower EU and others clearly setting out a target of deploying 10 million tonnes/year of renewable hydrogen capacity in the EU itself by 2030, while importing 10 million tonnes/year of hydrogen from reliable supplier countries. By 2050, the EU will promote the large-scale use of green hydrogen in areas where it is difficult to achieve zero carbon emissions through electrification. The European Commission released the transitional implementation rules of the EU Carbon Border Adjustment Mechanism (CBAM) in May 2023, and CBAM proposes that the EU will levy a carbon border tax on some imports from 2026 onwards, with the first batch of industries to be included in the scope of the levy including iron and steel, cement, electricity, fertilisers, aluminium and hydrogen. Among them, green hydrogen will be exempted from the carbon tariff. Under the background of the carbon tariff, the hydrogen imported into Europe in the future will basically be green hydrogen, and the green hydrogen equipment segment will be the first to benefit.

The goal of the United States in developing electric fuels is to occupy the high ground of strategic emerging technologies and to ensure the comprehensive strength of the United States nation Therefore the cost and performance of hydrogen in the process of production, storage, transport, and commercial applications are taken as the main objectives in policy formulation, with the expectation that technological research and development will catalyse leapfrogging and breakthrough technologies to realise the economics of hydrogen energy and to enhance international competitiveness.

Japan was one of the first countries to develop electric fuels. Constrained by the limitations of land resources and geographic environment factors, Japan has been actively developing the hydrogen energy industry and creating a hydrogen energy society as a core strategy to achieve energy independence and promote economic development from a very early stage. Japan has issued several hydrogen energy policy documents, planned strategic and technical routes for the realisation of a hydrogen energy society, vigorously promoted the application of hydrogen energy in the fields of transport, housing, heavy industry and petroleum refining, and focused on promoting the construction of a global supply chain that can produce and transport hydrogen in large quantities.

South Korea's hydrogen-fuelled vehicles and fuel technology are world-class, but the hydrogen industry is still in its early stages of development. In 2018, the Korean government identified the "hydrogen economy" as one of the three strategic investment areas for innovation and growth, aiming to boost economic innovation and growth and create more jobs through the development of hydrogen energy. South Korea's latest hydrogen policy proposes to expand, establish, and enhance the hydrogen industry, with the goal of establishing a clean hydrogen supply chain and fostering a world-leading hydrogen industry, with the aim of becoming a global hydrogen power plant.

Different policy objectives and pathways

The EU follows a progressive development strategy focused on enhancing infrastructure, expanding production capacity, building networks, and large-scale applications. The "EU Hydrogen Strategy" specifies the EU's strategic plan for 2020 to 2050. Between 2020 and

2024, the EU planned to construct several green hydrogen electrolysis plants, each with a capacity of up to 100MW. The goal was for Europe's total green hydrogen production capacity to reach 6GW and yield over 1 million tonnes of green hydrogen annually. By 2030, all blue hydrogen plants will be fully equipped with carbon capture and storage facilities and it is expected that the annual green hydrogen production in the EU will exceed 10 million tonnes, with a total green hydrogen production capacity of 40 GW. From 2025 to 2030, several regional industrial centres for hydrogen production will be established, based on the ongoing increase in green hydrogen production capacity. The focus from 2031 to 2050 will be on large-scale application of hydrogen in energy-intensive industries.

The U.S. has expanded markets and capacity by focusing on cost reduction, performance improvement, and demand creation. This approach has also promoted the development and scale-up of clean, affordable, and reliable e-fuel technologies. The 2020 "Striving for the Planet" Hydrogen Initiative aims to reduce the cost of green hydrogen by 80% targeting $1 /kg within a decade, and to increase hydrogen demand fivefold. The June 2022 U.S. Presidential Resolution authorises the U.S. Department of Energy to use the *Defence Production Act (DPA)* to boost domestic production of five key energy technologies, including electrolysers, fuel cells, and platinum group metals, to accelerate the development of a clean energy economy.

Japan has been continuously adjusting and optimising its hydrogen development goals and strategies in line with the Energy Basic Plan. The country is actively working to change its energy use structure through initiatives such as the hydrogen fuel cell end-use revolution and the import of hydrogen resources from overseas. Initially leveraging the Energy Basic Plan to advance fuel cell technology research, development and project demonstration, Japan released the world's first National Hydrogen Energy Strategy, proposing goals and directions for 2050 based on the 2030 target, encouraging industry, academia, and government to build a hydrogen energy society. The Sixth Energy Basic Plan focuses on two core objectives: combating climate change and transforming Japan's energy supply and demand structure. It aims to reduce the cost of hydrogen to the same level as fossil fuels by 2030 and accelerate its commercial application.

South Korea is expanding the hydrogen market by popularising hydrogen-fuelled vehicles to create large-scale demand for hydrogen. In December 2021, the South Korean government released its first Basic Plan for Hydrogen Economy Development, proposing that hydrogen in South Korea will account for 33 % of final energy consumption and 23.8 % of electricity generation by 2050, making it the largest source of energy, surpassing petroleum. In November 2022, the government unveiled its Hydrogen Economy Development Strategy. It plans to popularise 30,000 hydrogen-powered commercial vehicles by 2030. Meanwhile, through technological innovation, it aims to master the core technology of each link in the hydrogen industry chain.

Support varies by sector

The EU has preliminarily promoted the development of renewable hydrogen through measures such as increased investment, higher carbon taxes, cooperation of member states, incentives for private investment, and increased public funding. Additionally, relevant companies receive preferential allocation of carbon permits, and hydrogen has administratively mandated quotas in energy consumption, among other measures, to support its development. In March 2023, the European Commission released its European Hydrogen Bank plan, which was launched in autumn of the same year with the first batch of renewable Hydrogen pilot auctions. With a dedicated budget of EUR 800 million (approximately RMB 5.8 billion), selected pilot projects will receive subsidies for up to ten years in the form of a fixed premium per kilogram of hydrogen produced .

The United States enacted the Infrastructure Investment and Jobs Act, explicitly earmarking $9.5 billion for hydrogen. These funds are designated for the construction of clean hydrogen centres, electrolysis hydrogen research and development, and clean hydrogen production and utilisation. In 2022, the U.S. *Inflation Reduction Act* proposed providing up to $3/kg in tax credits for green hydrogen, along with hydrogen production and investment tax subsidies. These measures aim to facilitate the transition from grey to green hydrogen, with the size of the subsidy based on the amount of carbon dioxide emitted during hydrogen production.

Japan has launched a 2 trillion yen green innovation fund to build a large-scale green hydrogen supply chain. This includes projects large-scale hydrogen supply chain construction and demonstration projects for hydrogen production by electrolysis using renewable energy and other power sources. The fund provides financial support for the construction of a large-scale hydrogen supply chain, hydrogen production from renewable energy sources and hydrogen application scenarios, such as the development of next-generation aircrafts, ship development, smart mobility, fuel manufacturing, and plastics manufacturing.

South Korea also provides generous purchase subsidies for consumers who buy fuel cell vehicles. The government has proposed expanding purchase subsidies for hydrogen buses and trucks, extending purchase tax and toll exemptions, and other measures to create demand for hydrogen. In.2021, South Korea's private sector planned to invest 43 trillion won in the hydrogen economy over the next 20 years, focusing on the development of industries in the hydrogen economy sector, including hydrogen energy production, storage, transport, and application.

Standard-setting in the context of national technological strengths

The EU’s hydrogen standardisation efforts primarily focus on hydrogen production, hydrogen storage and transportation, infrastructure construction, safety, and test specifications. Standardisation is organised and promoted by the European Committee for Standardisation (ECS) and other institutions. They coordinate the standardisation work of the Member States, develop European standards and carry out regional certification, and facilitate trade and technical exchanges within the EU. Each country’s standardisation work will be carried out by the national standardisation organisations, based on the International Organisation for Standardisation (ISO), the International Electrotechnical Commission (IEC), as well as other relevant technical standards. The national standardization organisations will formulate their own hydrogen energy standards according to the technical specifications of the country.

The U.S. has prioritised standardization in the early stages of planning for hydrogen development. The government has formulated supporting standards for hydrogen safety, production, storage and transportation, refuelling stations, and energy applications, making it the most active and productive country in the development of hydrogen energy technology standards. In particular, the U.S. has continued to study and improve the standard system for fuel cell vehicles. It has established special working groups focused on ‘terminology, safety, interface, performance, emissions and energy consumption, and recyclability’ to promote related work.

Japan's hydrogen standardisation framework is organised and implemented by the Japan Industrial Standards Survey. The country’s standards in fuel cell vehicles, smart grids, hydrogen storage technology, and hydrogen safety are at the forefront of the international community. Particularly in the field of fuel cells, Japan has developed a comprehensive system of standards and regulations to support its fuel cell research and development, passenger car development, hydrogen storage and transportation, and miniaturisation of hydrogen applications. This unique core technology has become a key competitive advantage for Japan in promoting the development of the hydrogen industry.

In Korea, standardisation work is carried out by the Korean Agency for Technology and Standards (KATS) and the Korean Standards Association (KSA), which are responsible for the unified management of standards policy, product safety, conformity assessment and technical regulations. At the same time, a "New and Renewable Energy Centre" has been set up in the new energy sector, responsible for the standardisation of new energy technologies as well as the evaluation and management of new energy projects. Currently, Korea has established 34 hydrogen energy standards, mainly focusing on fuel cells. In April 2023, Korea released its hydrogen fuel cell standards for ships, aiming to advance the development of hydrogen-fuelled new shipbuilding.

Table 9-4 Status and positioning of hydrogen development in major regions of the world

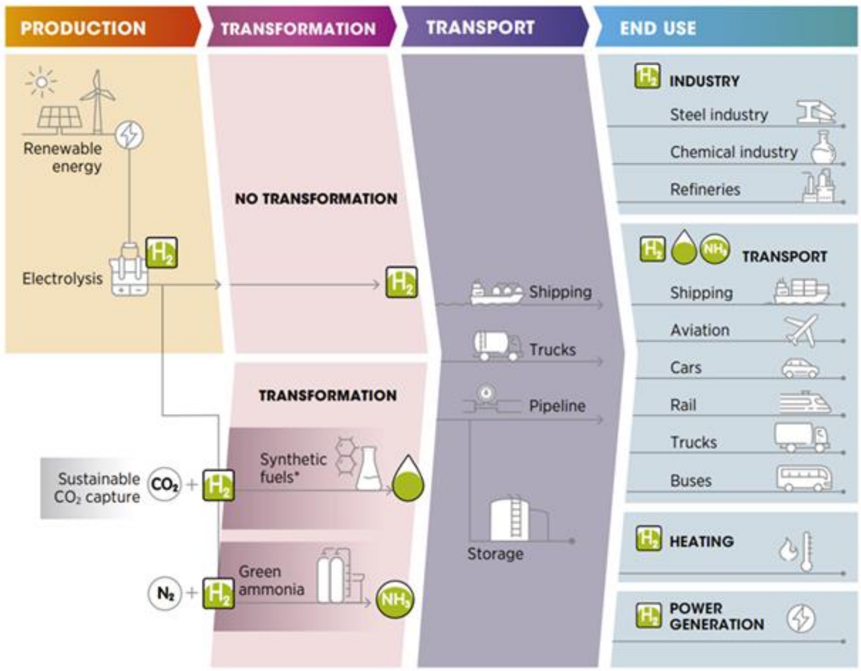
Region (not necessarily formal administrative unit)	Nations	Status quo	Focus
EU	Germany, France	▪ On the hydrogen production side, low-carbon hydrogen fuel is produced by electrolysis of water using renewable energy, and the green hydrogen supply system scaled up. ▪ In terms of hydrogen utilisation, green hydrogen is used in a variety of fields, including natural gas and hydrogen blending, distributed fuel cell power or heat generation, hydrogen steelmaking, chemical production and hydrogen fuel cell vehicles.	Renewable hydrogen production for deep carbon reduction
Japan and South Korea	Japan, Korea	▪ Dependence on imported hydrogen from overseas ▪ Focus on hydrogen fuel cell applications in automotive and domestic sectors ▪ Leading technologies in materials and equipment, concentration on leading enterprises	Gaining a competitive edge in the development of key technologies and emerging industries
Australia, Canada and China	Australia, Canada, Middle East	▪ Leveraging its resource advantages, the countries aiming at a diversified low-carbon hydrogen supply system to expand the export demand of hydrogen in emerging markets.	New Growth Opportunities for Exporting Resources and Foreign Trade
United States of America	United States of America	▪ Focusing on the important role of hydrogen in achieving local carbon neutrality targets ▪ Emphasis on R&D and large-scale demonstration across the entire chain of "production-storage-transmission-distribution-usage", and the systematic development of core technologies, the industrial technology chain, industrial chain layout and supply chain construction in hydrogen energy.	As a medium- and long-term strategic technology reserve

Global outlook for e-fuels

The IRENA asserts that enhancing energy efficiency levels, increasing electrification and renewable energy can achieve 70% of the carbon reduction target. However, hydrogen is essential to achieve deep emissions reductions in hard-to-abate sectors such as heavy industry, long-distance transport, and seasonal storage (as shown in Figure 9-1).

According to IRENA's 1.5°C scenario, hydrogen consumption would account for 12% of global end-use energy consumption in 2050 and contribute 10% to global carbon reductions.

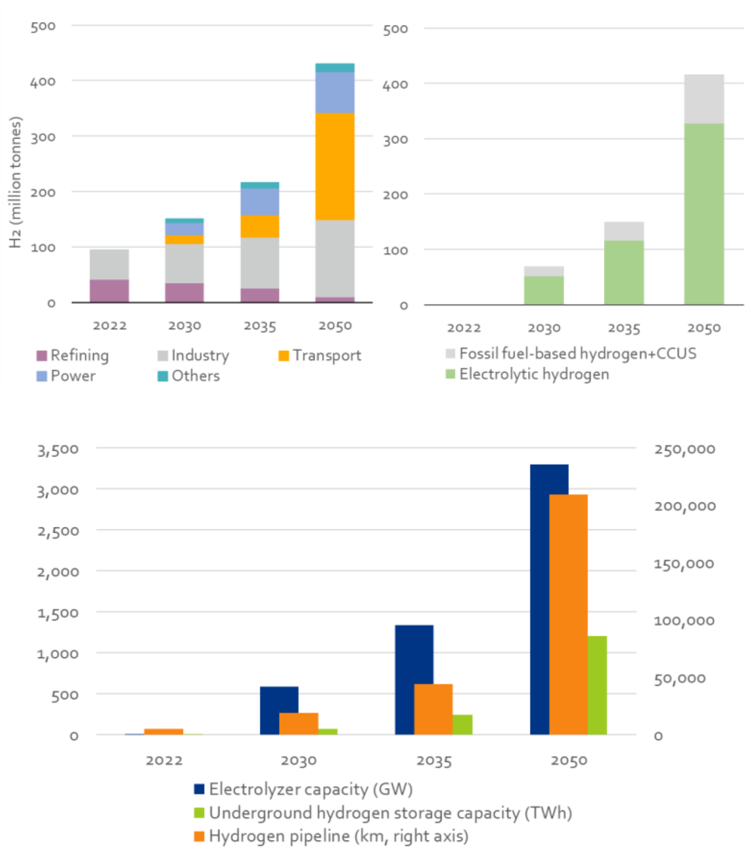
Figure 9-1 Hydrogen production and consumption patterns



Source: International Renewable Energy Agency

According to the IEA, total global hydrogen consumption in 2022 was approximately 95 million tonnes. Of this, 42 million tonnes were used in petrochemical refining, while 53 million tonnes were consumed in the industrial sector. According to the Net Zero Emissions Scenario (NZE), total global hydrogen consumption is projected to reach 150 million tonnes by 2030. Of this, the petrochemical refining consumption will have declined to 35 million tonnes. However, industrial hydrogen demand is expected to increase to 71 million tonnes. Hydrogen demand in the transport and power generation sectors will grow rapidly to 16 million tonnes and 22 million tonnes respectively. Global hydrogen consumption will reach 430 million tonnes by 2050, with hydrogen demand for industry, transport and power generation of 139 million tonnes, 193 million tonnes and 74 million tonnes ,respectively. Low-carbon hydrogen (hydrogen from renewable energy or from fossil energy + CCUS) will account for 98% of all hydrogen production. Additionally, there will be a significant increase in the scale of electrolysis equipment, hydrogen pipelines and underground hydrogen storage infrastructure (as shown in Figure 9-2).

Figure 9-2 Global hydrogen consumption and production (up) and infrastructure outlook (bottom) for net-zero emissions scenario



Source: International Energy Agency

According to projections by the International Hydrogen Energy Council, in a net-zero emissions scenario, global hydrogen demand is expected to reach 660 million tonnes by 2050. This would account for 22% of global final energy demand and avoid 7 billion tonnes of CO_2 emissions annually. Cumulatively, low carbon hydrogen could reduce global CO_2 emissions by 80 billion tonnes by 2050, roughly twice the current annual anthropogenic emissions and would account for 11% of global carbon emissions reductions under the net-zero emissions scenario. By 2050, blue hydrogen is projected to account for 20-40% of supply (140-280 million tonnes), while renewable hydrogen will account for 60-80% of the supply (400-500 million tonnes of hydrogen). Additionally, installed hydrogen from electrolysis is expected to reach 3-4 TW, corresponding to 4.5-6.5 TW of renewable energy generation capacity.

9.4 The role of electricity for e-fuels in the deep decarbonisation of China's energy system

E-fuels are an important component of carbon-neutral energy systems

Achieving the goal of carbon neutrality requires completely overturning the fossil-energy-dominated energy system established since the Industrial Revolution. In its place, a new global energy structure dominated by non-fossil energy must be constructed. Electricity-based fuels are a crucial element of the future national energy system. By leveraging the roles of green hydrogen, green ammonia, green methanol and other electricity-based fuels as key carriers for the efficient use of renewable energy, and their advantages in large-scale, long-term energy storage, we can optimize the allocation of diverse energy sources across different regions and seasons. This approach will also promote the systematic integration of hydrogen, electric, and thermal energy, facilitating the creation of a modern, multi-faceted, complementary and integrated energy supply system. Additionally, electric fuels are crucial for the green and low-carbon transformation of energy end-use sectors.

Strengthening the green supply of electric fuel can foster diverse hydrogen consumption ecosystems and enhance China's energy security. For the construction of a new energy system, it is essential to maximise the supporting role of electric fuels in carbon neutrality. This involves exploring the potential for sector coupling applications of electricity, hydrogen and heat, and guiding diversified applications in accordance based on local conditions. Such efforts will promote the transformation of energy consumption in transport, industry and other energy-intensive sectors, support the green development of high energy-consuming and high emission industries, and reduce greenhouse gas emissions.

E-fuels are a crucial solution for addressing challenges in electrification

From a clean and low-carbon perspective, large-scale electrification is a powerful tool for achieving carbon emission reductions in China, across varies sectors. For example, replacing oil-fuelled vehicles with EVs in the transport sector and replacing traditional boilers with electric heating in the building sector. However, there are still sectors where direct electrification is challenging for achieving carbon reduction. These include steel, chemicals, road transport, shipping and aviation.

With the dual attributes of energy fuel and industrial raw material, electric fuels can play an important role in the above areas that are difficult to deeply decarbonise. In the transport sector, long-distance road transport, railway, aviation and shipping consider electric fuels as a key solution to reduce carbon emissions. Currently, there are more than 20,000 hydrogen fuel cell vehicles, primarily consisting of passenger cars and medium- to heavy-duty lorries. In the industrial sector, hydrogen can replace coke and natural gas as a driver for emissions reductions, significantly reducing carbon emissions from iron and steelmaking. Using renewable electricity for electrolysis to produce hydrogen and then synthesise chemical products such as ammonia and methanol, significantly reduces carbon emissions in the chemical sector. In the building sector, combined efficiency through cogeneration can reach up to 85%. Hydrogen fuel cells generate electricity for the building, while the waste heat can be recovered for heating and hot water. For transporting hydrogen to building terminals, hydrogen can be blended into natural gas at a rate of less than 20% and delivered to thousands of homes through a well-developed domestic natural gas pipeline network. In the power sector, electric fuels can serve as a new form of energy storage. During periods of low electricity demand, electric fuels are produced with a surplus renewable electricity by electrolysis. During peak demand periods, the fuel is then used to generate electricity through fuel cells or turbines. Electricity-to-fuel energy storage can be utilized as a large-scale seasonal storage, depending on the varying output of solar, wind and water resources.

The development of e-fuels depends on technological advancements and cost reductions

Currently, the cost of producing hydrogen from electricity remains high. In West China, where renewable energy resources are relatively abundant, the cost of green electricity is widely lower than 0.3 RMB/kWh. This results in electricity costs for a green hydrogen project of approximately 20 RMB/kgH2. When factoring in the depreciation of the electrolysis and other equipment, as well as operation and maintenance costs, the total production costs of green hydrogen amounts to approximately 25 RMB/kgH2. This is 2-3 times higher than for hydrogen production from fossil energy.

The geographical mismatch between supply and demand increases the difficulty of hydrogen storage and transport. The existing method of transporting compressed hydrogen bundled together on tube trailers for short-distance transport cannot meet the needs for large-scale, long-distance transport. The future of long-distance hydrogen storage and transport includes various technologies and modes such as compressed gaseous, cryogenic liquid, solid alloys, organic liquids, synthetic fuels. Additionally, different transport methods like roads, railways, waterways, pipelines and power grids will be utilised. However, as renewable electricity costs decrease and storage and transport technologies advance, the economics of green power and electricity-based fuels will improve. These advancements are expected to lead to widespread acceptance and use. In an energy hub, electricity-based fuels can more easily be integrated with heat, cold, fuel and other energy sources to establish an interconnected modern energy network. The integration forms a highly resilient energy supply system, enhancing the overall operational efficiency, economy and security of the new energy system.

10 Industry sector transition

10.1 Main findings

- In recent years, the achievements of the low-carbon transformation of China's industrial sector have attracted worldwide attention, as evidenced by the continued adjustment of the industrial structure, the accelerated application of new technologies and processes, the significant improvement in the level of energy conservation and environmental protection, and the accelerated substitution of clean and low-carbon energy sources.
- The results of the modelling show that through the continuous promotion of energy-saving and low-carbon process technologies, the large-scale application of clean energy such as electricity and hydrogen, and the continuous adjustment of the industrial structure. China is fully capable of supporting the steady and rapid development of the industrial economy with less energy resource input and lower carbon emissions.
- To turn the vision of low-carbon transformation into reality, China's industrial sector needs to undertake four major strategic actions. The first goal is to establish a modern, high-valued industrial system that fulfils the requirements of Powerful Manufacture target while achieving a 40% to 60% reduction in the production of energy-intensive and high-emission products like crude steel and cement. The second objective is to create a recycling-integrated organizational structure, progressively increasing the share of recycled steel, aluminium, and plastics to over 50%. The third aim is to adopt digital, intelligent, and highly efficient production model, implement advanced energy efficiency projects in key industries, and maximize the potential of digital and systematic energy efficiency improvements. The fourth goal is to transform the energy consumption structure by promoting the replacement of traditional fossil fuels with electricity and hydrogen, targeting a share of around 70% for electricity and hydrogen by 2060.

10.2 The effectiveness of China's low-carbon industrial transformation

Industry is the main area of energy consumption and carbon emissions in China and has a significant impact on the construction of ecological civilization and the achievement of carbon neutrality. In recent years, China's industry has maintained stable and rapid development and has made outstanding achievements in promoting low-carbon transformation, setting up a "China model" of low-carbon industrial transformation for the world.

Positive progress in industry structural adjustment

China has started the supply-side structural reform, "phasing-out backward capacity" in coal, iron, and steel industry are ahead of schedule. According to data from the Ministry of Industry and Information Technology, during the *13th Five-Year-Plan* (FYP) period, the country achieved significant progress in reducing production capacity. Crude steel production capacity was cut by over 170 million tonnes, while 140 million tonnes of "local steel" production capacity were eliminated. Additionally, more than 1 billion tonnes of outdated coal production capacity were withdrawn, and over 20 GW of obsolete coal power generation units were shut down—all completed two years ahead of schedule. These achievements exceeded the production capacity reduction targets set for the 13th FYP. Since the start of the 14th FYP further reductions include over 40 million tonnes of steel production capacity, with outdated production capacity in the electrolytic aluminium and cement industries largely phased out. Focusing on strategic emerging industries, China has issued special development plans and supporting action projects to continuously promote the adjustment of the internal structure of the industry sector. Data from the National Bureau of Statistics (NBS) shows that by the end of 2022, the added value of strategic emerging industries such as new-generation information technology, high-valued equipment and new energy vehicles accounted for more than 13% of GDP. The adjustment of industrial structure has led to the upgrading of product structure. In 2023, the national output of new energy vehicles was 9,587,000, with one in every three cars being a new energy vehicle. Photovoltaic module production has been ranked first in the world for 16 consecutive years, and the global share of the output and production capacity of polycrystalline silicon, silicon wafers, battery wafers, and modules has reached more than 80%. In 2023, the combined export amount of the "new three products" exceeded RMB 1 trillion.

Accelerated application of new technologies and processes

R&D in green and low-carbon technologies has accelerated, and, in some key areas, China has become the “top runner”. Under the guidance of the national green development and energy-saving and carbon reduction policies, innovative resources of the whole society have been accelerated to converge in the field of green and low-carbon technologies, and several innovative technologies and processes have emerged. For instance, taking the direct cracking of crude oil to olefin as an example, this technology follows the general trend of "conversion from oil", which can skip the refining process of crude oil and directly convert crude oil into ethylene, propylene and other chemicals, thus greatly shortening the production process, lowering the cost of production, and significantly reducing energy consumption and carbon emissions. In 2023, China has successfully achieved the direct cracking of crude oil to olefin. In 2023, China successfully achieved the world's first industrialized application of direct cracking to olefins, becoming the global leader in this process technology route.

The integration of AI has accelerated the progress of low carbon development. Intelligent manufacturing paradigm can effectively save energy and raw material and improve the efficiency of energy and resource use. In the past 10 years, China has relied on a new generation of information technology and complete digital infrastructure to vigorously promote the fusion of industrialisation and informatisation with the "China's Smart Manufacturing" that has led the global digital transformation. Since 2018, the World Economic Forum has announced 11 batches of global smart manufacturing "lighthouse factory" listing a total of 153 enterprises, of which China accounts for 62, and of the 21 announced in 2023, China accounts for 11.

Synergistic promotion of energy conservation, pollution reduction and carbon reduction

Industry is the top priority of China's energy conservation efforts, with the National Development and Reform Commission, the Ministry of Industry and Information Technology and other departments issuing benchmarks for the energy efficiency of key products and equipment. Furthermore, China is implementing major energy-saving, carbon-reducing, upgrading and transformation projects and actions in key industries, such as iron and steel, petrochemicals and chemicals, non-ferrous metals and building materials. Compared with 2014, energy consumption per unit of added value of the national industry has dropped by more than 20%, resulting in energy savings of more than 900 million tonnes of standard coal, a reduction of SO_2 emissions by 2.5 million tonnes and NOx emissions by more than 2.7 million tonnes, and a cumulative reduction of carbon dioxide emissions by nearly 2 billion tonnes. At the same time, the energy efficiency level of major products has been significantly improved. Compared with 2014, China's 2022 comparable energy consumption of tonnes of steel has decreased by more than 25%, the comprehensive energy consumption of cement by more than 7%, the AC power consumption of electrolytic aluminium by nearly 5%, the comprehensive energy consumption of synthetic ammonia by more than 6%, and the comprehensive energy consumption of paper and cardboard by more than 10%. The energy savings formed by the above products alone exceed 220 Mtce, which is almost equivalent to the energy consumption of a moderately energy consumption of a medium-sized developed country.

Energy conservation and efficiency have promoted the upgrading of the manufacturing industry and the cultivation of new business models, releasing new kinetic energy for economic development. To date, the annual output of energy-efficient motors has reached 170 GW. Furthermore, we have vigorously eliminated small, inefficient coal-fired industrial boilers and promoted the development large-scale, automated and highly efficient boilers. The thermal efficiency of new coal-fired boilers has been reduced to no less than 80%, and the thermal efficiency of gas-fired boilers has been reduced to no less than 92%. The energy saving and efficiency market mechanism is improved and the development of contract energy management, integrated energy services and other new business models cultivated. Energy saving and efficiency related work has produced quality results, promoted industry upgrading, and expanded the industry, leading to spillover benefits. These efforts have not only contributed to stable growth and employment, but have also added a "new business card" to Made in China.

Accelerated substitution of clean and low-carbon energy sources

China has solidly promoted work related to the optimisation of the structure of coal-fired industrial boilers and the cleaner use of energy. The number of coal-fired industrial boilers has been reduced from a peak of more than 500,000 to 73,000 at present, and the fuel structure of boilers has been fundamentally improved; with regard to industrial kilns, regions have promoted the substitution of natural gas fuels in accordance with local conditions, and the proportion of natural gas-fuelled kilns in ceramics, glass and other industries has been significantly increased, generating multiple benefits in terms of energy conservation, environmental protection and improved product quality.

In terms of electrification, in recent years, conductive heating, microwave heating and other new electric heating technology progress rapidly, the world has entered the era of "electrification 2.0". Currently, China's industrial electrification rate has reached 26%, higher than many developed countries. In the development of hydrogen energy, as one of the key paths for deep decarbonisation of industry, China is actively carrying out hydrogen energy application demonstration, and the application of green hydrogen chemical industry and hydrogen metallurgy has taken a key step towards industrialisation, so as to prepare technology for the medium- and long-term development of achieving the goal of green decarbonisation. By the end of 2023, China has planned more than 45 green methanol projects, with a combined annual production capacity of more than 15 million tonnes; more than 60 green ammonia projects, with a combined annual production capacity of more than 14.5 million tonnes; and nearly 20 low-carbon and clean hydrometallurgy projects, with a combined annual production capacity of more than 12 million tonnes.

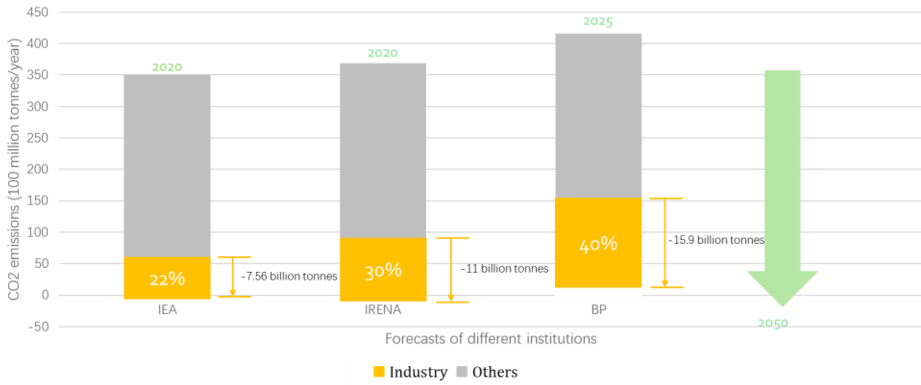
10.3 Prospects and typical cases of low-carbon transition in global industry

At present, actively responding to climate change has become a global consensus. Industry is an important area of carbon dioxide emission and is characterized by large carbon emissions, complex causes and high difficulty in carbon reduction, and its low-carbon transition has received increasing attention. The IEA, IRENA, BP and other organizations have respectively constructed a global vision for sustainable development and explored the goals and paths of low-carbon development in different fields, and the main conclusions on the low-carbon transformation of industry include the following three aspects.

Industry will make a significant contribution to the global achievement of sustainable development goals

Currently, about 30% of global carbon dioxide emissions come from the industry sector, so industrial decarbonization will have a significant impact on global carbon emissions reduction. The IEA believes that in order to achieve the global temperature rise target of "1.5°C", global carbon dioxide emissions from energy-related and industrial processes will need to fall from about 35 billion tonnes in 2020 to close to zero in 2050, of which the industrial sector will reduce by more than 7 billion tonnes, accounting for 22% of global carbon emissions. IRENA forecasts that global carbon emissions will need to fall from 36.9 billion tonnes in 2020 to -0.4 billion tonnes in 2050, and that industrial carbon emissions will fall from 9.16 billion tonnes in 2021 to -1.84 billion tonnes in 2050, contributing to 30% of global carbon emissions reduction. BP expects that the world will achieve net-zero emissions by 2050. net-zero emissions in 2050 would total 39.6 billion tonnes of CO2, with the industrial sector contributing 15.9 billion tonnes, or up to 40% (as shown in Figure 10-1).

Figure 10-1 Projected contribution of industry to global carbon emission reductions by different organisations

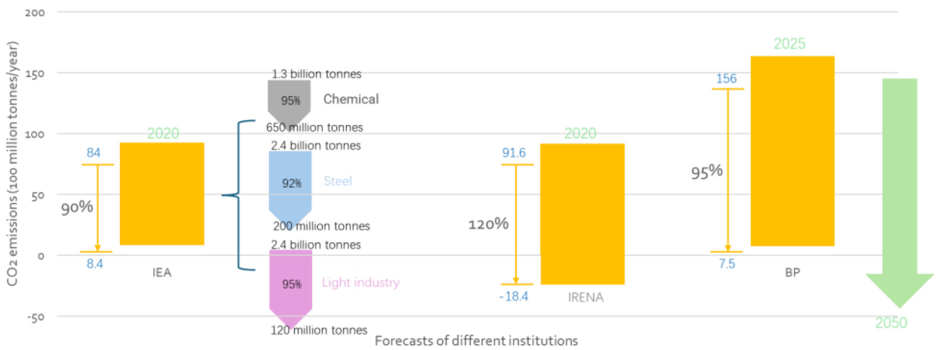


Low-carbon transformation of industries will contribute huge carbon emission reductions

Carbon emissions from industry and its key sectors will drop significantly. the IEA expects that CO2 emissions from the industry sector will drop from about 8.4 billion tonnes in 2020 to 840 million tonnes in 2050, a reduction of up to 90%; IRENA forecasts that the industry sector will reduce emissions by 11 billion tonnes, about 120%, and achieve negative carbon emissions. ; and BP forecasts that carbon emissions from the industrial sector will drop from 15.6 billion tonnes in 2025 to 7.5 billion tonnes in 2050, a reduction of about 95%. Furthermore, they expect that carbon emissions from the industrial sector will drop from 15.6 billion tonnes in 2025 to 750 million tonnes in 2050, with a reduction of about 95%.

The IEA analysis indicates that carbon emissions from key industries will significantly decrease by 2050. Specifically, emissions from the chemical industry are expected to drop from 1.3 billion tonnes in 2020 to around 0.65 billion tonnes, representing a 95% reduction. For the iron and steel industry, emissions will fall from 2.4 billion tonnes in 2020 to 200 million tonnes in 2050, a 92% reduction. Additionally, emissions from the light industry, which were about 2.4 billion tonnes in 2020, are projected to decrease to 120 million tonnes by 2050, achieving a 95% reduction rate (as shown in Figure 10-2).

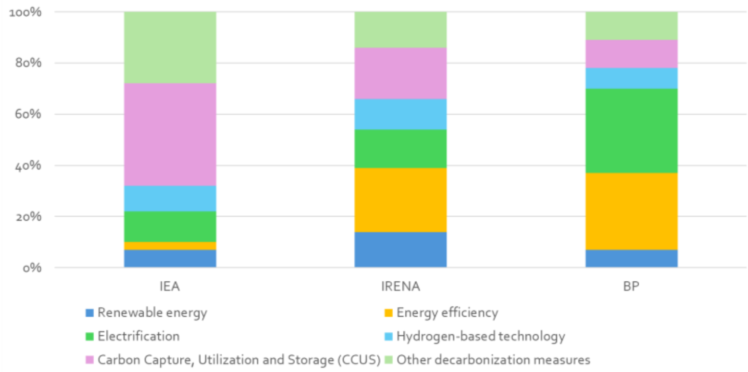
Figure 10-2 Different organisations' forecasts of the effects of emission reductions in industry and major sectors



Industrial decarbonisation requires comprehensive innovation in process technology and energy use.

The industry sector is difficult to decarbonize by only electrification due to the large amount of feedstock and high temperature heat demand, it needs to promote a comprehensive innovation in process technology and energy use based on a significant increase in energy efficiency. IEA believes that recycling and reuse of plastics, more efficient use of nitrogen fertilisers, and energy efficiency measures should be taken in the near term. By 2050, nearly 60% of emissions reductions will be achieved using technologies currently under development (large-scale prototypes or demonstration scale), with hydrogen and CCUS technologies together contributing around 50% of the emissions reductions from heavy industry. IRENA promotes hydrogen combined with electrification, that could meet 27% of the emissions reductions from industry, with energy savings and efficiency improvements contributing 25% of the reductions. Hydrogen and its derivatives will account for 12% of end-use energy by 2050 and will play a key role in energy-intensive sectors such as steel and chemicals. BP believes that energy-intensive sectors need to improve energy efficiency and apply competitive technologies on the market to reduce carbon emissions by 2030. Subsequently introduce innovative solution such as CCUS and hydrogen-based technologies. For light-industry sectors, continued electrification will be the most important way to reduce carbon emissions (as shown in Figure 10-3).

Figure 10-3 Projected industrial carbon reduction pathways and contributions by different organisations



10.4 Outlook for low-carbon transformation of Chinese industry

In the future, China will continue to adjust its industrial structure, upgrade its production technology, and change its energy consumption patterns. China's industrial economic development is expected to be gradually decoupled from its carbon emissions by significantly improving energy efficiency, electrifying a high proportion of its production processes, and innovating in the use of hydrogen energy, and achieve the strategic shift from "big to strong". This will further be consolidating China´s position as a hub in the global division of industrial labour.

Scenarios for a low-carbon transition in Chinese industry

The research group adopts a scenario analysis method and sets up two scenarios, BCNS and ICNS, to forecast the energy demand of the industrial sector. In BCNS, China will firmly fulfil its NDC of carbon peak attainment and carbon neutrality, based on the demand of the domestic market, and steadily push forward the low-carbon transformation of the industrial sector by relying on its own low-carbon technologies. In ICNS, carbon neutrality becomes one of the primary goals of each country and region, the global industrial chain supply chain is unimpeded, and China's industrial economy will give full play to its comparative advantages to serve the global market, while international cooperation in low-carbon technology accelerates, thus promoting high-quality development of the industrial sector and substantial emission reductions.

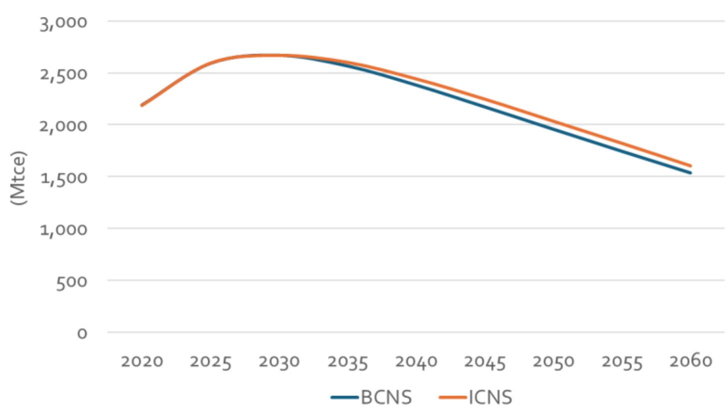
In the process of scenario analysis, a combination of qualitative and quantitative analyses was adopted to examine the macro-socio-economic factors, policy factors and possible future evolutionary trends affecting the supply and demand of energy, and quantitative analyses of the industrial structure, the intra-industrial structure, the product structure and scale, and the demand for consumption were carried out. For the scenarios set, the possible development of production restructuring, energy consumption restructuring and technological progress in various sectors under different scenarios was simulated with the help of modelling tools.

Outlook for end-use energy demand in the industrial sector

In terms of total volume, the industrial structure will shift towards high-valued industries. Energy consumption in traditional, energy-intensive sectors is expected to peak, while energy use in emerging areas, such as advanced manufacturing, will continue to grow. As a result, the overall growth of energy demand in the industrial sector is expected to slow down.

According to the results of the model, as shown in figure 10-4, the end-use energy demand in the industrial sector will peak around 2030 and begin to decline steadily. In BCNS, the end-use energy demand in the industrial sector is expected to be 1.53 billion tonnes of standard coal in 2060, a decline of about 30% compared with that of 2020.In ICNS, due to China's gradually strengthening role in the global industrial division of labour, the industrial economy will gain more development momentum and potential space, and energy demand will be slightly higher than that in BCNS, with the end-use energy demand in the industrial sector expected to be 1.61 billion tonnes of standard coal in 2060 (as shown in Figure 10-4).

Figure 10-4 Outlook for industrial sector end-use energy demand



Outlook for end-use energy demand in major industrial sectors

China's industry sector energy consumption is dominated by the four major high energy-consuming industries (ferrous metals, construction materials, non-ferrous metals, and petrochemicals and chemicals) will be significantly altered. in 2020, the end-use energy consumption of the four major high energy-consuming industries will account for as much as 78.8% of industrial end-use energy consumption, whereas in BCNS and ICNS, the share will drop to around 60% in 2060. In contrast, the high value-added industries represented by machinery manufacturing, transportation equipment, and pharmaceuticals will see a significant increase in their energy demand. In BCNS, the energy demand of the three high value-added industries in 2060 is 1.8, 2.3, and 2.6 times higher than that of 2020, respectively; in ICNS, the figures have been further boosted to 2.1, 3.0, and 3.5 times higher (as shown in Figure 10-5 and Figure 10-6).

Figure 10-5 Outlook for end-use energy demand by sector in BCNS

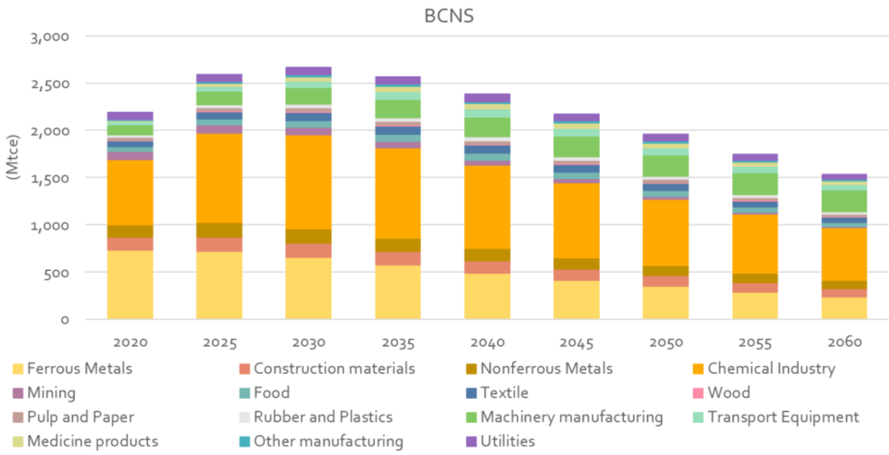
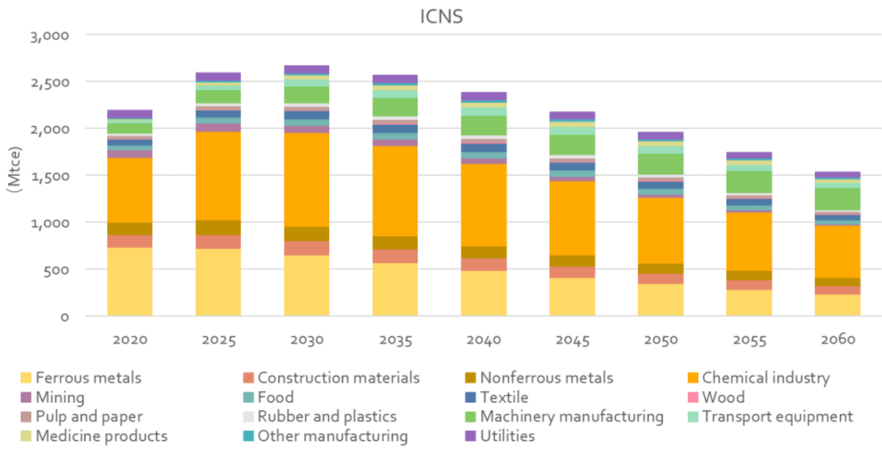


Figure 10-6 Outlook for end-use energy demand by sector under the ICNS



Outlook for energy demand by fuel

In terms of energy varieties, the energy structure of the industrial sector will undergo a leapfrog change, realizing a direct upgrade from and energy system based on coal to electricity and hydrogen. in 2020, coal (including coke, etc.) will account for more than 45% of the industrial end-use energy structure, with BCNS and ICNS scenarios dropping to less than 2%, and will be replaced by the high-speed development of electricity and hydrogen, with the rate of electricity-hydrogenation rising from 25% in 2020 to 64% and 68% in 2060, of which the share of electricity demand will reach 49% and 53% respectively, and the share of green hydrogen demand will reach about 15% (as shown in Figure 10-7 and Figure 10-8). Although there will still be a small amount of fossil energy used in China's industrial sector in 2060, it will be utilised as feedstock, such as naphtha and coke, which are used as chemical raw materials and reducing agents, respectively.

Figure 10-7 Structure of industrial end-use energy in 2060 in BCNS

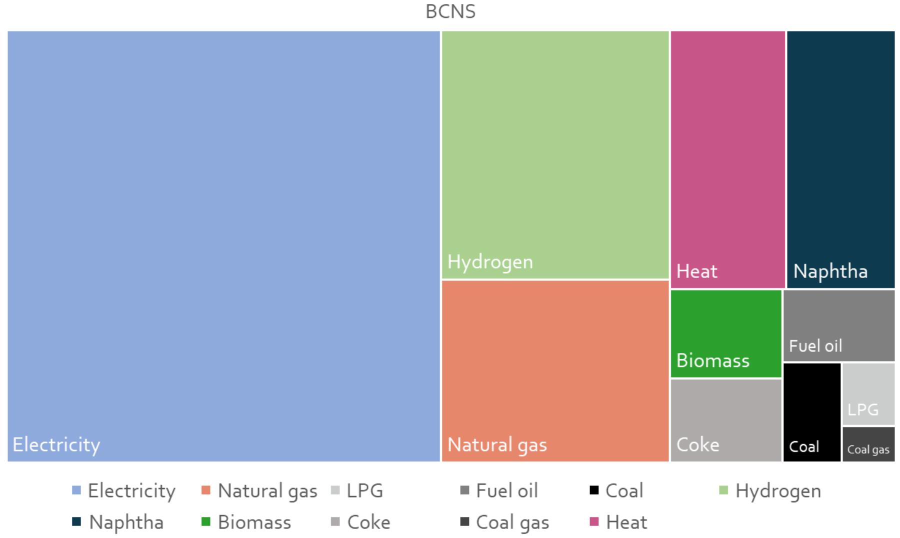
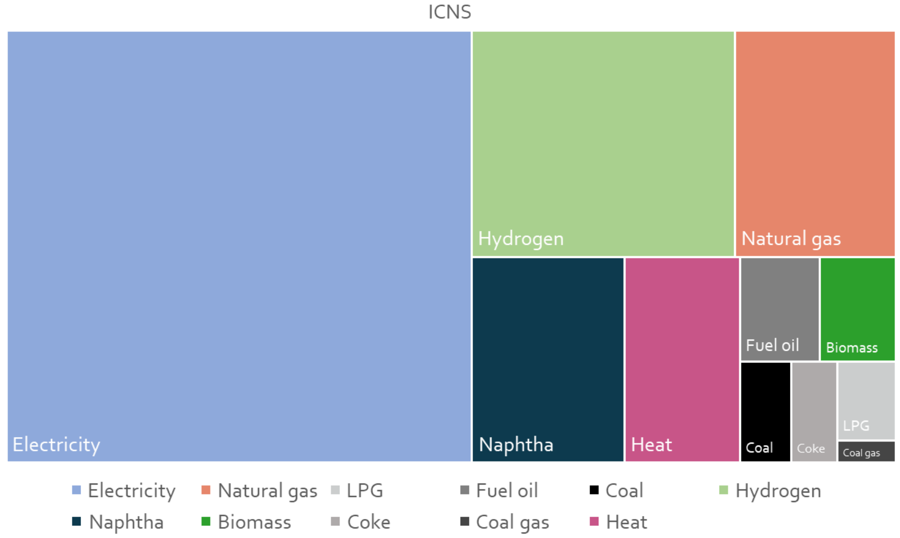


Figure 10-8 Industrial end-use energy structure in 2060 under the ICNS



Major strategic actions for low-carbon transformation of industry

In the future, China needs to comprehensively implement industrial structure adjustment measures, such as process optimisation, energy conservation, energy efficiency, low-carbon energy substitution and take active and powerful measures, so as to successfully complete the transformation from traditional to new-type industrialisation.

Establishing a modern and high-valued industrial system

Promoting traditional industries develop toward to high-valued, efficient and sustainable. On the supply side it is necessary to promote the elimination of backward production capacity, optimize the productivity layout and give full play to the benefits of the economy of scale. On the demand side, optimizing the supply chain and enhancing the value-added of products.

This will help achieving the objective of "double decoupling": decouple the demand growth rates from both material and energy consumption. To accelerate the process of optimization and upgrading the industrial structure, it is necessary to shift the focus of development from high energy-consuming industries to high value-added, high-tech and strategic emerging industries, and focus on breakthroughs in key technologies and core equipment in the fields of automation, such as high-end numerically-controlled machine tools, new materials and new energy sources. Overall, this strategy will increase the chance to achieve the goal of creating more value with less energy inputs. In 2060, the outputs of China's high-value-added industries, light industries and high-energy-intensive industries, would be almost even.

The phenomenon of "large-scale demolition and construction" should be reduced and eliminated, and the scale and pace of building area and infrastructure construction should be controlled, so to reduce the unreasonable demand for energy-consuming raw materials. Parallelly, it is necessary to improve the performance and quality requirements of basic raw materials, and vigorously develop and promote green processes, lightweight and long-life products such as high-strength steel bars and high-grade concrete. The remaining capacity to produce raw materials should focus on the export strategy, reduce the export of high-emission and low-value-added products, and promote the transformation of the international trade pattern in a low-carbon direction. The output of traditional energy-consuming products such as iron and steel, cement and ammonia will strive to reach the peak in the 14th Five-Year Plan period, and the output of ethylene, PX and methanol will strive to reach the peak in the 15th Five-Year Plan period or around 2030. Finally, the output of crude steel, cement and other major energy-consuming products will decrease by 40% to 20% by 2060 as compared with 2020. In 2060, the output of major energy-intensive products such as crude steel and cement will be reduced by 40-60% compared with 2020.

Finally, it is important to promote the optimization of the spatial distribution of high-energy-consuming and high-emission production capacity. Based on factors such as market demand, upstream and downstream industries and infrastructure support, the development of energy-consuming industries/capacity clusters will be guided in an orderly manner, so as to better utilize economies of scale. Relying on the advantages of clean energy resources in the central and western regions, China will gradually promote the transfer of iron and steel, non-ferrous metals, and chemical production capacity to the relevant regions. It is also building a low-carbon, high-quality regional cooperation network, improving the editing capacity of the industrial chain, promoting the linkage of outward direct investment in the manufacturing industry and the domestic industrial chain, increasing production capacity cooperation with the "Belt and Road", ASEAN and other countries and regions, and promoting the formation of a more reasonable and mutually beneficial regional industrial chain, supply chain and value chain, based on the comparative advantages of each region.

Developing circular economy

Gradually upgrading the level of resource recovery and recycling is essential for reducing environmental impact, conserving raw materials, and promoting a more sustainable and circular economy. As industrialisation and urbanisation continue to advance, China has gradually entered the stage of generating a large amount of waste resources, and the amount of resources such as scrap steel, aluminium and plastics will increase significantly, creating opportunities for adjusting the process structure of high-energy-consuming products. In the process of moving towards a carbon neutral era, the production process structure of raw material products will gradually change from the current primary resources to renewable resources. Currently in China, in addition to paper and cardboard, recycled aluminium, copper, plastics, steel and other renewable resources routes accounted for a relatively low proportion of 18%, 30%, 20% and 15%, respectively, and in 2060 this proportion will be raised to 60%, 70%, 50% and 50%, renewable resources routes will become the main raw material product production process, to achieve the transition from the primary resources routes to renewable resources routes. .

Promoting ecological links and integrated development among enterprises and between industry and cities. Under the realistic conditions of industrialisation shifting from roughness to intensification and the deep integration and development of industrialisation and urbanisation, there is an urgent need to make major adjustments to the traditional disorderly mode of industrial development, and it is necessary to rethink the relationship between the various components and members of the industrial system, as well as to re-examine the relationship between industry and the city. On the basis of an in-depth understanding of the operating characteristics of the materials, such as associated data gathering , energy sources and value chain of processes enterprises, and according to the characteristics of each economic activity unit through the comprehensive use of clean production, such as eco-design, green manufacturing, green supply chain management and other means, China will optimise the raw material, energy and information supply chain , build a multi-targeted production system, establish Business-to-Business and Business-to-Society eco-links to realise the efficiency maximisation of resource and energy utilisation and the minimization of waste to achieve environmental pollution emission minimisation and other goals.

Applying digital and energy efficient technologies

At present, the energy efficiency improvement work has entered the "deep water zone", and it is necessary to explore the energy saving potential with new concepts and perspectives, relying on innovative technologies and new models. To achieve the optimal use of energy it is necessary to apply energy-saving technologies and equipment in all aspects of the process. Furthermore, it is necessary to optimize the production organization, the process routes, the configuration of production units and the division of labour, . In the process of moving towards the goal of carbon neutrality, energy efficiency in the industrial sector will continue to improve, and the energy consumption of long-process steelmaking, electric furnace steelmaking, cement clinker and ethylene plants will maintain a steady decline, with a 15%-20%t drop in energy consumption in 2060 compared with 2020.

The integration and development of informatisation increases the potentials for energy saving. “Digital energy-saving” refers to the application of digital technology, real-time monitoring of major energy-using equipment and processes, dynamic search for excellence, interactive feedback to reduce energy losses, improving energy efficiency and energy-use refinement of the management level. Enterprise practice has shown that the application of digital means can enhance product energy efficiency by more than 10%, but also helps to improve the flexibility and quality of manufacturing. In the future, it is necessary to accelerate the deep integration of industrialisation and information technology, and to tap more digital energy-saving potential.

Promoting electrification and using of hydrogen

Accelerating electrification in the industrial sector. Future industrial energy conservation and carbon reduction should consider the trend of energy transformation in a forward-looking manner, and new projects should make greater use of electrified energy-using means and equipment to better adapt to changes in the energy supply system.

In terms of stock, China should accelerate the promotion of advanced production technology such as electric heating and automation control to replace traditional fossil energy technology and equipment and make use of the roofs of factories and open spaces in factories to develop renewable energy sources, so as to change enterprises from energy consumers to energy "prosumers", producer and consumers. At the same time, the flexibility of industrial electric (electricity) equipment should be strengthened and upgraded, and more contributions should be made to the construction of a new energy system dominated by renewable energy sources, with the electrification rate of the industrial sector striving to reach more than 50% by 2060.

On the other hand, electric technologies are still in phase of research and development for most of the energy-intensive industry sectors. Promote the scaling up of hydrogen energy as a green feedstock and low-carbon fuel is mandatory for some of the industrial sub-sectors and crucial for the deep decarbonisation of the industrial sector. Considering that China will still have a certain scale of demand for ammonia, methanol and olefins in the future, hydrogen energy will play the role of a green feedstock and be widely used in the petrochemical, chemical and iron and steel industries. At the same time, hydrogen energy is also an important alternative for deep decarbonisation in the high temperature process heating sectors. In the future, it is necessary to coordinate the scale of hydrogen energy supply, cost, carbon emissions and other factors, and gradually carry out green hydrogen to replace grey hydrogen in the petrochemical industry, chemical industry, iron and steel industry and other industries, as well as hydrogen metallurgy, natural gas doping and other technology demonstrations. 2060 hydrogen energy demand in the industrial sector is expected to be more than 250 million tonnes of standard coal (about 60 million tonnes) or more.

Milestones and implementation road map

The future low-carbon transformation of industry is a strategic and global change process that requires comprehensive innovation in concepts, technologies, modes and paths, with the aim of becoming a global manufacturing leader by mid-century, realizing the goal of Powerful Manufacture , with the value added of industry approaching RMB 100 trillion in 2060 (at 2020 prices), and with industry accounting for around 30% of GDP. The proportion of industry in GDP will remain at around 30%. China will gradually build a globally leading green and efficient production system and increase industrial energy productivity fourfold. While achieving high-quality development of the industrial economy, the industrial sector will go through three phases to gradually move towards carbon neutrality: the peak-reaching period, the over-peak period, and the deep emission reduction period. Different phases have different development characteristics, different major contradictions in carbon reduction, and different emission reduction paths and priorities.

- The peak period (2024-2030) will be "controlling production capacity, improving quality, focusing on energy efficiency and promoting environmental protection". The supporting role of high-carbon industries/products for economic and social development should be addressed, and the reduction of production should be guided by the reduction of demand. Strictly prohibit a "violent production restrictions", and intensify efforts to curb unreasonable demand, reduce the level of demand in society, and guide the development of high-carbon industries to reduce the amount of CO2 emissions. At the same time, China must fully understand the role of energy saving on energy growth "pressure reducing valve", increase energy saving and efficiency efforts. Furthermore, it is necessary to accelerate the promotion of advanced energy-saving technologies and equipment, the exploration of digital transformation, and tap the potential of digital energy saving.
- The theme for the development of the industrial sector during the over-peak period (2030-2050) is "target forcing, system optimization, advantage reconstruction and technology leadership". During this period, China has basically completed industrialization and urbanization, and energy demand has stabilized, creating a better environment for carbon emission reduction. There will be still shortcomings in low-carbon technologies and industries, so during the over-peak period, China should adhere to the principle of optimal cost-effectiveness and gradually carry out the substitution of high-carbon stock in an orderly manner. More importantly, during the peak period, we need to face the goal of carbon neutrality and carry out technological research and application exploration in iron and steel, chemical

industry, aviation and other "hard-to-abate areas", to ensure that China is in the leading position of global low-carbon technology.

- During deep emissions reduction (2050-2060), industrial sector development will be "intelligent, digital, networked and carbon-free". During this period, China will accelerate its progress towards the ranks of medium-developed countries, and carbon constraints will be increasingly strengthened, becoming one of the most important constraint variables. The period of deep emission reduction will be a key period for China's industrial sector to obtain new development momentum in carbon reduction. Deep global decarbonization and the rising cost of carbon emissions will give rise to many low-carbon industries and technological development, and it is important to grasp this round of change and make low-carbon an important leader in development.

Different sectors would achieve carbon peaking and neutral in different pace. Direct carbon dioxide emissions from the industrial sector will strive to peak around 2025; carbon emissions from the iron and steel, cement and non-ferrous metal industries production processes and low-carbon energy sources, industrial enterprises will provide society with high-quality raw materials and products with zero carbon emissions throughout their life cycle. With the large-scale application of green production processes and low-carbon energy, industrial enterprises will provide society with high-quality raw materials and products with zero carbon emissions throughout their life cycles. Specifically, high energy-consuming industries such as iron and steel, cement and other industries have entered the stage of saturation and reduction, and their energy consumption and carbon emissions will decrease steadily. Petrochemical and chemical industries still have some room for incremental expansion in the near and medium term, especially ethylene, propylene, paraxylene and some downstream fine chemicals, and their outputs will also see a large increase, so that the peak of the industry's energy consumption and carbon emissions will be delayed compared to the iron, steel and cement sectors , The chemical sector will probably lag behind the industrial sector as a whole and, at the same time, the petrochemical and chemical industry product structure, process routes, the way of energy use will be a major change.

The low-carbon transformation of the industrial sector will drive the development of related industries and trigger a new round of technological innovation, investment, and business opportunities. Towards the goal of carbon neutrality by 2060, China's industrial sector will be transformed into intensive, recycling, efficient and low-carbon, which will lead to the development of a series of industries such as energy conservation and environmental protection, clean energy, vein industries such as recycled plastics and recycled metals, new materials manufacturing, green electricity and green hydrogen production, for example, the output of recycled plastics and recycled metals will be increased from less than 20% to more than 50%, and the proportion of green electricity and green hydrogen consumption will be increased from about 25% to more than 70%.

10.5 Low carbon transformation paths and cases in China's iron and steel industry

The iron and steel industry is an important basic industry of China's national economy and is also one of the industrial sectors with the highest energy consumption and carbon emissions, making carbon emission reduction a difficult and challenging task. In the future, under the premise of safeguarding the industrial chain security of the steel supply chain, we should promote demand reduction, adjust the structure of production processes, improve energy efficiency and accelerate low-carbon energy substitution, so as to strive to achieve early peak performance with lower carbon emissions and lay the foundation for carbon neutrality.

Promoting demand reduction and structural optimisation

Rationally guiding steel demand is a source control tool for carbon emission reduction in the steel industry. Steel is one of the most important basic raw materials and is widely used in all sectors of the national economy. In recent years, more than 50% of China's steel has been used in the construction industry, 17% in machinery and equipment manufacturing, and 8% in transport equipment manufacturing. China has been in industrialization, and urbanization development in the late stage. The annual new completed building area has been basically stable at 4 to 4.2 billion square metres, it is expected that the "14th Five-Year Plan" will gradually fall back to 3.5 billion square metres by extend the life of infrastructure for steel for construction purposes and by reducing "large-scale construction".

In machinery and equipment and transportation equipment manufacturing, China has been the world's largest producer of machine tools, automobiles, domestic and overseas market demand has been high. There is a strict need to optimise the product structure, improve the use of steel strength and other ways to stabilise the steel demand in related areas. Although new infrastructure such as 5G base stations and extra high voltage will boost steel demand, it will not have a significant impact on crude steel output due to the small base. Therefore, in the construction, machinery, automotive and other major steel-using areas of steel demand reasonable guidance, China's crude steel output is expected to peak in the 14th FYP period. In conclusion crude steel output in 2060 is expected to be 550-600 million tonnes.

Gradually increase the proportion of electric arc furnace steelmaking

Increasing the proportion of EF steel is an important measure to significantly reduce the carbon emission intensity of crude steel. The energy consumption of tonnes of steel in short-flow electric furnace steel is only about 1/3 of that in long-flow, and if all the power used comes from renewable energy, it can realise near-zero emission steelmaking, and accelerating the increase of the proportion of electric furnace steel is a must for the iron and steel industry to realise the carbon peak and carbon neutrality. Internationally, the proportion of electric furnace steel in developed countries is more than 30% (the EU average of 42%, Japan is close to 30%, the United States more than 60%), compared to

2020, China's electric furnace steel production accounted for only 10%, there is more room for improvement. Up to now, China's iron and steel accumulation has exceeded 10 billion tonnes, per capita accumulation of more than 700 million tonnes, the future availability of scrap resources will increase significantly, the development of electric furnace steel has a better resource security. We have constructed a "bottom-up" analytical model to measure the availability of scrap resources at different points in time from the three areas of construction materials, end-use goods and production processes, and made a judgement on the development of EF steel in China based on the parameters of equipment investment and electricity price. The results show that China's share of EF steel will increase slightly to 12%-15% in 2025, to 20% or more in 2030, and is expected to reach more than 50% in 2060.

Implementation of the Ultimate Energy Efficiency System Project

Energy saving and energy efficiency is the most economical and effective way to reduce carbon emissions in the steel industry in the near to medium term. "During the 13th Five-Year Plan period, China's iron and steel industry has achieved remarkable results in energy saving, but the level of energy efficiency varies among different iron and steel enterprises, and there is still potentials for improvement for the industry as a whole. "Since the 14th Five-Year Plan, China's iron and steel industry has been implementing the Ultimate Energy Efficiency Project, which aims to improve the energy efficiency of iron and steel enterprises through the rapid promotion and application of mature technologies, collaborative research and development of technologies with common problems, and synergistic enhancement of the national governance capacity. Further, the industry's self-regulation capacity through a series of policies, regulations, standards, and so on will enhance the process to increase efficiency in the sector. Currently, the Ultimate Energy Efficiency System consists of 50 energy-saving technologies, which can improve energy efficiency by 10%~15%. It is worth mentioning that in the past, energy saving in the iron and steel industry was mainly focused on each process unit, and the interface technology to improve energy efficiency between processes is an important new area for energy efficiency improvement in the iron and steel industry in the future, such as the "one-can-to-the-end" and "near-net-forming" technologies. The development of interface technology can realize the articulation, matching and co-ordination of material flow, energy flow, temperature, time and other parameters in the production process to achieve the effect of compactness, continuity and high efficiency, thus improving the efficiency of energy use.

In summary, through the implementation of the extreme energy efficiency project, the energy consumption of steelmaking in 2060 is expected to decrease by 15%-25%compared with 2020.

Development of hydrometallurgy and green power alternatives

Optimising the energy mix is the way to achieve deep carbon reduction in the medium and long term. The fossil energy consumed by the steel industry is used partly as fuel to provide high-grade heat and partly as raw material to reduce iron ore. On the fuel side, coal and other fossil energy sources can be replaced by electric heating, nuclear heating, and pure hydrogen combustion. On the raw material side, coke will be replaced on a large scale by renewable energy-produced green hydrogen and hydrogen metallurgy. All of the above energy restructuring measures are important supports for the steel industry to achieve carbon neutrality. However, due to the long iron and steel production process, the close connection between upstream and downstream links, and the complex balance of the energy system, energy restructuring will "pull one hair and affect the whole body", and it is more difficult to replace clean energy, especially electric energy. Although in recent years hydrogen metallurgy technology in the global attention, China's Baowu, Hesteel, JISCO and other iron and steel enterprises have carried out hydrogen metallurgy pilot demonstration. However, from the existing pilot project situation, hydrogen steelmaking there is a technical immaturity, high cost, green hydrogen resource supply is insufficient and other issues, it is expected that after 2035 can usher in the rapid development of 2060 hydrogen-based vertical furnace direct reduction of iron production is expected to be raised to 20% ~ 30%, the blast furnace ironmaking process will also be mixed into the hydrogen in order to replace the use of coke.

11 Heating for buildings

11.1 Main findings

- Heating is the largest area of energy consumption in the building sector. Currently, heating accounts for over 30% of China's total building energy use, with more than 70% of the sector's coal consumption dedicated to this purpose. As a result, decarbonising heating is critical to achieving low-carbon development in the building industry2.
- China's vast geographical area and diverse climate mean that heating methods vary across different climate zones and building types. In northern urban areas, heating consumption is particularly high, and centralised heating systems are the norm. Coal-fired combined heat and power (CHP) plants, along with large coal- and gas-fired boilers, are the primary heat sources, with CHP alone contributing over 50%. In contrast, rural buildings houses in the northern region and urban residential buildings in hot-summer/cold-winter (HSCW) region are dominated by decentralised heating methods.
- Internationally, different countries have adopted various approaches to low-carbon heating. Denmark, for example, emphasises highly efficient district heating systems, incorporating renewable energy and waste heat. The United States, on the other hand, relies mainly on decentralised heating, with heat pumps seen as a key tool for decarbonising heating systems in the future.
- For China, the path forward must be tailored to regional conditions. In northern urban areas, centralised heating will remain dominant, focusing on replacing fossil fuels with waste heat and renewable energy. In rural areas and urban buildings in HSCW regions, decentralised heating using air-source heat pumps will take priority. Public buildings in these regions would also focus on heat pump systems adapted to local resource availability. Additionally, China should continue promoting ultra-low and near-zero energy buildings, along with deep energy retrofits of existing structures.
- By following the transformation mentioned above roadmap, China aims to ensure that by 2060, the building sector's heating energy will predominantly come from waste heat and renewable electricity, achieving zero-carbon heating.

[2] Building heating mainly includes space heating, domestic hot water, and steam for special-purpose buildings. Space heating is the dominant part and, in this chapter, building heating only refers to space heating.

11.2 History and effectiveness of China's low-carbon transition in building heating

The heating methods of Chinese buildings are diverse. To promote the low-carbon transformation in building heating, the Chinese government has made continuous efforts and achieved significant results.

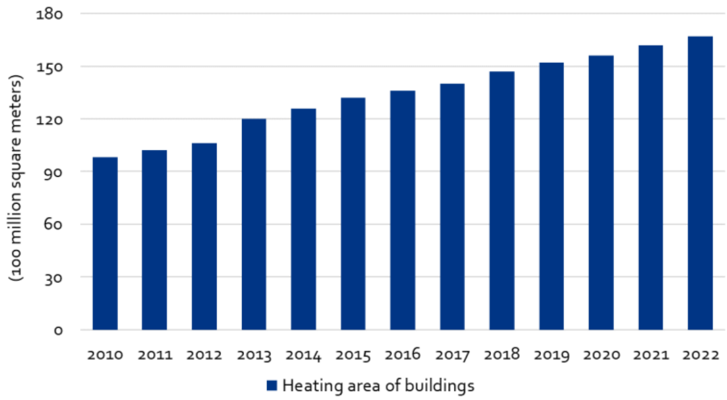
Current status of building heating

China has a vast territory and diverse climates. The heating methods for different climate zones and various special-purpose buildings present different characteristics.

Status of heat supply in towns and cities

Northern urban areas are dominated by centralised heat supply and supplemented by individual heating. These areas have a high energy consumption for heating and are dominating the overall heat supply for buildings in China. Northern China has cold winters, leading to high heat demand per unit of building area. Urban areas have long relied on centralised heating systems as the main heating method, making them dominant for building heating in China. In 2022, the urban heating area in northern China was about 16.7 billion square metres (as shown in Figure 11-1), with a primary energy consumption of about 220 Mtce, accounting for about 19.4% of the primary energy consumption in the building sector. The primary energy consumption intensity for heating is about 13.0 kgce/m^2. The centralised heating in northern cities and towns is mainly carried out through municipal district heating networks. The heat sources mainly include coal-fired heat and power cogeneration, large-scale coal-fired boilers, large-scale gas-fired boilers, and gas-fired cogeneration. Some areas also use regional or building-level centralised heating system. These include colleges and universities, institutions, and commercial districts. Here the heat sources mainly being various types of heat boilers and large-scale heat pump systems. Municipal and regional or building-level district heating account for nearly 90% of the heating area in northern cities and towns. The remaining buildings mainly use decentralised heating methods such as air-source heat pumps, gas wall-hung boilers and electric heaters.

Figure 11-1 Heating area of buildings in northern cities and towns, 2010 to 2022



Source: Building Energy Efficiency Research Centre, Tsinghua University

Urban buildings in hot-summer and cold-winter regions are dominated by decentralised heat supply, and the energy intensity of heat supply is relatively low. Compared with northern regions, the average outdoor temperature in winter in hot summer and cold winter regions is relatively high, relatively short heating periods, and the heat demand per unit area is relatively low. Therefore, building heat supply in the region has not been a mandatory requirement for a long time, and most cities do not have municipal district heating supply systems. Residential buildings primarily use household air-source heat pumps, gas wall-hung boilers, electric heaters and other decentralised heating methods. Public buildings mainly use building-level central heating methods, such as various types of boilers and heat pump systems. The region's heating energy consumption is currently much lower than the level of the northern region.

In recent years, as the level of economic and social development and the living standards of residents continue to improve, the demand for better indoor comfort in hot summer and cold winter areas has increased. Some cities have started to build district heating networks, similar to those in the northern region. The heating period has also increased, leading to an increase in the building heating energy consumption.

Current status of rural heating

Rural areas are dominated by diversified decentralised heat supply, with a gradually increasing share of commercial energy consumption in recent years. There are also no mandatory requirements for building heat supply in rural areas, meaning that it is up to the individual users. The overall thermal performance of rural buildings is not as good as that of urban areas, so the heat demand per unit of floor area is higher than that of urban buildings in the same area. However, the overall heating energy consumption in rural areas is lower than that of urban buildings because heat is supplied only part of the time and to part of the space, keeping a lower indoor temperature.

China launched the Clean Heating Initiative in 2017, prior to which heating in rural buildings was mainly based on traditional methods such as small coal stoves, *kangs* and charcoal pots. Biomass such as fuel wood, straw as well as bulk coal was the main fuels consumed for heating. After the implementation of clean heating policy, affected by environmental policies, climate conditions, resource availability and other factors, the rural heating show regional differences. In key areas for air pollution control, such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Fenwei Plain, rural buildings primarily use air-source heat pumps, electric heaters, and gas wall-hung stoves, supplemented by biomass furnaces. The biomass-rich northeastern region primarily use biomass for heating, supplemented by electric heating. In addition, most of the northwestern region, apart from Xinjiang, a combination of biomass stoves, air-source heat pumps, electric heaters, and wall-hung gas boilers are used. Xinjiang primarily promotes electric heating. Due to the continuous improvement of living standards, rural heating in hot summer and cold winter areas are also gradually shifting towards mainly air-source heat pumps and electric heating.

Policies for low-carbon transition in building heating

Reducing carbon emissions from building heating requires, on the one hand, reducing the demand for heat in buildings and, on the other hand, reducing the proportion of high-carbon heat sources. For a long time, the Chinese Government has been making continuous efforts and taking a series of policy measures to address these two aspects.

Continuous upgrading of building energy efficiency standards

China began its building energy-efficiency efforts in the 1980s, when the government started to develop building regulations to improve the thermal efficiency of buildings. The first of these was the energy-saving design standard for residential buildings in the northern heating region issued in 1986. It required new buildings to reduced energy consumption by 30% compared to the 1980-1981 local average level, also known as the 30% energy-saving standard. Since then, China has introduced energy-saving design standards for residential and public buildings in different climate zones and has continuously tightened the requirements. Currently, 75% energy-saving standards are implemented for residential buildings in frigid and cold regions. In other regions residential buildings must meet a 65% energy-saving standard, and public buildings a 72% energy-saving standard. The "Carbon Peak Implementation Plan for Urban and Rural Construction" was issued in 2022. This requires that new residential buildings in frigid and cold regions achieve an 83% energy-saving requirement, and 75% for new residential buildings and 78% for new public buildings in other regions, by 2030. The above energy-saving standards are mandatory. However, before 2000, the enforcement of these standards was ineffective. Since the 11th FYP, the building energy-saving authorities have paid close attention to the implementation of the standards, and enforcement of the mandatory standards have increased. The rate of implementation of energy-saving standards in the current design and construction phase have reached 100 %. Additionally, the Chinese Government has issued a standard for near-zero energy buildings (GB/T

51350-2019) as a recommended standard. This provides a basis for accelerating the construction of ultra-low-energy, near-zero energy and zero-energy buildings.

Continue promoting energy-efficiency renovations of existing buildings

In parallel with the introduction of energy-efficient design standards for new buildings, China has gradually initiated energy-efficiency retrofitting of existing buildings. This has been one of the priorities in successive Five-year Plans for building energy efficiency. The work began with existing residential buildings in northern heating areas and gradually expanded to public buildings and residential buildings in other climate zones. During the 11th FYP period, China implemented heat metering and energy-saving renovation of existing residential buildings in northern heating areas. The focus was on weak areas such as external walls, windows and doors, and heating systems. Measures included adding heat insulation and replacing windows and doors. A total of 182 million square metres of buildings underwent energy-efficiency renovations. Additionally, China initiated the construction of an energy-saving supervision systems for governmental office buildings and large public facilities. Energy consumption statistics, energy audits and energy-efficiency announcements for public buildings have been promoted, which has boosted enthusiasm for energy-saving operations and renovations. During the 12th FYP period, China initiated energy-saving renovations of existing residential buildings in hot-summer and cold-winter areas and gradually explored energy-saving renovation models for these areas. Eleven key cities for energy-saving renovation of public buildings were identified. These drove the implementation of the renovation of 110 million square metres across the country. In frigid and cold areas, energy-saving renovations were combined with the renovation of dilapidated buildings in rural areas. The 13th and 14th FYPs further clarified the targets for energy-saving renovations of existing buildings. In addition, after China launched its clean heating programme in 2017, energy-saving renovations were carried out of some buildings in parallel with the promotion of heat-source substitution in rural areas in the north.

Vigorous optimisation of the heat source structure

Implementing efficient and clean heat sources is not only an important element of energy conservation, but also an important requirement for environmental protection. During the 11th FYP period, China prioritised regional combined heat and power (CHP) projects as one of the ten key energy-saving topics. Urban coal-fired heating boilers were replaced with centralised heating using CHP, effectively improving the energy efficiency of the heating system and reducing pollution. During the 12th FYP period, the action plan for air pollution prevention and control called for accelerated construction of centralised heating projects in the industrial sector and the promotion of technologies such as ground-source and air-source heat pumps, and heat and power cogeneration. In 2017, China began to promote clean heating and issued the *Northern Region Clean Heating Plan (2017-2021)*. The plan put forward the overall goal of reaching a 70% clean heating rate in the northern region by 2021. It set differentiated goals for the "2+26" key cities, urban areas, counties, and rural areas. Regions were encouraged to choose heating sources according to local conditions, including renewable energy, natural gas, electricity, industrial waste heat, and clean coal. Pilot areas were identified to lead the way, and five groups of 88 clean heating pilot areas were established. In 2022 the "Urban and Rural Construction Sector Carbon Peak Implementation Programme" was released. Here, low-carbon heating sources in buildings were promoted, including comprehensive utilisation of the heat from cogeneration, industrial surplus heat and nuclear excess heat, based on local conditions.

Establishment of a sound incentive mechanism

To support the promotion of energy-saving and carbon reduction in heating, the Chinese government has developed corresponding incentive mechanisms. In 2007, the Ministry of Finance issued the "Interim Measures for the Administration of Incentive Funds for Heat Measurement and Energy-saving Retrofitting of Existing Residential Buildings in the Northern Heating Areas". With this, special central financial funds and rewards standards were established. These funds subsidised the energy-saving building renovations in the northern heating areas, and more provinces and cities arranged special subsidy funds for local financial support. In 2012, the Ministry of Finance issued the "Interim Measures for the Administration of Subsidies for Energy-saving Retrofitting of Existing Residential Buildings in Hot Summer and Cold Winter Areas", which expanded the central financial subsidies to the middle and lower reaches of the Yangtze River and its surrounding areas, involving a total of 12 provinces and municipalities. In 2017, four ministries and commissions jointly issued the "Notice on the Pilot Work on Central Financial Support for Clean Heating in Winter in the Northern Areas", which set up award and subsidy standards to support the work of building energy-saving retrofitting according to the size of the cities. Reward standards were based on the size of the city to set up the award and subsidy standards to support the pilot clean heating areas. The central government cumulatively arranged more than RMB 100 billion of award and subsidy funds for the five batches of pilot areas, pulling the local financial and social capital investment of more than RMB 400 billion. In addition to financial support, China has also supported the low-carbon transformation of building heating by improving prices, taxes, financial and other incentive mechanisms. For example, in 2017, the NRDC issued the "Circular on Opinions on Price Policy for Clean Heating in Northern Regions", which requires the comprehensive use of price support policies such as improving peak and valley prices, ladder prices, and expanding market-based trading to establish a price mechanism conducive to clean heating. The relevant regions have successively introduced specific pricing policies accordingly.

Results of low-carbon transition of building heat supply

After years of efforts, China has achieved significant results in promoting the low-carbon transformation of building heating, mainly in the following areas:

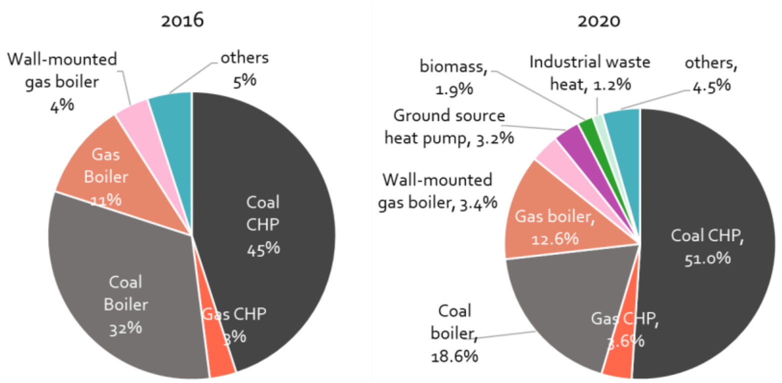
Significant increase in the proportion of energy-efficient buildings

Over the years, the implementation of energy-efficient design standards for new buildings in urban areas has given a strong impetus to the growth of energy-efficient floor space. By the end of 2023, China had cumulatively constructed 32.68 billion square metres of energy-efficient buildings. The energy-efficient buildings in urban areas account for more than 64% of the built area, an increase of nearly 30 percentage points compared with a decade ago. The construction of ultra-low-energy and near-zero energy buildings has also been accelerating in recent years, with more than 43.7 million square metres built. The continuous promotion of energy-saving renovation of existing buildings has also further increased the scale of energy-efficient buildings. By the end of 2020, China had completed energy-saving renovations of more than 1.7 billion square metres of urban residential buildings, nearly 300 million square metres of public buildings. The increase in the proportion of energy-efficient buildings has overall strongly reduced the average heating energy demand per unit area of buildings.

Significant optimisation of heat sources for heat supply

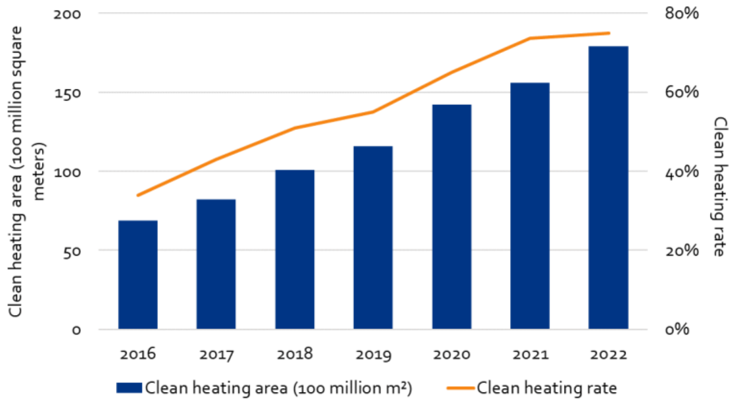
Research data shows that the heat sources for heat supply in northern urban areas improved significantly in 2020 compared with 2016. The share of coal-fired boilers decreased by 13 percentage points, while the share of coal-fired heat and power cogeneration increased by 6 percentage points. The share of other clean and low-carbon heat supply methods, such as heat pumps, biomass, and industrial waste heat, increased by about 6 percentage points (as shown in Figure 11-2). In 2023, the rate of clean heating in China's northern areas has approached 80%, and the area of clean heating has grown from 6.9 billion square metres in 2016 to 17.9 billion square metres in 2022 (as shown in Figure 11-3).

Figure 11-2 Structure of heat sources for district heating in northern towns and cities



Source: Building Energy Efficiency Research Centre, Tsinghua University

Figure 11-3 Clean heating area and clean heating rate in the northern region, 2016 to 2022

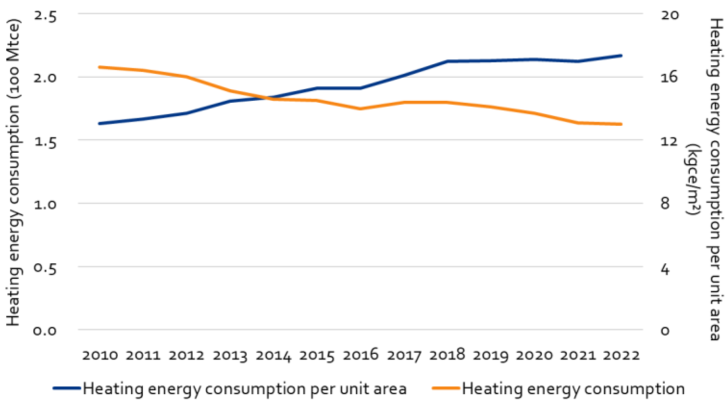


Source: Clean Heat Industry Council

Significant reduction in building heating consumption

Benefit from the improvement of building energy efficiency and the optimisation of heat source structure, the energy consumption of heat supply per unit area in northern urban areas has significantly decreased. From 2010 to 2022, the heating area increased by more than 70%, while the energy consumption for heat supply only increased by 33%. The resulting energy consumption per unit area for heating decreased from 16.6 kgce/m^2 to 13.0 kgce/m^2 , a reduction of 21.7% (as shown in Figure 11-4).

Figure 11-4 Building heating energy consumption and heating energy consumption per unit area in northern urban areas



Source: Building Energy Efficiency Research Centre, Tsinghua University

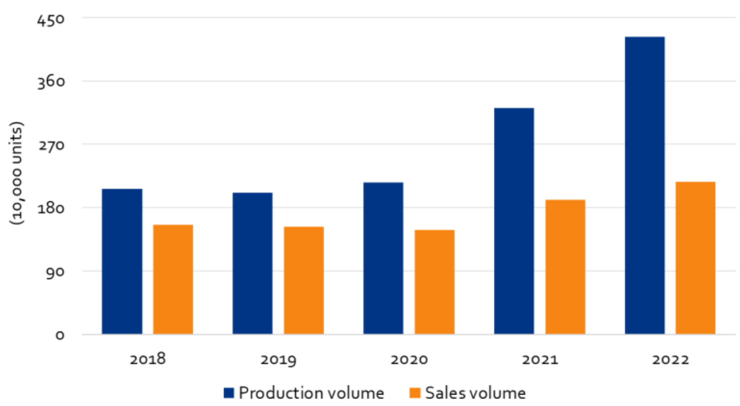
Significant improvement in air quality

The clean heating sources has also significantly improved winter air quality in the northern region. Data shows that in the autumn and winter of 2019 to 2020, the average PM2.5 concentration and the number of heavily polluted days in Beijing-Tianjin-Hebei and the surrounding areas dropped by 33% and 61%, respectively, compared with three years ago, before the clean heating initiative. Rural clean heating contributed to PM2.5 emission reductions of 39% in the Beijing-Tianjin-Hebei area and 35% in the Fenwei Plains. The National Energy Administration pointed out that clean heating contributed to more than one third of the improvement of the average local PM2.5 concentration and the improvement of the comprehensive air quality index.

Rapid development of clean heating technologies and industries

Policies promoting low-carbon transition of building heating has also driven the accelerated development of related technologies and industries. In recent years, breakthroughs have been made in heat pump technology, both making it applicable to a wider range of regions and significant cost reductions. There has been a significant increase in the production and sales volume (as shown in Figure 11-5). At the same time, the scale of the clean heating industry has steadily increased, and from 2017-2022, the number of enterprises grew from 7,700 to 8,300, and the number of employees grew from 1.1 million to 1.21 million.

Figure 11-5 Domestic heat pump production and sales volume, 2018 to 2022



Source: Clean Heat Industry Council

11.3 International experience with low-carbon transition of building heating

There are advanced technologies and policy practices in the international arena that can provide useful references for China in the promotion of low-carbon transition of building heating. This section compiles experiences of Denmark and the United States and summarises insights for China.

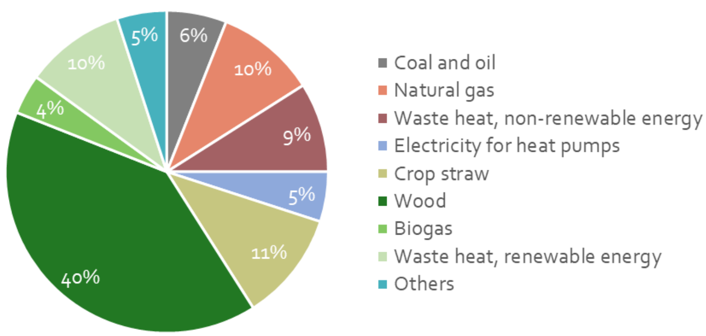
Denmark

Current status of heat supply

Denmark is located in the north of Europe. The Jutland Peninsula bords Germany to the south, the North Sea to the west and Norway and Sweden to the north. Denmark's climate is temperate oceanic, with cold winters and cool summers. The weather is mild and stable, usually without extreme weather conditions.

Two-thirds of Danish households are heated through district heating systems. The Danish district heating system is recognised as one of the most efficient heating systems in the world. The system integrates a wide range of renewable energy sources or waste heat, such as wood, straw and biogas, with only 16% of the heat source being fossil fuel. CHP plays an important role in the system. In 2012, 66% of the district heat supply came from CHP (as shown in Figure 11-6). The Danish district heating system operates at lower temperatures than conventional district heating systems, with supply and return temperatures of only 70/40˚C, which is another reason its high efficiency. At the same time, the Danish district heating system is equipped with automatic control devices at all levels, which can accurately distribute heat to end-users to reduce heat losses, and end-users can adjust the amount of heat supplied through self-control devices to meet their own differentiated needs for comfort. In addition, the Danish district heating system can also provide domestic hot water for households.

Figure 11-6 Danish energy structure for district heating



Source: Danish Energy Agency (DEA)

Historical review of heat transformation

As early as 1903, Denmark started using district heating systems and establishing heating networks. Prior to the oil crisis, district heating networks were set up around large power plants or in municipalities without power plants to take advantage of cheap heavy oil. After the oil crisis in 1973, Denmark began to develop a heating policy and rapidly deployed district heating systems. In 1976, Denmark launched its first energy plan aimed at reducing dependence on oil and shifting to the use of coal and renewable energy sources.

In 1979, Denmark formally enacted the "Heating Act", to promote the efficient and economic use of energy for heating. The act aimed to reduce oil dependence by expanding the area for district heating and increasing the use of natural gas. The "Heating Act" provides the guiding framework for heat planning in Denmark and the basis for regulation of almost all heat-related aspects. The "Heating Act" has been continuously adapted to the changing energy situation, but its core principles remain valid today. Over the decades, the Act has led to a gradual shift from a high-carbon heat system based on coal, supplemented by natural gas, to a cleaner, lower-carbon heat system based on renewable energy sources. From 1994 to 2020, the share of coal-fired heating decreased from 49.6% to 5.5%, while renewable energy heating using wood increased from 7.1% to 39.1%.

Policy mechanisms for heat transition

The "Heating Act" has provided a clear direction for Denmark to promote the transformation of heat supply at different times. However, it requires supporting incentives and constraints to promote the implementation of the objectives and tasks, for which a series of economic incentives and administrative policies have been introduced in Denmark.

In terms of economic incentives: in 1982, Denmark introduced a tax on coal used for heating. In 1992, a CO_2 tax was introduced along with a new subsidy for natural gas-fired CHP plants. The tariff system for natural gas-fired CHP plants included a peak-load price, a high-load price, and a low-load price. This has facilitated the expansion of natural gas-fired CHP plants and the installation of thermal storage units due to the high peak-load price. In 2000, the tariff system was adjusted from a fixed price to hourly pricing based on supply and demand, transforming the role of conventional CHP systems as it strives for low-carbon and economic integration with the electricity system. After 2000, heat companies with capacities over 20MW were included in the EU carbon emissions trading system, increasing incentives to use biofuels. In 2004, a subsidy scheme for CHP plants was launched and legislation called for lower taxes on gas and electric boilers in CHP systems. In 2018, Denmark incentivised the use of heat pumps for district heating through a lower tax on electricity. In recent years, the Danish government has further reduced taxes on electricity for heating and subsidised heat pump investments.

Administrative policy: Denmark does not allow landfilling of combustible waste and prohibits straw burning in fields. This promotes the use of combustible waste and biomass resources for district heating systems.

Future heating transition roadmap

The Danish Government has set national goals for greenhouse gas emissions reduction: achieving climate neutrality by 2045 and a 70% reduction by 2030 compared to 1990 levels. To achieve these goals, the contribution of the heating system is crucial. Denmark will continue to take relevant measures to achieve fossil fuel neutrality in the district heating sector between 2030 and 2035. Specific steps include:

1) Raising energy-efficiency standards for new buildings and retrofitting of existing buildings.

2) Replacing individual oil and gas-fired heating boilers with district heating systems. In areas unsuitable for district heating, stand-alone electric heat pumps will be used. It is expected that by 2035 all buildings will be heated by non-fossil fuels.

3) Optimising district heating sources and operations by using industrial waste heat, biomass, and combustible waste to replace fossil fuels. Inefficient CHP units will be replaced with heat pumps, and natural gas will be replaced with biomethane to supply peak demand, and sector coupling realised through heat storages. By 2028-2035 it is expected that natural gas-fired cogeneration plants will be 100% converted to biomethane.

4) Using heat pumps to fully utilise waste heat from infrastructure such as wastewater treatment plants, data centres, power substations, gas compressors, and underground systems.

5) Further improve incentive mechanisms such as taxes, prices, subsidies, and carbon trading to promote low-carbon transition of heat supply.

6) Focus on the training of technicians and managers related to the district heating industry.

United States

Current status of heat supply

In the United States, heating energy consumption accounts for about one-third of commercial building energy consumption and about 40%, or more, of residential building energy consumption. Influenced by climate and other factors, building heating energy consumption varies greatly from state to state. Building heating in the United States is dominated by decentralised methods, such as home boilers and heat pumps, which are used as heating equipment in 73% of American homes. District heating is more common in densely populated urban areas such as New York and Boston. For example, the New York City district heating system operated by Con Edison is the largest in the United States, providing steam to about 1,500 buildings in Manhattan, covering 10% of the city's large buildings.

Historical review of the transition

Building heating in the United States has undergone several major changes. In the early 20th century, coal was the primary fuel used to heat residential and commercial buildings. Coal stoves were common at the time, though they caused significant pollution. By the mid-20th century, there was a gradual shift away from coal to cleaner, more efficient, and easier-to-use natural gas. By the 1970s, natural gas had largely replaced coal. At the end of the 20th century and the beginning of the current century, with the development of heat pump technology, the rising price of natural gas, and a consensus on the need to combat climate change, natural gas heating began a gradual shift to electricity. While natural gas heating is still prevalent in many areas, with only 13% of households using heat pumps to heat their homes, heat pump usage is climbing rapidly, with heat pump sales up 15% year-on-year in 2020.

Policy mechanisms for heat transition

Building heating policies in the United States are largely set by states and municipalities on their own, with the federal government having an oversight function but limited authority. The policy orientation varies from state to state, with California, New York and a number of other states developing policies to promote the transition of heating systems to electric heat pumps. This while states with abundant natural gas resources, such as Texas and Pennsylvania, have reservations about the heating transition.

There are three broad categories of policies related to building heating in the United States. The first is building standards and permits. States and municipalities are increasingly adopting stringent building standards, including phasing out fossil fuels in new construction and using high-efficiency heating systems, such as heat pumps. Net-zero energy building standards are being pursued in states such as California and New York. The second category is financial incentives. The federal government has introduced several financial incentives, such as the "Inflation Reduction Act" of 2022, which provides substantial tax credits and rebates for the installation of heat pumps and other energy-efficient appliances. In addition, low-interest loans are available to homeowners and businesses for taking energy-efficiency improvement measures. The third policy category is the "Energy Star" programme. Established by the Environmental Protection Agency, this programme promotes energy-efficient products and practices. Over the years, the programme has significantly increased the market penetration of energy-efficient technologies. Efficient heating products, including heat pumps that meet Energy Star standards, are widely adopted.

Future heating transition roadmap

Looking at the latest policies, there are two key areas to advance the low-carbon transition in building heating in the United States.

On the one hand, there is a push to implement more stringent building energy efficiency standards. In 2022, the Biden Administration issued the "Federal Building Performance Standards", which require federal agencies to reduce building energy use by 30% by 2030 and electrify equipment and appliances. In June 2024, the U.S. Department of Energy clarified the definition of net-zero buildings, setting minimum energy-efficiency standards at the federal level, including the adoption of advanced energy-efficient technologies. "Energy Star" and other standards were set as minimum requirements. The initiative aims to standardise the definition and practice of net-zero buildings across states and facilitate the promotion of net-zero buildings.

On the other hand, the U.S. is actively promoting high-efficiency, low-carbon heating, such as heat pumps. The recent building standards include support for building electrification and will expand financial incentives for efficient heating systems. Federal and state incentives will drive the transition from fossil to electric heat pumps for building heating. For example, the U.S. Climate Alliance has committed to deploying 20 million heat pumps by 2030. In addition, states such as California and Massachusetts are actively promoting technological innovations, such as exploring the integration of smart grid technologies and demand response management to improve the efficiency and reliability of electric heating systems.

Implications for China

The practices of Denmark and the United States in promoting the low-carbon transition of building heating offer valuable lessons.

Improve national heating regulations

The Danish "Heating Act" provides a clear legal framework for the construction of district heating systems in accordance with optimal economic and social benefits. It provides an all-round basis for heat planning and industry regulation. China can learn from this successful experience to improve national-level heat supply regulations. This would provide a stronger legal basis for heat supply industry management and provide better legal support for the implementation of provincial heat supply management regulations and local heating plans.

Sound incentive policies for low-carbon heat supply

Denmark and the United States have focused on using diverse economic incentive policies, such as financial, tax, and pricing measures, to promote the low-carbon transition of heating. China has mainly used financial subsidies and has also introduced some local price incentive policies but has relatively few tax policies. In the future, China may consider promoting the development of low-carbon heat sources through mechanisms such as heating fuel taxes and carbon taxes.

Promote low-carbon heating transition based on national conditions

Both Denmark and the United States have fully considered the resource endowment and economy in the selection of low-carbon heating paths. The United States allows states to have different path orientations and transition paces. China's different climate zones, different types of buildings should also be combined with climate characteristics, resource endowment, energy characteristics, economic conditions, etc. This approach will help design differentiated transition paths, the development of diversified low-carbon heat sources and low-carbon heating methods, promoting the gradual phase-down of fossil fuel heating.

Vigorously develop heat pump and heat storage technologies

Denmark and the United States both consider heat pumps as an important technology for the low-carbon heating transition. China's clean heating efforts in recent years have also promoted the large-scale promotion and application of heat pump technology. This can be further strengthened in the future to enhance technological innovation, research and development, expand the scope of application, and enrich the market application scenarios. Denmark's district heating systems generally include heat storage facilities. Denmark is also committed to researching long-cycle heat storage technology, such as cross-seasonal heat storage. For China to fully utilise all kinds of waste heat and renewable resources in the future, heat storage facilities are essential. China should actively prepare the relevant technologies.

Continuously advancing building energy-efficiency

Both Denmark and the United States attach great importance to reducing building heating demand at source by improving building energy efficiency. The United States is actively promoting the construction of near-zero energy buildings. For a long time, China has also been focusing on improving the level of energy efficiency in buildings and continuously improving energy-saving standards and energy-saving retrofitting. China has a vast building stock, of which about one-third of urban buildings are still not energy-efficient and there would be a large demand for new buildings in the future. To avoid the lock-in of high energy consumption for heating, it is necessary to both increase energy-saving retrofitting of existing buildings and accelerate the large-scale development of ultra-low-energy and near-zero energy buildings.

11.4 Pathways and prospects for low-carbon transition of China's building heating

By accelerating the proportion of energy-efficient buildings and vigorously optimising the heat source structure, China's building heating end-use energy demand is expected to decrease significantly. The heat sources will mainly be various types of waste heat.

Transformation pathways

China's practice of promoting energy saving and carbon reduction in the field of building heat supply over the years has laid a good foundation for further low-carbon and zero-carbon transformation of heat supply in the future. International practices of promoting low-carbon transitions of building heat supply have also provided useful reference for China. Combining China's situation and international experience, this study concludes that the core path for low-carbon heating is still to reduce heat demand and optimise the heat source structure. At the same time, it is necessary to design differentiated pathways for different regions and building types, and to improve the supporting policy system.

Multiple measures to reduce building heating demand

Building heating demand can be further reduced by upgrading the thermal performance of the building envelope and applying passive technologies. Different measures are needed for urban, rural, new buildings, and existing buildings.

Accelerating the promotion of ultra-low/near-zero energy buildings

Ultra-low-energy buildings can save more than 50% energy than buildings that meet the 65% energy-saving standard. Near-zero energy buildings can save 60% to 75% more energy compared to the same standard. Therefore, promoting the large-scale development of ultra-low-energy/near-zero energy buildings would help to further reduce building heating demand. It is recommended that the relevant departments should develop a top-level design for the large-scale development of ultra-low/near-zero energy consumption buildings. They should set clear medium- and long-term development goals, considering the level of economic development, technology and industrial base of different regions. They should formulate a step-by-step and region-by-region plan for promoting the development of ultra-low/near-zero energy consumption buildings. Government-invested public buildings should take the lead in building according to ultra-low/near-zero energy building standards. At the same time, it is recommended to strengthen technology research and development and industry cultivation. Applicable technology systems should be proposed for different regions and building types. Focus should be on promoting the development of key components and equipment such as domestically produced high-performance windows and doors, sunshade systems, heat preservation materials, and high-efficiency fresh air heat-recovery equipment, to accelerate the reduction of incremental costs. In addition, it is recommended to actively promote green and low-carbon construction, explore the use of prefabricated methods to build ultra-low/near-zero energy buildings and strengthen the application of green building materials in them.

Increase energy-saving retrofitting of existing buildings

Relevant practices shown that, under the premise of technical and economic feasibility, energy-saving retrofits can achieve over 20% energy savings. There are still many non-energy-efficient buildings in China. Energy-saving retrofits should be further intensified to uncover more energy-saving potential. It is recommended to conduct a comprehensive mapping survey of existing urban buildings and establish a retrofit database based on energy-efficiency diagnostics. Cities should set clear targets and progress arrangements for the retrofitting of existing buildings. Energy-saving retrofits should be integrated with urban renewal, transformation of old districts, large-scale equipment updates, and clean heating initiatives, etc. Innovative business operation models should be explored to attract social funds for retrofitting existing buildings. For different regions and building types of differentiation in the focus of the retrofits is required. To reduce heating energy consumption, buildings in frigid and cold regions should focus to the external wall insulation, windows and doors upgrades, heating pipe network insulation, and intelligent control retrofits. Buildings in hot summer and cold winter regions should consider the needs for winter insulation and transitional season cooling, focusing on improving the thermal insulation performance of the building envelope and improve the winter windows and doors airtightness. Public buildings should focus on the energy-saving operation of central air-conditioning systems and intelligent retrofits. Rural areas can promote micro retrofits of walls, doors, windows, roofs, floors and other structures on a voluntary and affordable basis or adopt passive energy-saving technologies, such as adding sunrooms.

Optimise the structure of heat sources according to local conditions

Increasing the proportion of low-carbon heat supply methods is key to decarbonising building heat supply. In the future, there is a need to adopt differentiated low-carbon heat source substitution programmes based on regions and building types.

Ultra-low/near-zero energy buildings: According to the building standards, the heating demand of new ultra-low/near-zero energy buildings is very low, and it is recommended that priority be given to the use of electric heat pumps for heat supply. New residential buildings should use individual heating. New public buildings should give priority to the use of centralised or decentralised heating, to avoid distribution losses from central heating, considering the functions and appearance of new public buildings.

Buildings in cities and towns in the northern region: Buildings which are not in the ultra-low/near-zero energy building categories have a high energy demand per unit area. It is recommended to continue to extend the use of centralised district heating, make use of the existing centralised district heating pipeline network resources, and make efforts to optimise the heat source structure. Waste heat from thermal power, nuclear power, industry (iron and steel, building materials, non-ferrous metals, chemical industry, etc.), data centres, sewage, etc should be utilized. It is recommended to develop biomass boilers, promote heat storage technology, and gradually replace the existing coal-fired and gas-fired heat sources (including peak heat sources). This, while optimising and upgrading of heat supply infrastructure, and vigorously develop intelligent heat supply. In areas with low building density or remote areas that difficult to connect to the centralised heating networks, priority is given to the promotion of air-source and ground-source heat pumps, medium- and deep-level geothermal heat, and solar heating.

Buildings in cities and towns in hot summer and cold winter areas: it is not appropriate to adopt district heating on a large scale. Residential buildings may use air-source heat pumps for individual heating and gradually replace gas with electricity. Public buildings may use heat pumps for centralised heat supply in buildings. The heat source should be chosen based on local conditions and cost-effectiveness. Options include the air-source, water source (groundwater, river water, wastewater, etc.), and ground source. When there is sufficient and convenient waste heat or renewable energy in the neighbourhood, centralised heat supply can also be considered. It is necessary to ensure that the end-use do not make rely on fossil energy.

Rural buildings: It is recommended that clean heating should continue to be promoted in northern farmhouses. Energy-saving renovation of farmhouses should be promoted simultaneously on the premise of technical and economic feasibility. Renewable energy building applications such as photovoltaic and solar thermal should be fully developed. In cold regions, use of air-source heat pumps would be prioritised for individual heating. In extremely cold areas where heat pumps currently are unsuitable, electric boilers, electric heaters, biomass stoves and other heating methods can be considered. It is recommended that air-source heat pumps are used for individual heating of farm buildings in hot summer and cold winter areas, gradually replacing the use of loose coal, and simultaneously promoting the construction and renovation of green farm buildings.

Sound safeguard mechanisms

To ensure an effective transition, it is necessary to improve the protection mechanism in terms of technology research and development, regulations and systems, and incentive policies.

In terms of technology, it is proposed to strengthen the research and development, demonstration and promotion of key technologies for low-carbon heat supply, such as heat pumps, waste heat recovery, long-distance heat transmission, cross-seasonal heat storage and intelligent heat supply. Establish necessary technology research tasks in key science and technology research and development special projects and increase financial support. Encourage collaborative innovation among industries, universities and research institutes, and promote the synergistic development of scientific and technological research and development, results transformation and industrial cultivation. Accelerate the construction of pilot demonstration projects for long-distance heat transmission and cross-seasonal heat storage and further demonstrate the technical and economic feasibility. Promote the application of relevant technologies in mature areas.

In laws and regulations, the regulations on heat supply management should be enhanced. The formulation of national-level heat supply laws and regulations would provide stronger safeguards when implementing national energy policies in the heating sector and provide better support for provincial-level heat supply management regulations and their implementation. Accelerating the promotion of heat metering and charging, implementing a two-part heat pricing system that combines the basic heat price and the metered heat price, and reasonably determining the proportion of the basic heat price and the end-use price of heat supply.

Regarding incentive mechanisms, improve financial, tax, price, financial and other economic incentive policies that are conducive to low-carbon heat supply. This should be combined with the air pollution prevention and control, clean heating, large-scale equipment renewal and other work. Increase financial funds to support the application of low-carbon heating technology such as building energy-saving renovation, waste heat heating, heat pump heating, and intelligent heating, and set up special funds when necessary. Implement tax incentives related to building energy efficiency and guide more enterprises in product and equipment manufacturing and energy-saving services to join the low-carbon heating transition. Improve price policies such as time-sharing tariffs and residential ladder tariffs to incentivise property owners and residents to choose low-carbon heating methods. Encourage banks, insurance and other financial institutions to combine the characteristics of low-carbon heating projects and innovate green financial products and services. Explore and study administrative incentives favourable to low-carbon heat supply transformation, such as floor area incentives and simplified approval process.

Introduction to analytical methods

In this study, the LEAP model was used for a scenario analysis of China's future end-use energy demand in the building sector through a bottom-up approach. This includes an analysis of end-use energy demand for building heating.

Heating energy consumption is affected by a variety of factors such as building functions, climatic conditions, thermal performance, and heating methods, the model is divided into four levels to consider the effects these factors. The levels are:

1) The model divides buildings into three categories: urban residential buildings, rural residential buildings, and public buildings
2) Bach category of buildings is divided into three climatic zones: northern region, transitional region (i.e., hot-summer and cold-winter region), and southern region
3) Buildings in each region are classified by energy-saving building standards into; non-energy-efficient buildings (not implementing any energy efficiency standards), energy-efficient buildings (including all buildings implementing energy efficiency standards up to the ultra-low-energy building standards), ultra-low-energy buildings, and near-zero-energy buildings.
4) Buildings with different functions, different regions, and different thermal properties are further subdivided according to the specific heat supply methods used.

In the model, parameters such as the total area of the three categories of buildings, the proportion of building area in different climatic zones, the distribution of buildings with different energy-saving levels, the demand for useful energy for heat supply, and the proportion of heat supply modes (technology distribution) are set. The total area of the three categories of buildings is set according to current and projected population and per capita building area. The proportion of building area in different climatic zones is current and projected population distribution. Useful energy demand for heat supply is a heat load indicator, i.e., heat demand per unit of building area (not equivalent to the consumption of energy for heat supply), and is mainly based on the current energy-saving design standards for each region and building type. Future projections mainly consider the changes in heating quality demand for residential and public buildings. The distribution of buildings with different energy-saving levels is based on the past implementation of building energy-saving standards and future promotion. This is determined using a stock analysis model. The distribution of heat supply technologies is based on existing research results and the transition pathways.

Considering the limited space of the report, this chapter will focus on two core parameters, namely the distribution of buildings with different energy efficiency levels and the distribution of heating technologies. It will show the results of the scenario analyses based on these settings. However, due to the limitations of knowledge and time, as well as the influence of continuous changes in technology and policies, there are inevitably inaccuracies in the setting of many parameters of the model, which may affect the results of the scenario analyses. The research team would continue to conduct relevant research and update the settings, results and conclusions in subsequent reports.

Key assumptions

This study sets up the distribution of buildings with different levels of energy efficiency and the distribution of heat supply technologies according to the transition pathway. Overall, the proportion of high-level energy-efficient buildings such as ultra-low-energy and near-zero energy will increase significantly in the future. Low-carbon and zero-carbon heat sources such as waste heat, renewable energy heat production and electricity will become dominant.

Significant increase in ultra-low-energy and near-zero energy buildings

Currently, the proportion of energy-efficient buildings and ultra-low/near-zero energy buildings vary by region and building type. Since China's building energy efficiency work began with urban residential buildings in northern regions, the proportion of non-energy-efficient buildings in this category is the lowest. This is followed by urban residential buildings and public buildings in hot summer and cold winter regions. Rural buildings have the highest proportion. Considering the relatively good foundation of energy efficiency in urban residential buildings in the northern regions, the promotion of ultra-low/near-zero energy buildings and the energy-saving renovation of existing buildings will be stronger and faster. By 2060, the proportion of ultra-low/near-zero energy buildings will be correspondingly higher.

In the future, China will continue to raise the energy-saving standard requirements for new buildings, accelerate the large-scale development of ultra-low/near-zero energy buildings, continue to carry out energy-saving renovation of existing buildings, and intensify the construction of green farm buildings. The proportion of non-energy-saving buildings in all regions and all types of buildings will continue to decline.

In BCNS, it is considered that new residential buildings in cities and towns in the northern region, new residential buildings in cities and towns in other regions, and new public buildings will fully implement the ultra-low-energy building standards in 2030, 2045 and 2040 respectively, and the near-zero energy building standards will be fully implemented in 2045, 2055 and 2050 respectively. In ICNS, due to smoother international cooperation and technology sharing after 2030, the promotion of ultra-low and near-zero energy buildings will be stronger, and the standards will be implemented five years earlier than that in BCNS.

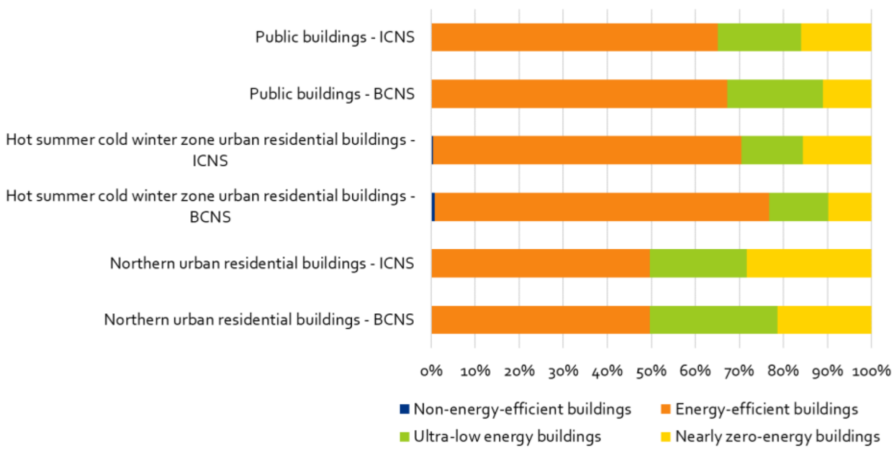
In BCNS, energy-saving renovations of existing buildings will continue, prioritising non-energy-saving buildings, followed by low-level energy-saving buildings, aiming to meet the current energy-saving standards after renovation. In ICNS, with lower cost of the technology compared with the BCNS, the promotion of energy-saving retrofit is stronger, with a higher cumulative renovation area. After 2030, the energy-saving retrofit rate in each FYP period will be at least five percentage points higher compared to the BCNS.

In BCNS, new buildings in rural areas are gradually constructed in accordance with energy-saving standards, and the development of near-zero energy buildings starts vigorously after 2040, with a gradual increase in the proportion of buildings. In ICNS, the promotion of energy-saving and near-zero energy buildings in rural areas is stronger, and the development of near-zero energy buildings starts to accelerate after 2035.

Overall, in both two scenarios, the proportion of non-energy-efficient buildings in urban and rural residential and public buildings in each region continues to decline and the proportion of near-zero energy buildings continues to increase. The proportion of energy-efficient buildings and ultra-low-energy buildings increases and then decreases. In 2060, the proportion of non-energy-efficient buildings in ICNS is lower than that in BCNS, and the proportion of near-zero energy buildings is higher.

Specifically, by 2060, the proportion of ultra-low-energy and near-zero energy buildings in **residential buildings in cities and towns in the northern region** in BCNS rises to 28.9% and 21.4%, respectively. In ICNS they reach 22.0% and 28.4%, respectively. The proportion of ultra-low-energy and near-zero energy **buildings in residential buildings in cities and towns in the hot-summer and cold-winter regions** in BCNS rises to 13.5% and 9.8%, respectively. In ICNS, these proportions will be 13.9% and 15.6%, respectively. The proportion of ultra-low-energy and near-zero energy buildings in **public buildings i**ncrease to 21.8% and 11.0%, respectively. In ICNS, these proportions will be 18.9% and 16.0%, respectively. In BCNS, the proportion of ultra-low energy and near-zero energy buildings in rural residential areas in the northern region will increase to 20%. In ICNS, this proportion will rise to 25%. The proportion of ultra-low-energy and near-zero energy **buildings in rural residential buildings in hot-summer and cold-winter regions** increases to 10% in BCNS and 15% in ICNS (as shown in Figure 11-7).

Figure 11-7 Distribution of buildings with different energy efficiency ratings by region and building type in urban area under two scenarios in 2060

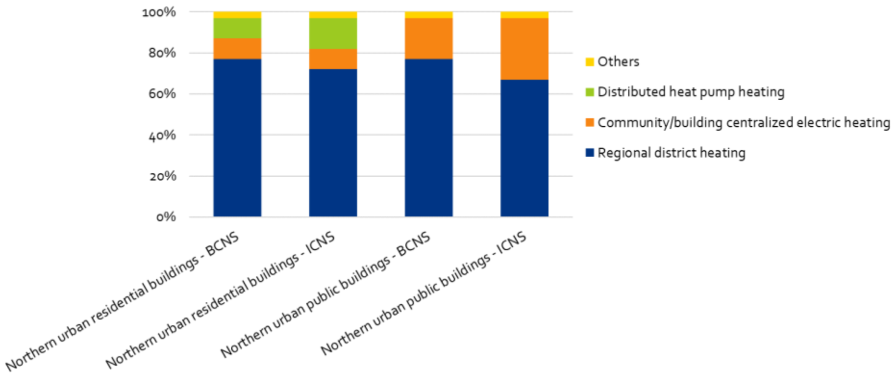


Continuous optimisation of the heat source structure

In accordance with the aforementioned low-carbon heat source alternatives, this study provides an outlook on the distribution of heat supply technologies in each region and building type. For ultra-low/near-zero energy buildings, heat pumps are considered for individual heat supply. For non-ultra-low/near-zero energy buildings, low-carbon heat source alternatives are identified based on climate and functional characteristics. Generally, for urban buildings in the northern region, with high energy demand per unit area, buildings are mainly supplied with centralised district heating system. Various types of waste heat resources and renewable energy power heating are used as the most important heat sources. Other regions and building types prioritise heat pumps for heat supply, and individual heat supply is adopted as far as possible. The details are as follows:

For urban buildings in the northern region, including residential buildings and public buildings, coal-fired and gas-fired boilers used on a community/building scale would be phased out and replaced by municipal district heating networks. In areas not covered by the district heating network, priority would be given to individual heat pumps and community/building heat pump systems for centralised heat supply. In areas where heat pumps are not suitable, electric boilers, biomass boilers and other renewable energy sources can also be considered. By 2030, coal-fired boilers in communities/buildings would be completely phased-out from the heat supply, and by 2040, gas-fired boilers in communities/buildings would be completely phased-out. At the same time, the heat source of the municipal district heating network accelerates the low-carbon transition, replacing fossil energy for heat supply by integrating various types of waste heat from power plants, industries, data centres, etc. Any deficit will primarily be met by heat pumps driven by renewable electricity, supplemented by biomass boilers and heat storage to meet peak heating demands. Considering that the transmission and distribution losses of centralised district heating are higher than those of district/building centralised heating and individual heating, and the overall energy efficiency is lower than that of heat pumps, the proportion of centralised district heating in ICNS is lower than that in BCNS. In BCNS and ICNS, the proportion of municipal district heating in urban residential buildings in the northern region will reach 77% and 72%, respectively. In urban public buildings in the northern region, the proportion of municipal district heating reaches 77% and 67%, respectively (as shown in Figure 11-8).

Figure 11-8 Distribution of urban building heating technologies in the northern region under the two scenarios in 2060



Note: Other includes biomass boilers, electric boilers and other renewable energy heating methods.

Buildings in cities and towns in hot-summer and cold-winter areas: residential buildings will gradually replace other heating methods with individual air-source heat pumps. Public buildings will completely phase out coal-fired boilers for heating by 2030 and gas-fired boilers for heating by 2040. Various types of heat pump systems or centralised heating will be used instead, depending on actual demand and local conditions. In some communities or commercial areas with abundant and convenient waste heat or renewable resources, centralised heating can be used under the premise of being efficient, low-carbon, and cost-efficient, and no direct use of fossil energy, but with a very low proportion. By 2060, in both scenarios, the proportion of individual heat pumps in urban residential buildings in regions with hot summers and cold winters will reach 95%. In public buildings in these regions, centralised and individual heat pump heating will each be 50%.

Rural buildings: air-source heat pumps are gradually being used for individual heating to replace small coal stoves, wall-mounted gas stoves, and direct electric heating such as electric boilers and heaters. In areas where climate conditions are not suitable for heat pumps, biomass stoves, direct electric heating and other heating methods can be considered. By 2040, small coal stoves will be completely phased out for heat supply, and by 2060, in BCNS and ICNS, the proportion of heat pumps for decentralised heat supply in rural residential buildings in the northern regions will reach 65% and 85%, respectively. The proportion of heat pumps for individual heat supply in rural residential buildings in regions with hot summers and cold winters will reach 75% and 100%, respectively.

Outlook

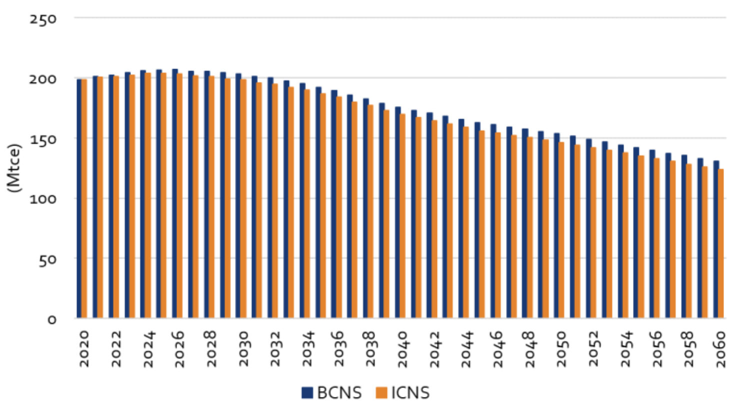
Based on the above pathways and parameters, this study provides an outlook for future building heating energy demand in China. The results show that China's building heating end-use energy demand in 2060 will be significantly lower than the current level and is expected to achieve zero carbonisation of heat sources.

Significant decline in end-use energy demand for heat supply

According to the energy consumption measurements in this study (considering industrial waste heat and rural biomass energy consumption), China's building heating end-use energy demand will decline significantly in the future. Different regions and building types show different trends in heating end-use energy demand changes. Overall, in ICNS, the low-carbon transformation of heat supply is faster and the decline in heating end-use energy demand is more significant.

In the northern region, urban building heating end-use energy demand will increase only slightly in the near term and decrease significantly in the long term. In 2020, urban building heating end-use energy consumption in the northern region of China was about 198 Mtce. With the growth of building area, the urban building end-use energy demand for heating in the northern region will rise slightly. Both scenarios reach peak heating demand before 2030. The peaks are about 207 Mtce in BCNS and 204 Mtce in ICNS. Subsequently, with the increase in the proportion of efficient low-carbon heating technologies, the end-use energy demand for heating in urban buildings in the northern region will decline rapidly, reaching 131 Mtce and 127 Mtce by 2060, a decrease of 34% and 38% compared to 2020, respectively (as shown in Figure 11-9).

Figure 11-9 End-use energy demand for heating in urban buildings in the northern region under two scenarios



The end-use energy demand for building heating in the hot summer and cold winter regions will first increase and then decrease, with a gentle rise and fall. In 2020, China's end-use energy consumption for building heating in the hot summer and cold winter regions was about 250 Mtce. Along with the continuous growth of building area, the end-use energy demand for building heating in this region will increase. Both scenarios would peak around 2035, with about 270 Mtce in BCNS and 260 Mtce in ICNS. Along with further improvement of the proportion of high-efficiency and low-carbon heating technologies, the end-use energy demand for building heating in cities and towns in the summer-heat-winter-cold region will steadily decline. By 2060, it will decrease to 220 Mtce in BCNS and 210 Mtce in ICNS, a decrease of 10% and 13%, respectively, compared to 2020.

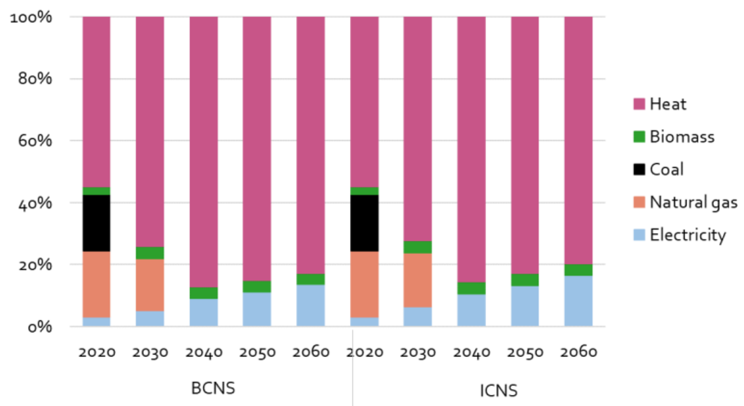
Rural residential building heating end-use energy demand continues to decline rapidly[3]. In 2020, China's rural building heating end-use energy consumption was about 160 Mtce, of which the northern region accounted for more than 80%. As the area of rural residential buildings continues to decrease and the proportion of efficient heat sources increases, the end-use energy demand for heating in rural residential buildings will continue to decline in both scenarios. By 2060, it will decrease to 18 Mtce in BCNS and 11 Mtce in ICNS, which is only 11% and 7%, respectively, of the 2020 levels.

Progressive zero-carbonisation of heating energy use

Zero-carbonisation of end-use energy for building heating is gradually being achieved as direct end-use fossil energy heating is phased out.

The end-use energy demand for heat in urban buildings in the northern region will be dominated by zero-carbon heat. In the two scenarios, the direct use of fossil energy in the end-use energy demand for urban building heating in the northern region gradually decreases. Coal would be completely phased out in 2030 and natural gas in 2040. The share of electricity demand continues to grow, reaching 14% in BCNS and 17% in ICNS by 2060. The share of heat demand for centralised district heating increases and then decreases, reaching 83% in BCNS and 80% in ICNS (as shown in Figure 11-10).

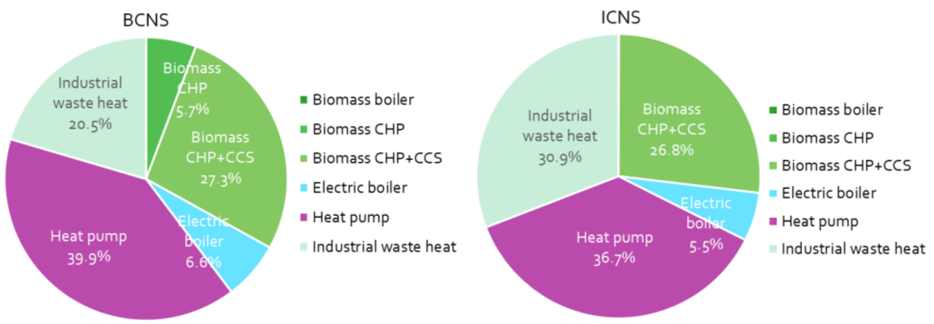
Figure 11-10 Structure of end-use energy demand for heat supply in urban buildings in the northern region under the two scenarios



[3] Including non-commercialised biomass energy consumption.

At the same time, heat production for centralised district heating is gradually becoming zero-carbon. The proportion of coal-fired, gas-fired cogeneration and boiler heat supply is gradually declining, and coal-fired heat production would be completely phased-out in 2050. The proportion of low-carbon, zero-carbon and carbon-negative heat sources, such as industrial waste heat, heat pumps, and biomass CHP with CCS, is gradually increasing. In 2060, in BCNS and ICNS, the proportions of industrial waste heat to the total heat production will be 20.5% and 30.9%, respectively. The proportions of heat production by heat pumps to the total heat production will be 39.9% and 36.7%, respectively (as shown in Figure 11-11).

Figure 11-11 Structure of heat sources for building heat production in 2060 under the two scenarios



The end-use energy demand for heating in urban buildings in hot-summer and cold-winter areas will be fully electrified. The direct use of fossil energy gradually decreases, and the proportion of electricity demand continues to increase. The direct use of coal for end-use energy demand will be completely phased-out by 2040 in BCNS and by 2035 in ICNS. The direct use of natural gas for end-use energy demand will be completely phased-out by 2055 in BCNS and by 2050 in ICNS. The end-use energy demand for heating will be fully electrified in 2055 and 2050, respectively.

The share of electricity in the end-use energy demand for building heating in rural areas will increase significantly. The share of fossil energy in the end-use energy demand for building heating in rural areas continues to decline. Coal will be phased-out by 2040 in BCNS and by 2035 in ICNS. By 2060, the share of electricity reaches 40% and 78%, respectively, with biomass energy accounting for the rest.

12 Digital and intelligent development

Building a digital China is an important driver for advancing Chinese-style modernisation in the digital age. In recent years, the world has entered the age of the digital economy, where the deep integration of digital technology and the real economy has become essential for industrial transformation, modernisation, and high-quality economic development. Currently, 'green' and 'intelligent' are key trends in energy transformation. Improving the level of digitisation and intelligence of the energy system not only aligns with the global shift towards a digital economy but is also essential for creating a new type of energy and power system.

The digital and intelligent development of China focuses on the power sector. China has actively promoted the digital and intelligent transformation of the energy sector, gaining experience in policy formulation, infrastructure development, business model exploration, and standardisation. Typical cases of digital and intelligent transformation of China's power system are showcased across four key aspects: generation, grid, consumption, and system operation.

However, China still faces five challenges in the digitalisation and intelligent development of the energy sector: lagging standardisation, limitations in business models, increasing information security risks, unclear data ownership, and insufficient computational power. Looking ahead, key technologies such as big data, cloud computing, artificial intelligence, blockchain, and digital twins will play a more significant role in advancing digitisation and intelligence in the energy sector. Further efforts are needed to enhance the policy framework, upgrade infrastructure, improve the standards system and cultivate innovative business models.

13 Technological assessment

An analysis of commonly used terms over the past decade shows how China's energy transformation and carbon reduction policies have gradually shifted. Initially, the focus was on new energy vehicles, energy saving and emission reduction actions, wind power development and feed-in tariffs, and air pollution prevention and control. Now, the focus includes key areas such as electric power market reforms, new energy market-based mechanisms, comprehensive air pollution prevention and control, energy intelligence and reserves, green and low-carbon energy transformation institutions, synergistic development of pollution and carbon reduction, as well as energy saving and efficiency. This shift highlights China's increasing emphasis on the synergy between energy saving, pollution reduction, and carbon reduction, prioritising the coordinated development of multiple energy sources, industries, and levels.

The analysis shows that China's energy transformation measures have significant benefits in terms of pollution and carbon emissions reduction. Compared to 2012, the reduction in fossil energy consumption in 2022 contributed to theoretical reductions of 53.6% in sulphur dioxide, 30.6% in nitrogen oxides, 9.3% in particulate matter, and 95.6% in carbon dioxide. In the future, with the substitution of non-fossil energy sources for fossil energy consumption such as coal, oil and natural gas, China's energy transformation will make an important contribution to the coordinated pollution and carbon dioxide reductions.

At the technological level, the ecological impacts of key energy transformation technologies are evaluated using the "footprint" concept, focusing mainly on water and carbon footprints. The analysis highlights that wind, solar PV and geothermal power have the lowest carbon/water footprints and the best overall environmental benefits. Hydropower, while having a small carbon footprint, has the highest water footprint among all studied power sources. Green hydrogen shows significant water and carbon-saving benefits compared to grey hydrogen. The carbon and water footprints of biomass utilisation in China are comparable to those of fossil energy, providing average environmental benefits. Lastly, CCUS offer significant carbon reduction benefits but also increase water consumption.

14 Regional transformation

Shanxi and Yunnan provinces are characteristically energy resource-rich provinces in China. Shanxi, located in northern China, has abundant coal resources. Yunnan, located in the southwest, is a less-developed province rich in hydropower and ecology and a favoured tourist destination. The energy transformation efforts in Yunnan and Shanxi serve as prime examples of the broader energy transformation in China's western regions.

Shanxi Province was designated as a "Comprehensive Energy Revolution Reform Pilot Zone" by the central government, making its energy transformation a valuable example for coal-rich northwestern regions exploring pathways for transformation. Over the past five years, Shanxi has improved its energy supply system, promoting clean and low-carbon energy consumption, advancing energy technology innovation, deepening reforms in the energy transformation framework, and expanding international energy cooperation. Shanxi has developed several examples of comprehensive energy bases, green and intelligent coal mining, and piloted electricity spot market reforms. The province has accumulated experience in balancing low-carbon energy transformation with supply security, promoting synergies between energy-saving, pollution reduction, and carbon reduction, and driving energy transformation through technological and institutional innovation.

In recent years, Yunnan's energy transformation efforts have focused on several key areas: Firstly, Yunnan has been rapidly advancing the construction of national clean energy bases, with large hydropower projects put into operation and wind and solar installations surpassing thermal power capacity. This leads to a steady increase in the province's capacity to transmit electricity from west to east. Secondly, Yunnan is actively developing a new power system by deepening energy system reforms, with the province taking a leading position in the latest round of electricity market reforms. The share of clean energy in the energy mix continues to rise, and the digitalisation and intelligence of the energy system have significantly improved. Thirdly, Yunnan is accelerating the energy revolution by fostering new green energy industries and leveraging green energy to cultivate advanced manufacturing. Fourthly, it constantly expands regional and international energy cooperation, particularly by fostering regional energy partnerships and mutual support with southern regions to promote clean energy development.

Yunnan still faces several challenges in its energy development and power supply. On the demand side, the rapid expansion of industrial activity is driving a surge in electricity demand. On the supply side, new energy projects are facing increasing constraints. Meanwhile, factors such as extreme weather, insufficient storage, and lack of capacity to meet peak loads in the power system pose challenges for supporting local industrial development and ensuring electricity transmission stability from west to east.

Thus, Yunnan must carefully balance the relationship between economic development, energy supply, and the ongoing energy transformation while further advancing its energy transformation efforts.

15 International cooperation

From an objective standpoint, the global urgency for energy transformation is increasingly pronounced. According to the 2024 Sustainable Development Financing Report released by the United Nations, about half of the 140 goals of the United Nations sustainable agenda have remained unmet. The progress of energy and climate-related goals is particularly lagging, highlighting the urgent need to strengthen international cooperation on the global energy transformation. The variation in energy transformation progress among different countries presents an opportunity for international cooperation on the energy transformation.

At the operational level, international cooperation to promote the global energy transformation faces four major challenges: first, the North-South divide in global climate governance is deepening, making it more difficult to form a global synergy for sustainable development. Second, South-South cooperation in the field of energy transformation faces multiple obstacles. Third, economic and trade frictions and geopolitical conflicts have heightened volatility in the energy market, raising the risk of international cooperation in energy transformation. Fourth, restructuring the global production and supply chain poses new challenges to international energy cooperation.

China has continued to deepen international cooperation on energy transformation in recent years, mainly in the following three areas. First, China has worked with major global economies and a vast number of developing countries to build high-level international cooperation platforms, foster closer energy partnerships, and advance the coordinated development of the global energy governance system. Second, China has focused on energy transformation within the Green Belt and Road Initiative framework and collaborated on constructing large-scale energy infrastructure, helping Belt and Road countries address challenges related to electricity access and affordability while contributing to local economic development and job creation. Third, China's rapid progress in new energy technologies and significant cost reductions will provide countries worldwide access to cutting-edge technology and equipment for energy transformation while sharing China's experiences in this area.

In the future, China will continue to promote international cooperation on energy transformation as a responsible great power. China will actively participate in international cooperation on energy governance and promote establishing a fair, equitable, balanced and inclusive global energy governance system. Committed to collaboration, China is dedicated to working with other countries to promote energy transformation and collectively address the challenges of global climate change.

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