China Energy Transformation Outlook

2024

Energy Research Institute of Chinese Academy of Macroeconomic Research

Executive Summary

Implementing Unit

Financial Support

Technical Support

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

Unless otherwise stated, 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
Remarks 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 sector. 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.

This *Executive 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.

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.

Lyu Wenbin

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Table of contents

Preface 1

Table of contents 3

The CETO 2024 team 5

Reading guide for China's Energy Transformation Outlook 2024 7

Key findings and recommendations of the scenario analysis 9

Research Background 9

Two scenarios for the energy transformation 9

Main findings 10

China energy flow charts 14

Part I: State of the energy transformation 17

Accelerating energy transformation is imperative as global climate change becomes increasingly severe 17

China continues to promote energy transformation 17

Part II: Pathways to net-zero emissions from China's energy system 19

Restructuring of primary energy and electricity demand 19

Energy transformation is a critical pillar in building China's carbon-neutral society 21

Electrification and energy efficiency are important ways for the end-use sector to move towards carbon neutrality 21

Achieving green power with wind and solar as the core 24

Building a flexible and secure new power system 27

Production-consumption simulation of new power systems 28

Energy transformation boosts the economy, society and jobs 30

Analysis of difficult challenges and uncertainties 32

Part III: Thematic analyses 35

New models of the new energy system 36

Building electricity markets adapted to a high proportion of renewable energy 37

Electrically produced synthetic fuels 37

Low-carbon transformation in the industrial sector 38

Low-carbon transformation in building heating 39

Digital and intelligent development of the energy sector 40

Synergistic impact of carbon and pollution reduction technologies in the energy sector 40

Energy transformation practices and achievements in typical provinces 41

International cooperation on energy transformation 42

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Reading guide for China's Energy Transformation Outlook 2024

The China Energy Transformation Outlook 2024 (CETO 2024) consists of a summary and three major sections and will be available on the programme website https://www.cet.energy.

The *Executive 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).

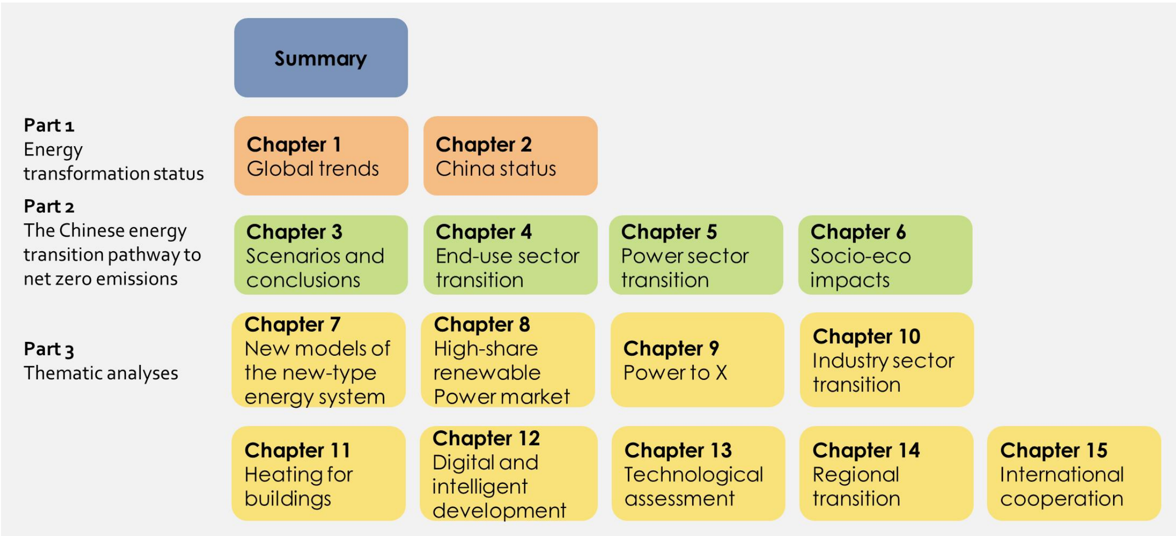
Part II presents scenario analyses of the outlook for China's energy system transformation up to 2060, with the goal of achieving carbon neutrality.[1] This section is divided into four chapters. Chapter 3 summarises the outlook for China's energy system transformation, including the scenario design 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 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.

[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.

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 trending topics, Part III offers standalone chapters that can be read individually.

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 and governments.

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 CETO 2024 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 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.

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 core is an necessary choice for energy transformation.

Decarbonising the energy supply is a lynchpin 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 central 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 wind and solar power 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. **Thirdly, the challenge of rapid power system transformation during rapid power demand 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, carbon-intensive energy products 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.

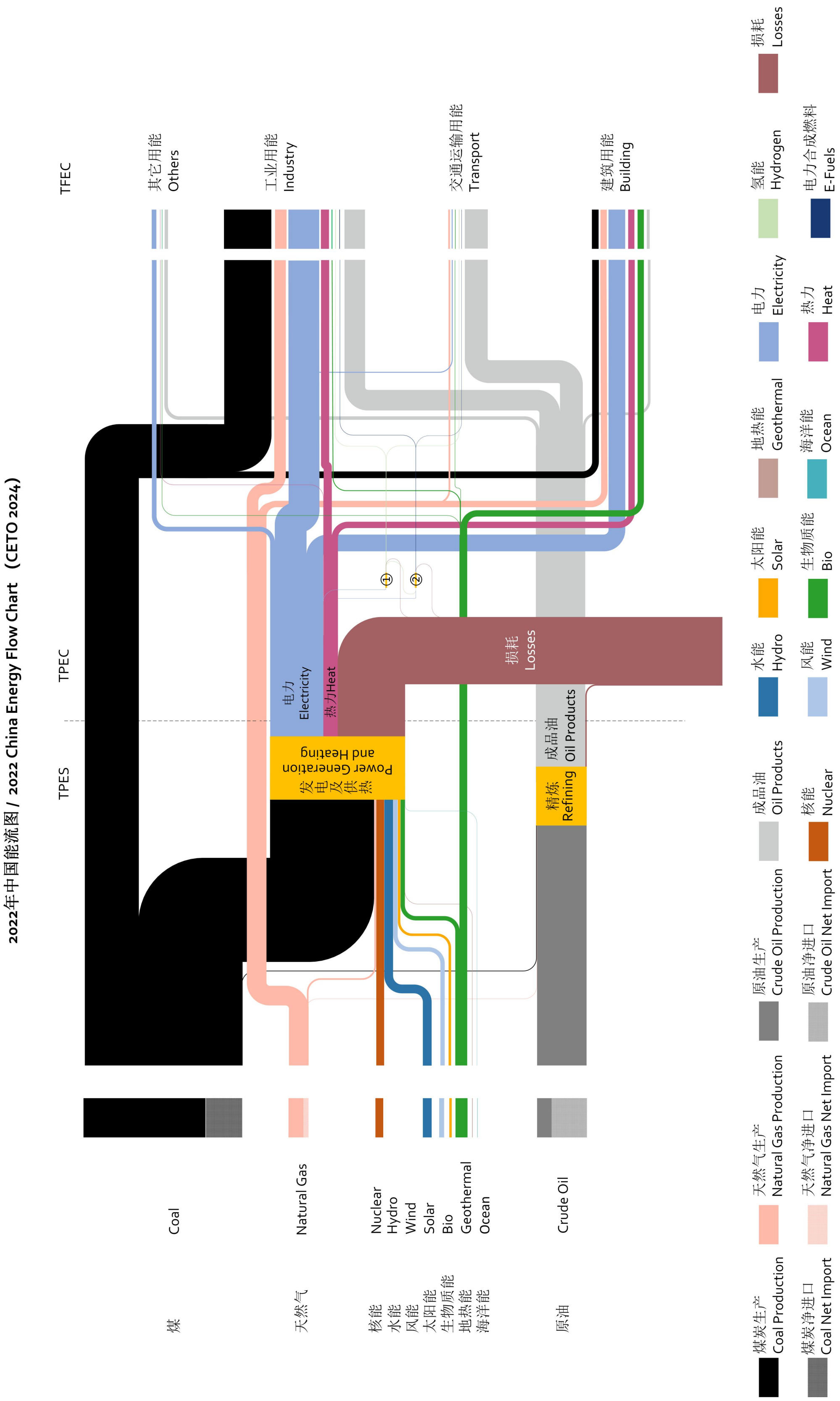
Looking ahead, there are uncertainties about China's low-carbon energy transformation. The main uncertainties are: Firstly, there is significant uncertainty around future adjustments to the industrial structure. Changes in the production of energy-intensive products such as steel, cement, electrolytic 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. 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 significantly to the global effort.

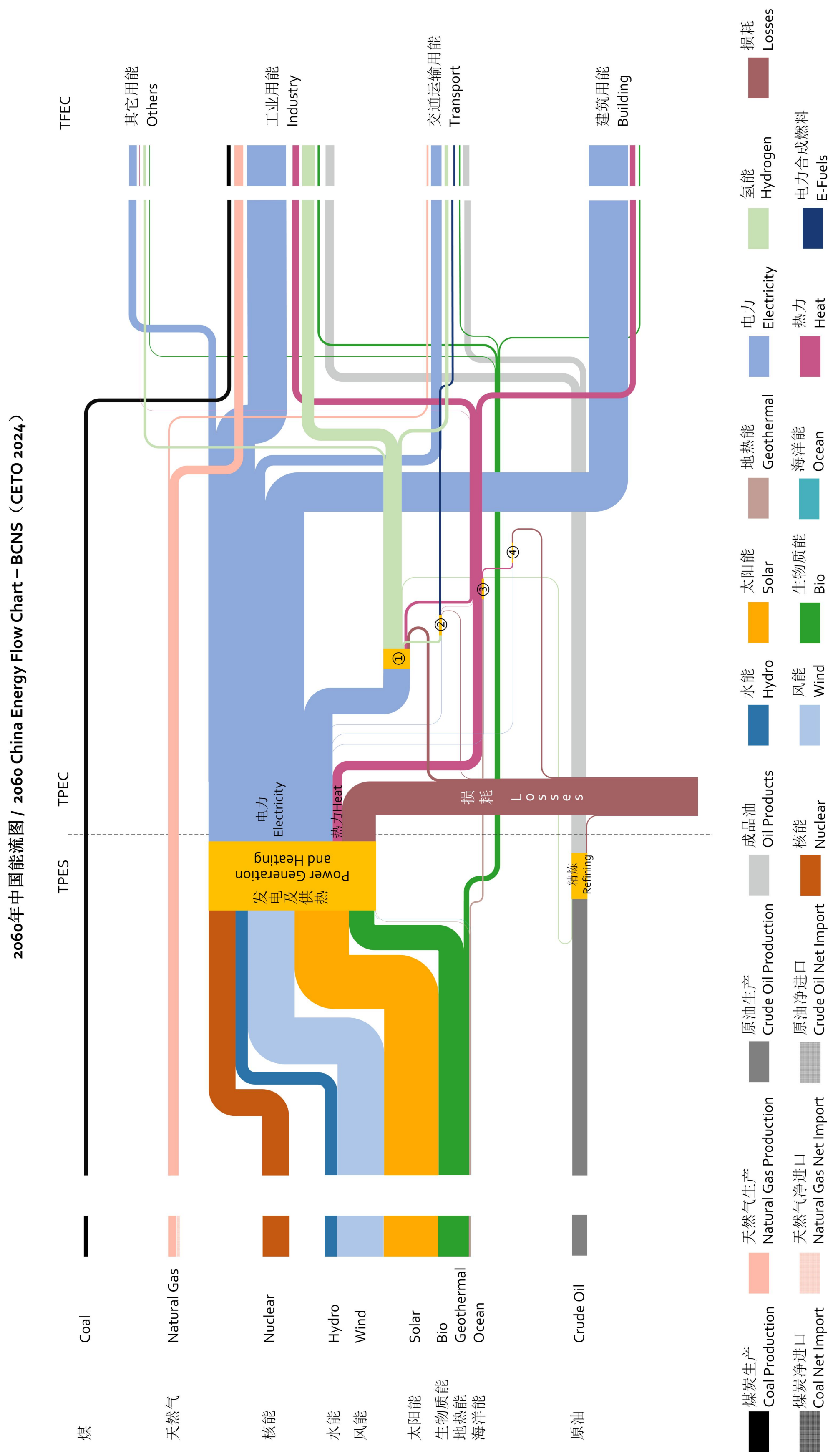
China energy flow charts

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



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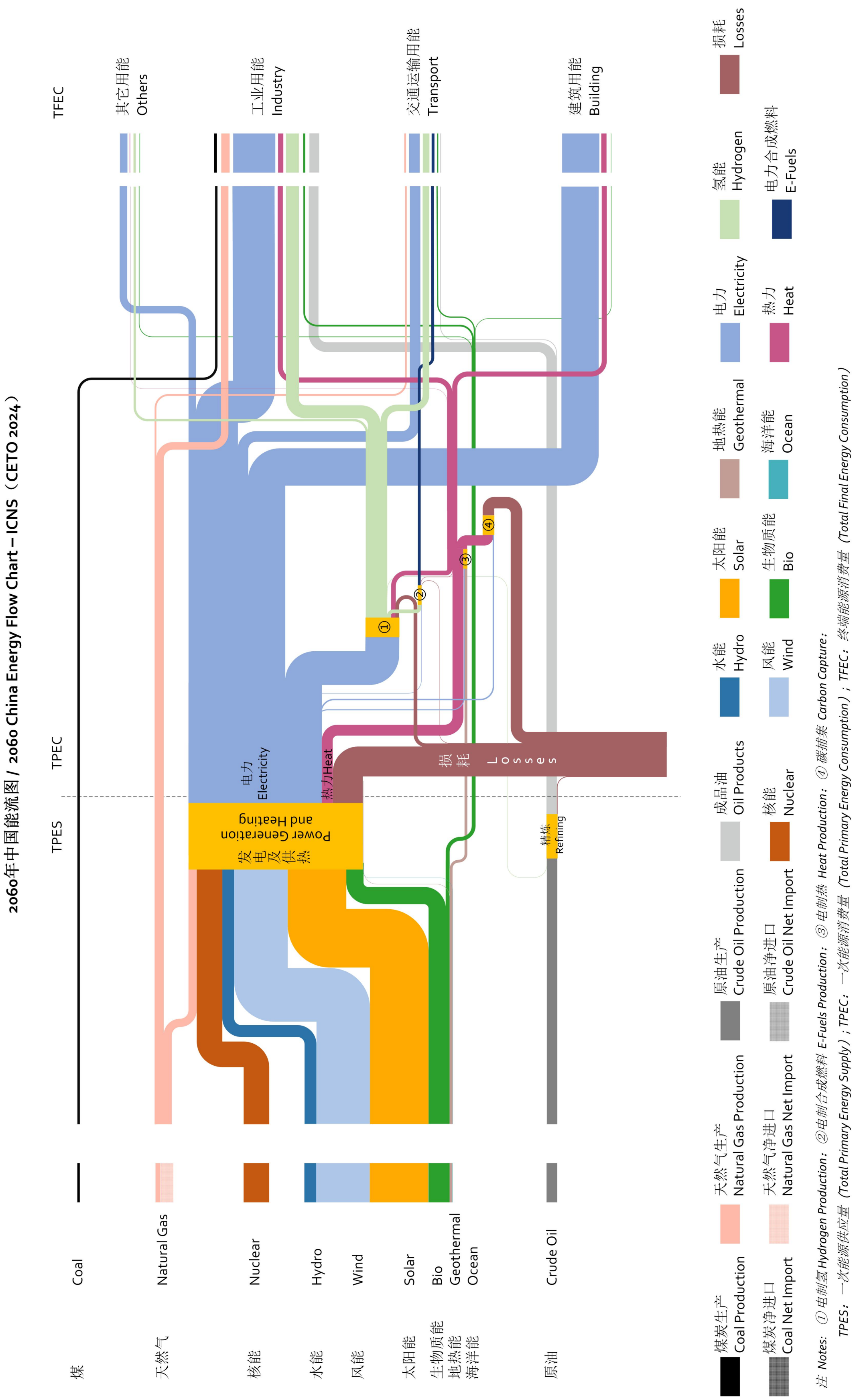
TPES：一次能源供应量（Total Primary Energy Supply）; TPEC：一次能源消费量（Total Primary Energy Consumption）; TFEC：终端能源消费量（Total Final Energy Consumption）

Figure 4 China energy flow chart in 2060 - ICNS



Part I: State of the energy transformation

Accelerating energy transformation is imperative as global climate change becomes increasingly severe

Global climate change is one of the greatest challenges facing the world today, and with global temperatures already rising by 1.45 °C in 2023 compared to pre-industrial times, combating climate change is increasingly urgent. Energy activities contribute 86% of global carbon dioxide emissions, and the energy transformation is one of the most important ways to mitigate climate change. However, achieving an energy transformation is not easy. It requires overcoming the trilemma of environmental sustainability, economic growth, and energy security. A range of factors must be addressed in a balanced way, including economic development, industrial transformation, supply security, and employment stability, to ensure that the transformation is sustainable. In recent years, international cooperation on energy transformation has only just begun, and there is a need to consolidate consensus and enhance synergies. In the face of the increasingly complex international political and economic situation and occasional geopolitical conflicts, it becomes even more necessary for countries to strengthen cooperation on climate change and jointly promote the energy transformation.

China continues to promote energy transformation

As the world's largest emerging economy, China has endeavoured to promote an energy revolution and has achieved significant progress. In 2014, Xi Jinping, General Secretary of the Chinese Communist Party, introduced a new energy security strategy focused on five central pillars: an energy consumption revolution, an energy supply revolution, an energy technology revolution, an energy governance revolution, and enhancing international cooperation in all aspects. Over the past decade, China has made significant strides in its energy revolution, establishing a crucial foundation for its future energy transformation. The success of China's energy transformation is primarily reflected in:

Energy conservation, efficiency improvement, and structural transformation of energy consumption have achieved significant results. From 2013 to 2023, China reduced its energy consumption per unit of GDP by over 26%. This positioned China as one of the fastest countries in the world to decrease energy intensity globally, saving approximately 1,400 Mtce in the process. The share of non-fossil energy in China's primary energy consumption rose from 10.2% in 2013 to 17.9% in 2023. Meanwhile coal consumption share dropped from 67.4% to 55.3% over the same period.

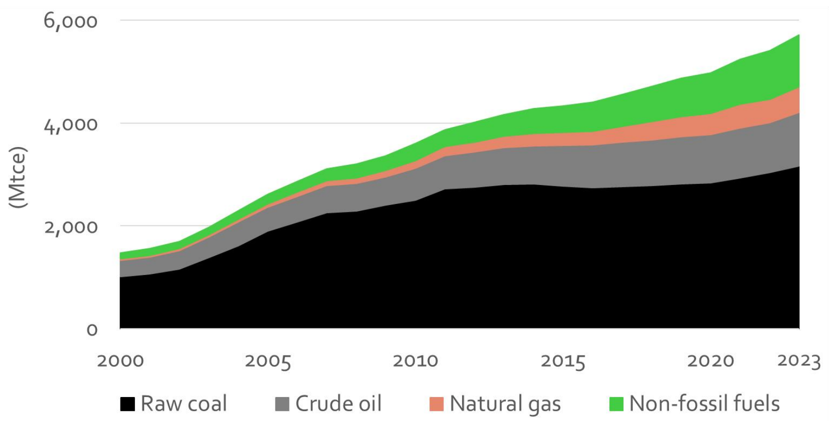
Green energy supply capacity has greatly increased. In 2023, China's installed capacity for new and renewable energy had increased tenfold over the preceding decade. China consistently ranked first globally in new renewable capacity installations for many consecutive years and accounts for about 40% of the global total. That year, the total installed power generation capacity reached nearly 3,000 GW, with more than half coming from non-fossil energy sources, surpassing thermal power capacity additions for the first time. In 2023, renewable energy generation reached approximately 3,000 TWh, supplying about one-third of China's electricity consumption. The cost of wind and photovoltaic power generation in China fell by 60% and 80%, respectively, over the past decade, underscoring the growing market-driven role of supporting the energy transformation.

Innovation in energy science and technology surged. China built a comprehensive wind power and photovoltaic industry chain, significantly increasing its capacity for R&D, design, and manufacturing of new products. The conversion efficiency of mass-produced advanced crystalline silicon photovoltaic cells exceeded 25%, and the maximum capacity of single wind turbines reached 18 MW. Exports of new energy vehicles, lithium batteries, and photovoltaic products surpassed 1 trillion RMB annually, with wind and photovoltaic products being exported to more than 200 countries and regions, supporting other countries in achieving the energy transformation.

The reform of the energy system is advancing steadily. Institutional reforms in coal, petroleum, natural gas, and electricity are progressing, with energy becoming increasingly commoditised. Following the principle of "regulating the middle and liberalising the two ends", competitive areas and segments have market-determined prices, while natural monopoly segments have regulated prices. Market-based electricity trading is also making headway, with both long-term and spot markets being accepted by users, reflecting the growing role of market forces in resource allocation.

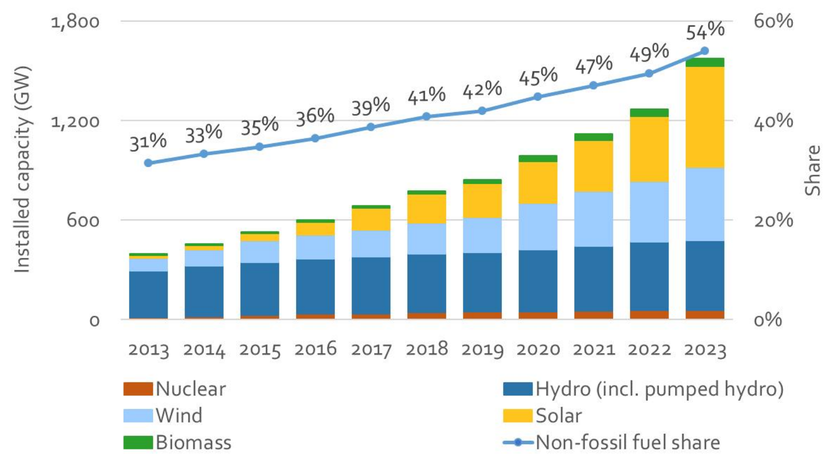
International energy cooperation aligns with global energy transformation goals. China strongly supports green, low-carbon energy development in emerging economies and has pledged not to build new coal power projects abroad. Instead, it has developed numerous hydropower, wind, and photovoltaic projects in Southeast Asia, Africa, and other Belt and Road countries, boosting local economies and improving living standards. Through the Belt and Road Energy Partnership with 29 countries, China has also launched training programs to enhance knowledge and capacity-building in developing nations, contributing to joint efforts in advancing energy transformations.

Figure 5 Total primary energy consumption and structure, 2000-2023



Source: National Bureau of Statistics

Figure 6 Installed power capacity from various types of non-fossil energy sources, 2013-2023



Source: National Energy Administration

Despite the positive progress in China's energy transformation, significant challenges remain, including immense demand pressure, increasing supply constraints, and the difficult task of green transformation. There is still a long way to go in advancing the energy transformation.

Part II: Pathways to net-zero emissions from China's energy system

Restructuring of primary energy and electricity demand

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 7). 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 8).

Figure 7 Total primary energy demand and structure, 2022-2060 (based on the calorific value method)

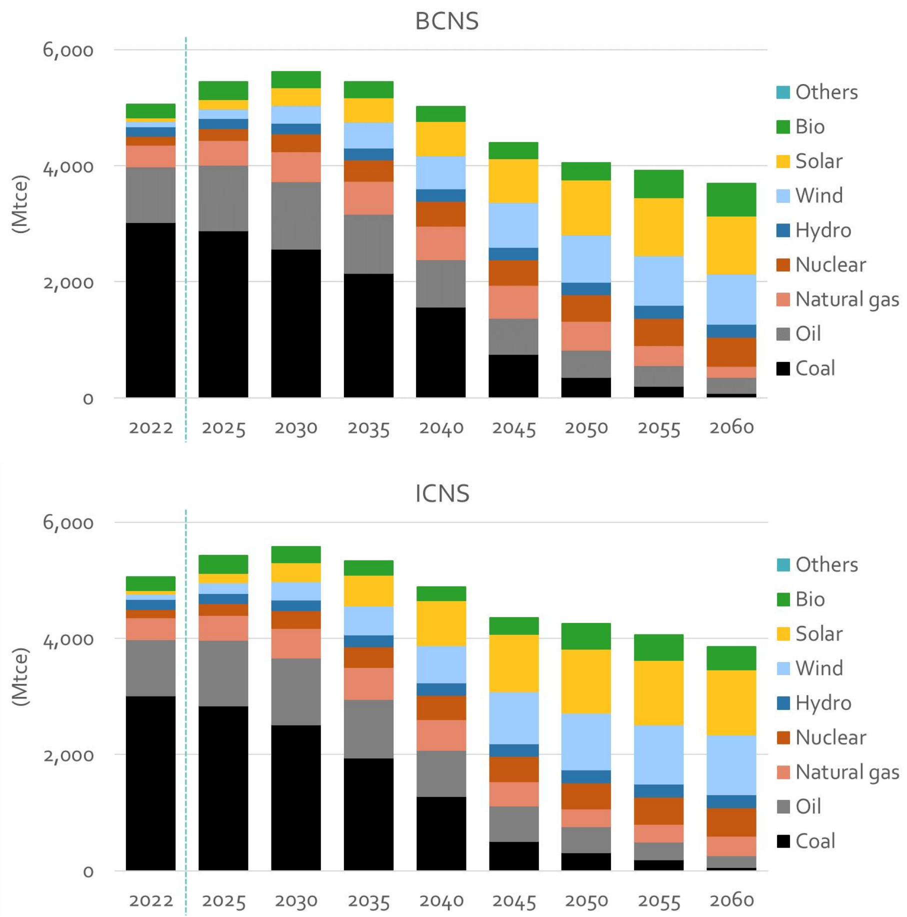
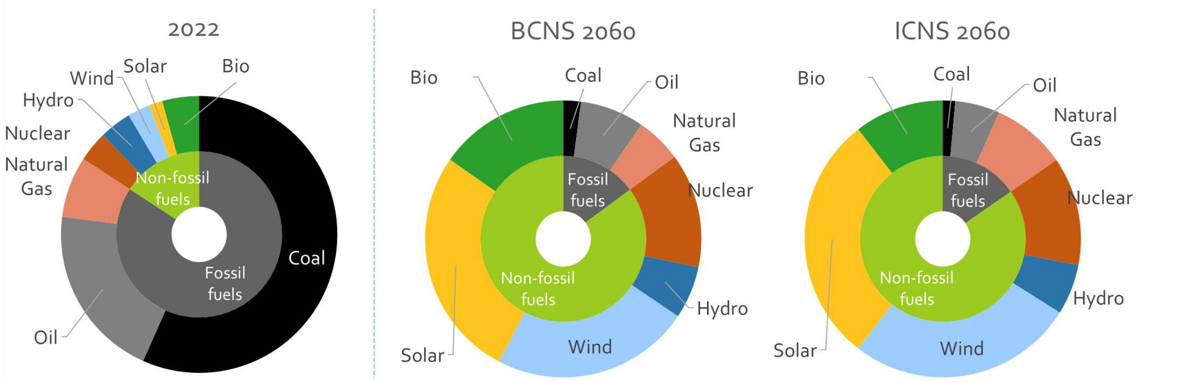


Figure 8 Comparison of primary energy demand structure between 2022 and 2060



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 (as shown in Figure 9). 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 10).

Figure 9 Total electricity demand and structure, 2022-2060

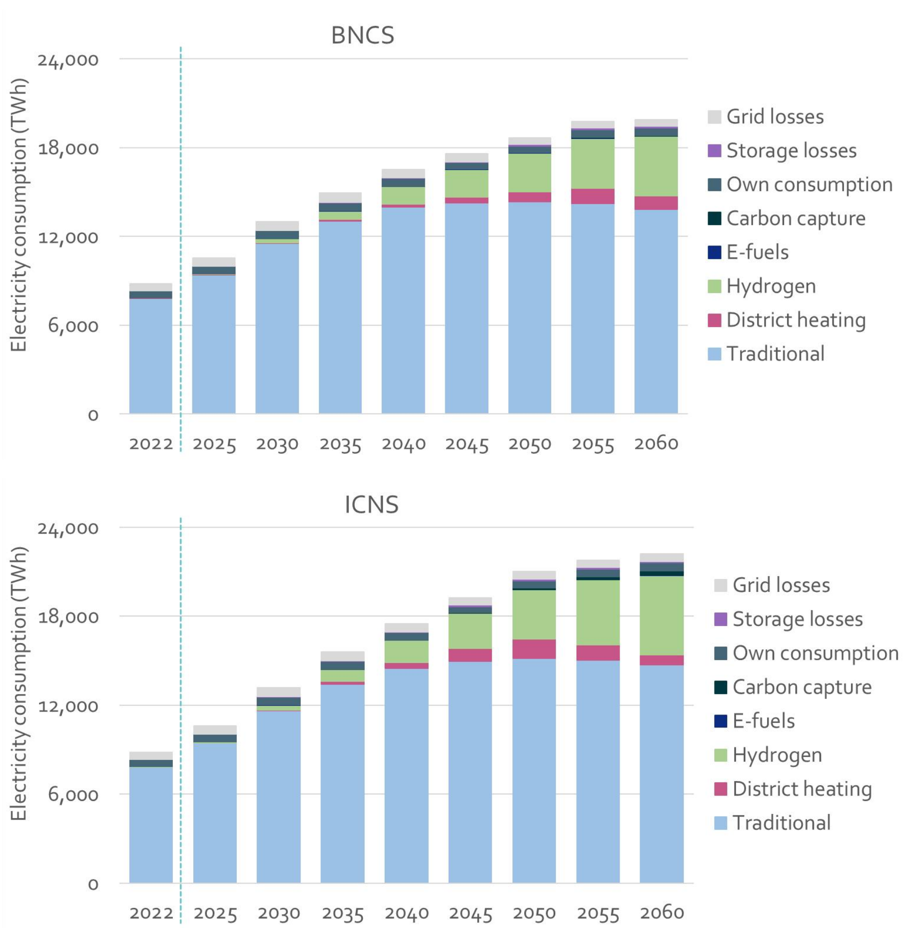
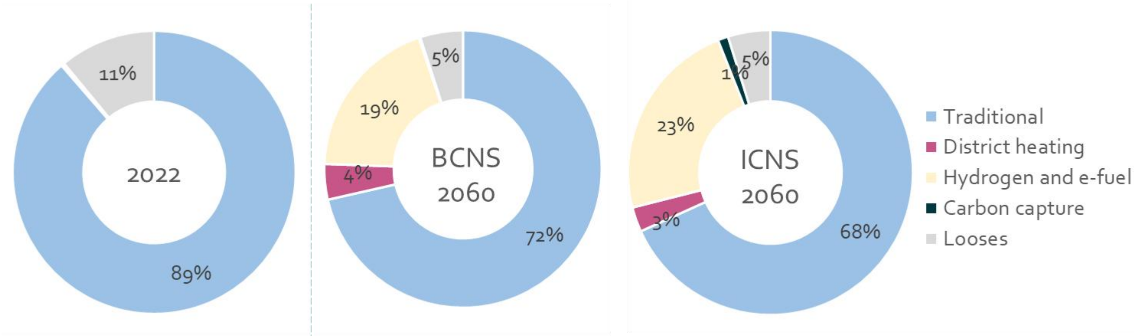


Figure 10 Comparison of electricity demand structure between 2022 and 2060



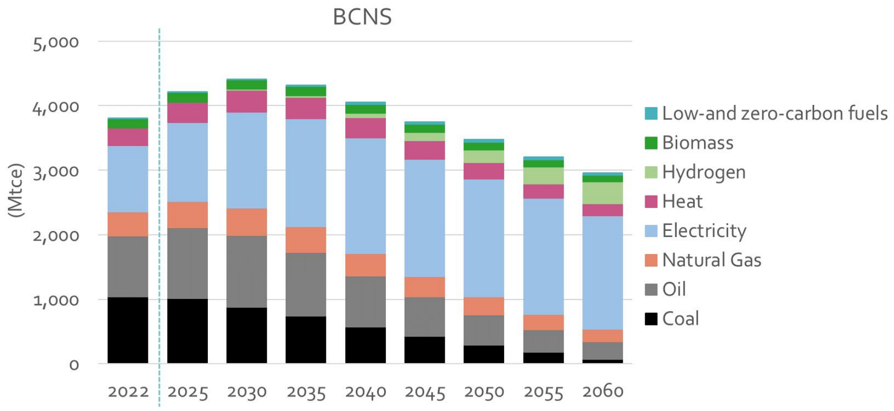
Energy transformation is a critical pillar in building China's carbon-neutral society

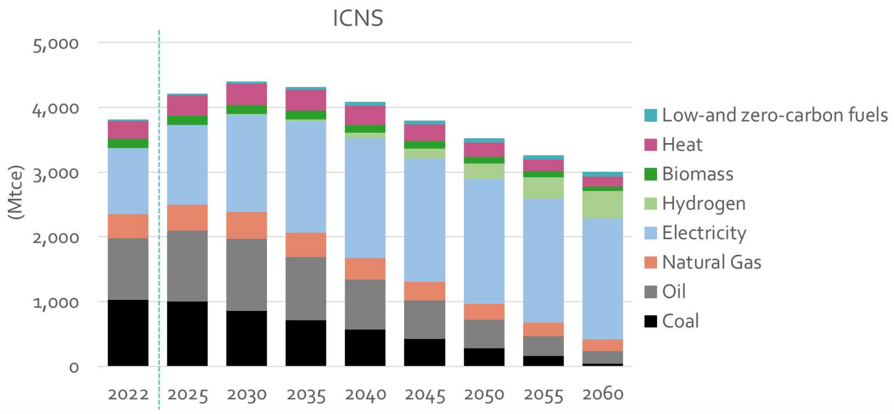
With the accelerated development of energy transformation technologies (including negative carbon technologies such as carbon capture) and related industries, China's energy system can achieve net-zero carbon emissions before 2060. Energy-related activities accounted for 86.5% of the country's total 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 11). During this transformation, the most important driver of end-use energy demand growth is the rapidly increasing electricity demand.

Figure 11 Total end-use energy demand and structure, 2022-2060

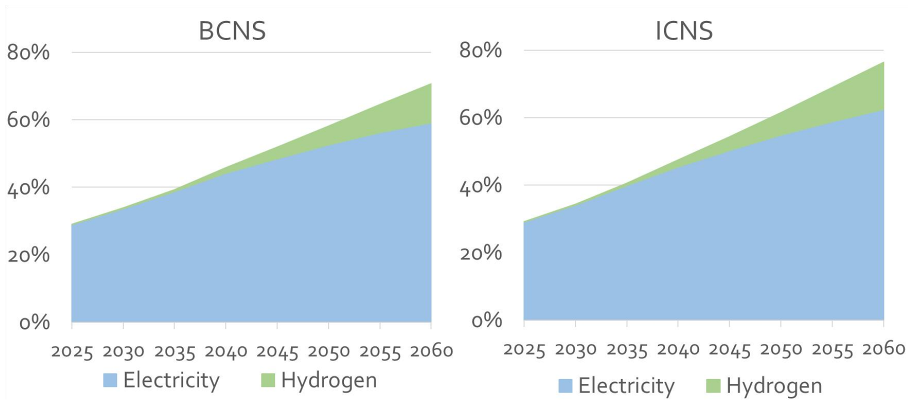




Note: Low-carbon and zero-carbon fuels mainly include synthetic fuels from electricity and biofuels.

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 12). By 2060, hydrogen will become the second-largest energy resource in China's end-use energy demand.

Figure 12 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% (as shown in Figure 13 and Figure 14).

Figure 13 Narrow electrification rates in end-use sectors, 2022-2060

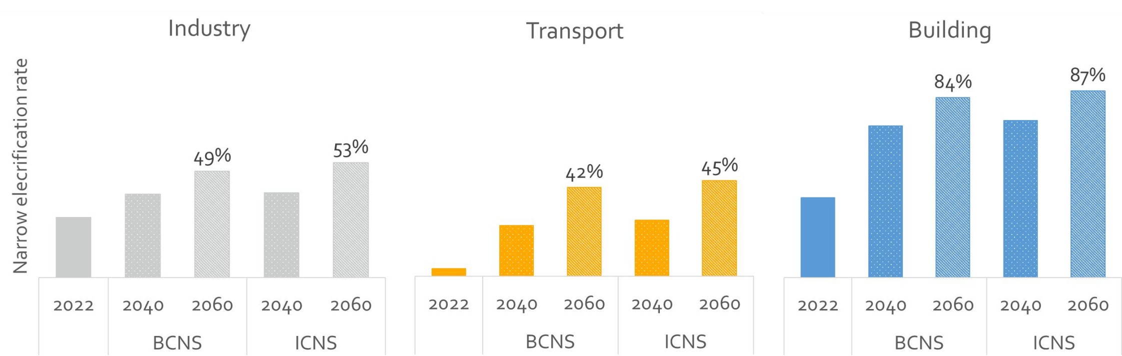
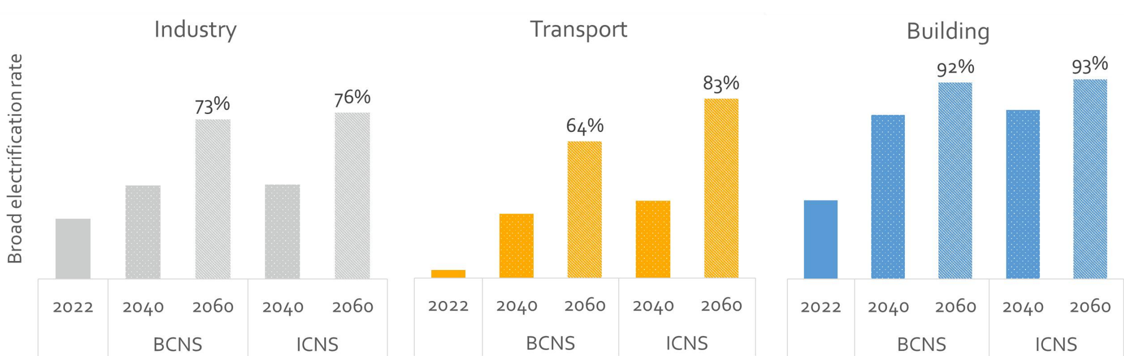
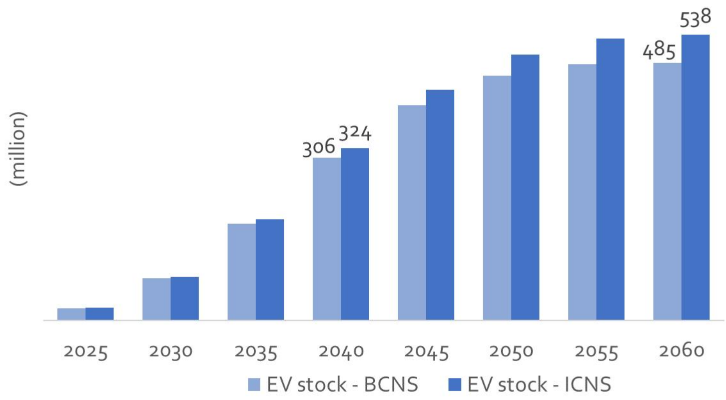


Figure 14 Broad electrification rates in end-use sectors, 2022-2060



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 (as shown in Figure 15). 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.

Figure 15 Electric vehicle stock, 2025-2060



"Flexible energy use" and "supply-demand interaction" in end-use sectors will be key components of the energy transformation. In industries such as non-ferrous metals, chemicals, light industry, electrical equipment needs to be modified to match cheaper yet volatile 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 load regulation of loads in the daily power balancing (as shown in Figure 25 and Figure 26). These technologies will be essential to meet the future needs of the energy transformation.

Achieving green power with wind and solar as the core

Accelerating the construction of a new type of power system that is clean and low-carbon, secure and abundant, economically efficient, coordinated in supply and demand, flexible and intelligent is a core initiative to promote net-zero emissions in the energy sector. By 2035, a new type of power system will have been initially built, and coal power will transition towards providing regulation and backup. By around 2050, net-zero emissions will have been achieved in the power sector. 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 16). 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. In 2060, bioenergy with Carbon Capture and Storage (BECCS) will have an installed capacity of more than 130 GW, further decreasing the carbon emissions of the energy sector. Strengthening international cooperation on energy transformation will help China to further improve its non-fossil energy supply capacity and grid security capacity.

Figure 16 Total installed power generation capacity and mix, 2022-2060

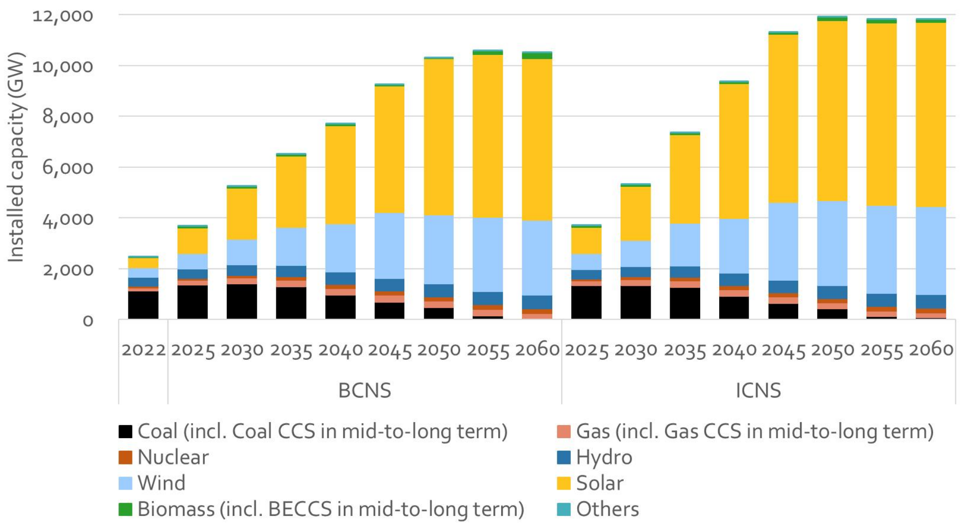


Figure 17 Total electricity generation and mix, 2022-2060

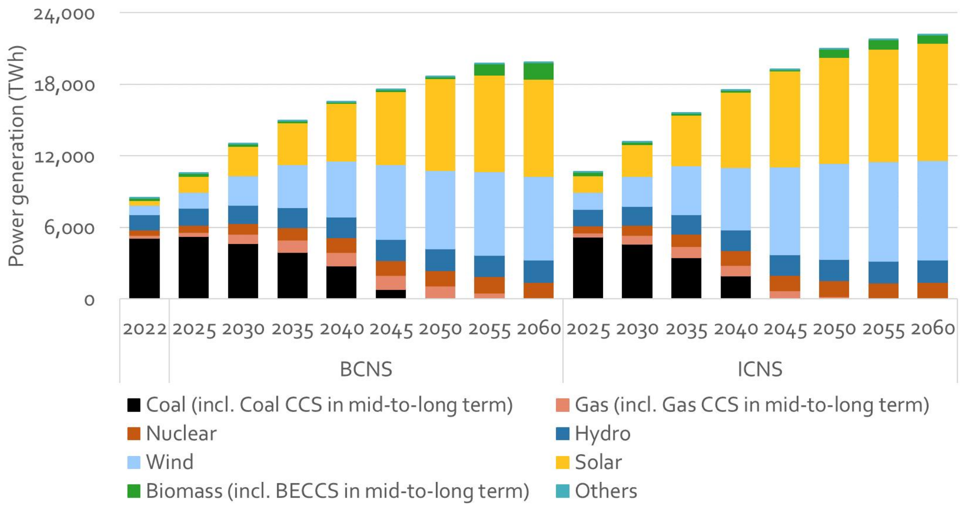


Figure 18 Comparison of total installed power generation capacity mix between 2022 and 2060

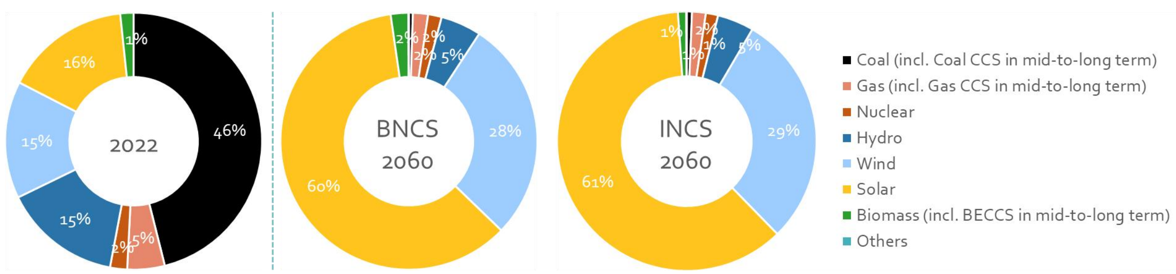
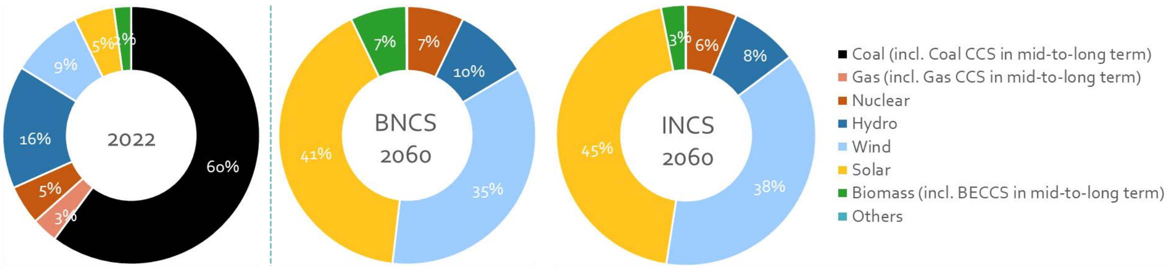


Figure 19 Comparison of total power generation mix between 2022 and 2060



Wind and PV installations are growing significantly, with distributed PV offering the greatest potential. In 2060, China's combined wind power and PV 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 power capacity. Among the installed PV power generation capacity, distributed PV accounts for 70%, which is dominant (as shown in Figure 21). 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 20 Installed wind power capacity and structure, 2025-2060

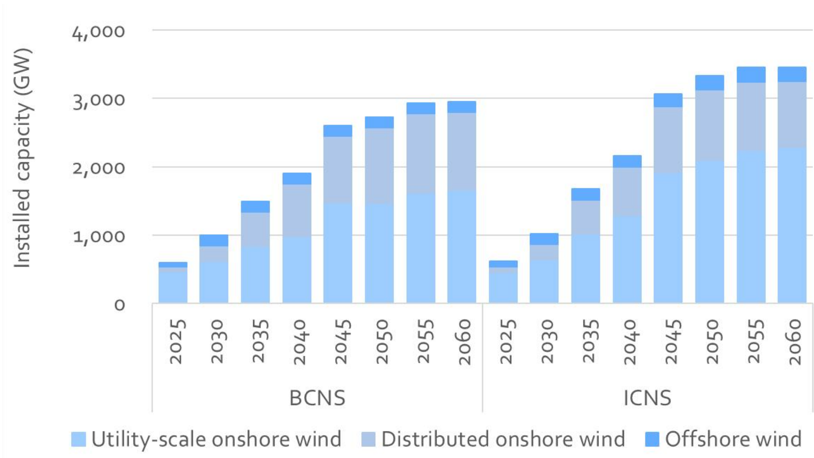
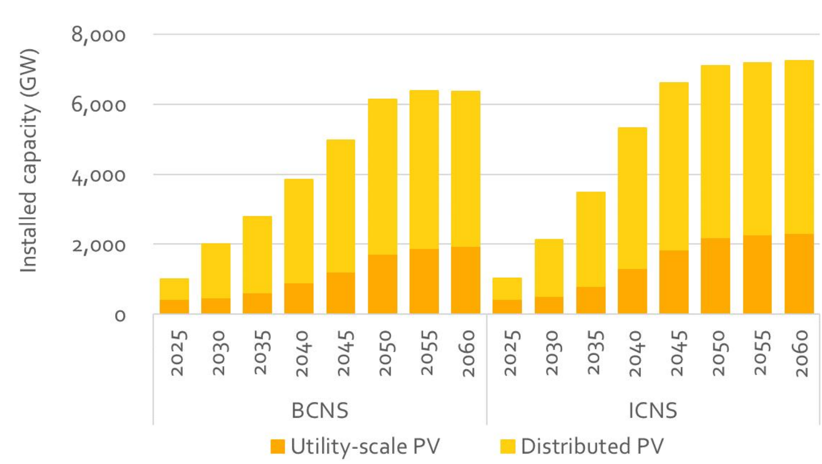


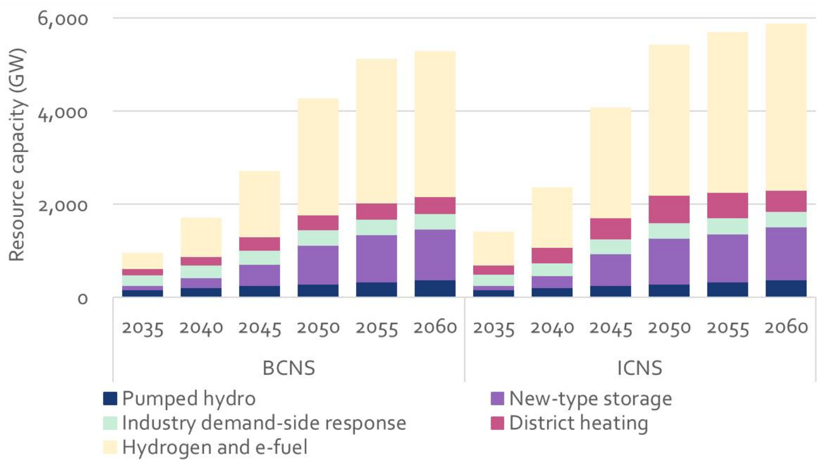
Figure 21 Total installed solar PV capacity and structure, 2025-2060



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 Figure 22).

Figure 22 Total pumped hydro and new-type flexibility resources demand and structure, 2035-2060



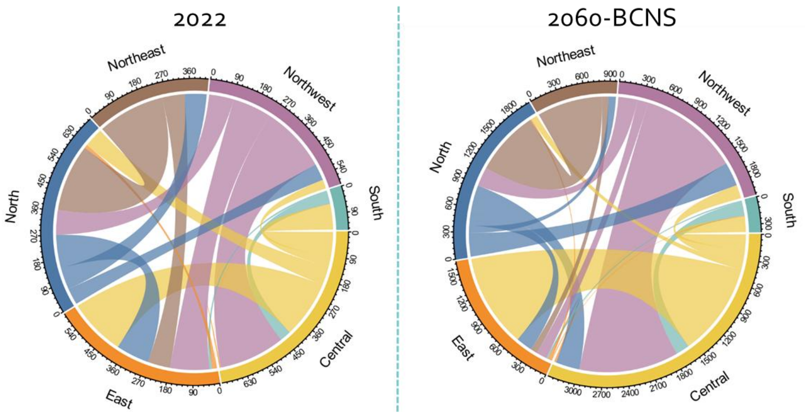
Note: New flexibility resources include new-type energy storage (electrochemical storage stations and EV-V2G), industrial demand response, electric heat production (electric boilers and heat pumps), and hydrogen and e-fuel.

Adhere 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 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 interaction capacity (EV-V2G) 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.

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% to 150% compared to 2022 (as shown in Figure 23).

Figure 23 Comparison of inter-regional electricity transmission between 2022 and 2060 (TWh)



Production-consumption simulation of new power systems

By 2060, the BCNS and ICNS scenarios are similar in that various types of energy storage and demand-side response resources, on multiple time scales, will replace traditional adjustable power sources as the primary sources of flexibility in the power system. Taking a typical summer week under the BCNS scenario as an example: during the day, with abundant sunlight, solar power output rapidly increases. When the power output exceeds the power load (as shown in Figure 25, on the first day at noon), pumped hydro, chemical storage, hydrogen and e-fuel production, EVs and industry demand-side response resources begin to charge. These flexible loads account for 60% of the total load during the peak load hour.

In the evening, as solar output decreases to zero and wind output increases (as seen on the fifth day in Figure 25), the electricity consumption of hydrogen and e-fuel production increases, their joint power load accounts for around 20% of the total load. When wind power output is low (as on the sixth day in Figure 25), pumped hydro, chemical storage facilities and EV-V2G systems begin discharging extensively, with the combined storage output reaching around 32% of the total power output.

Figure 24 Hourly power balance for a week – summer 2022

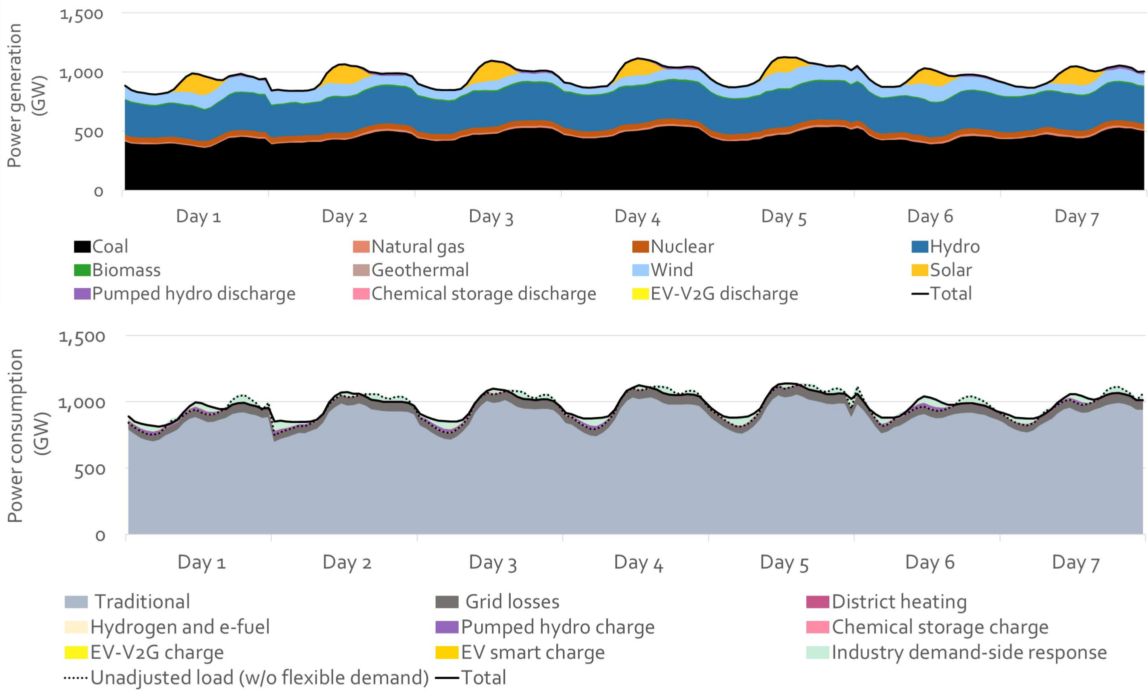
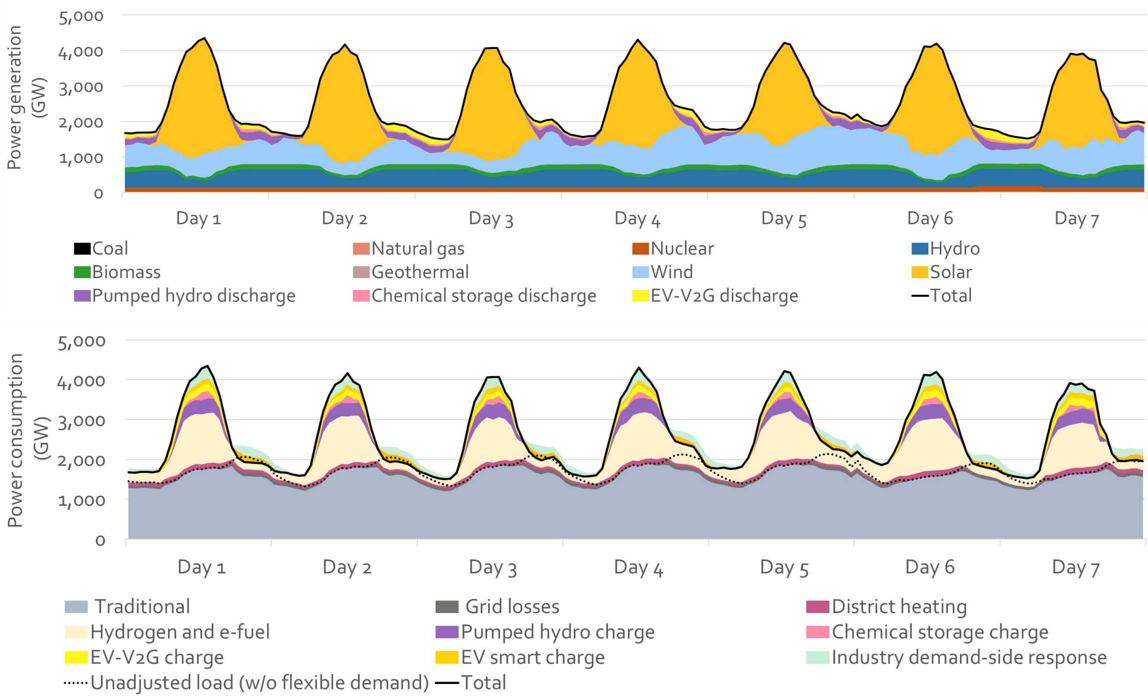
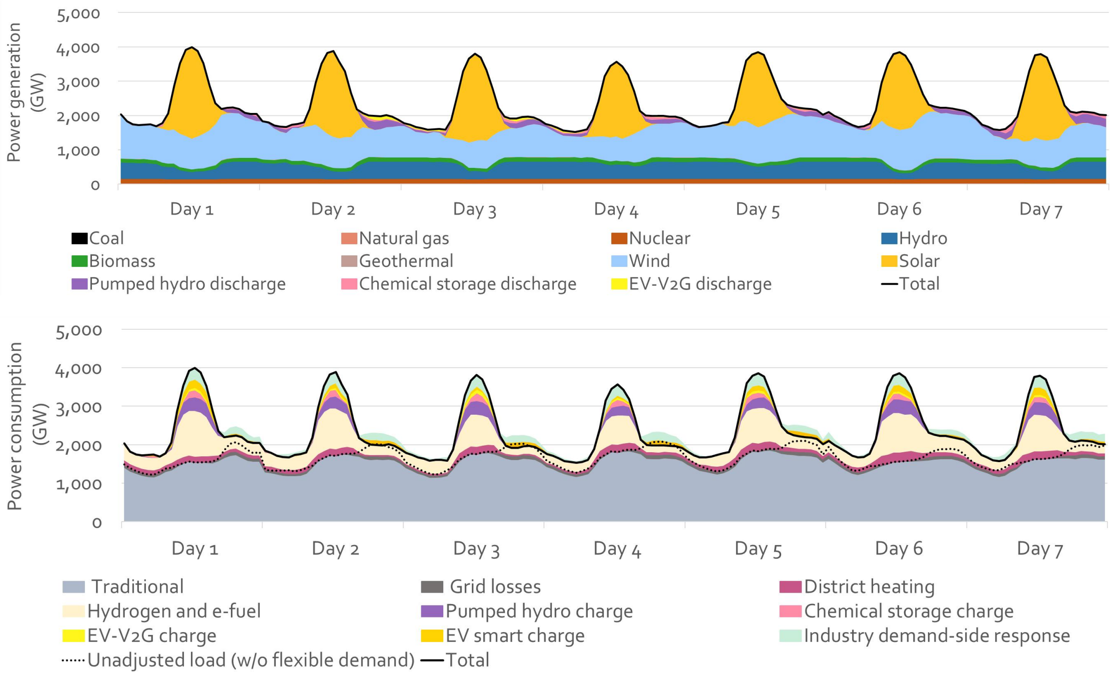


Figure 25 Hourly power balance for a week in the BCNS scenario – summer 2060



Note: The charts show the national power output (top) and power load (bottom) by hour. The total power output and total power load are equal at all times, indicating that power supply and demand achieve a dynamic balance. The black solid line represents the shape of the power load curve after flexible resources have come into play, including base loads (traditional end-use sector power load, grid losses) and flexible resources (pumped hydro, chemical storage, EV-V2G, district heating, hydrogen and e-fuel production, EV smart charge and industrial demand-side response). Industrial demand-side response and EV smart charge can shift load from night to day, thereby flattening the load curve at night (power load curve before shifting, shown as the black dotted line).

Figure 26 Hourly power balance for a week in the BCNS scenario – winter 2060



Energy transformation boosts the economy, society and jobs

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.

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 27, Figure 28, Figure 29 and Figure 30).

Figure 27 Electricity sector's contribution to economic growth, 2025-2060

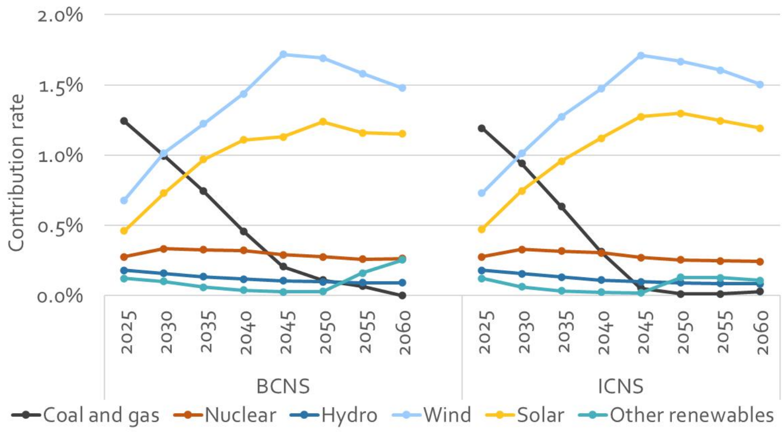


Figure 28 Size of employment related to the wind power industry, 2025-2060

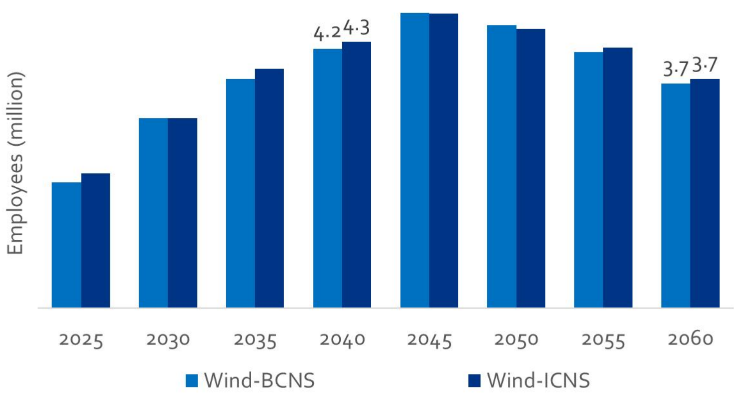


Figure 29 Size of employment related to the solar power industry, 2025-2060

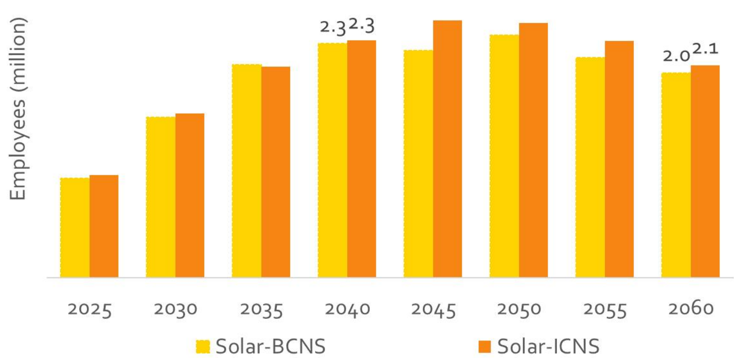
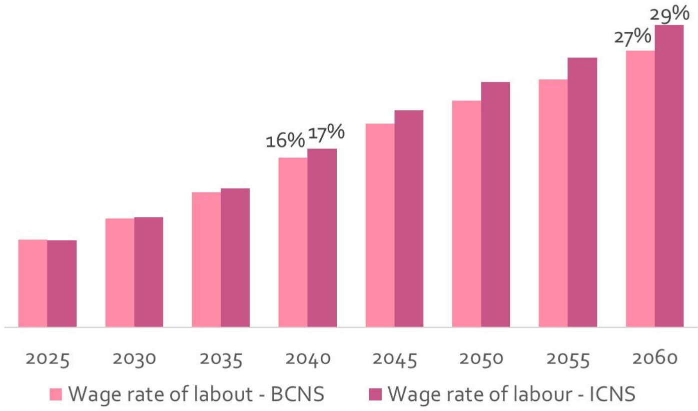


Figure 30 Trends in labour wage rate growth, 2025-2060



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. **Thirdly, 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: 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.

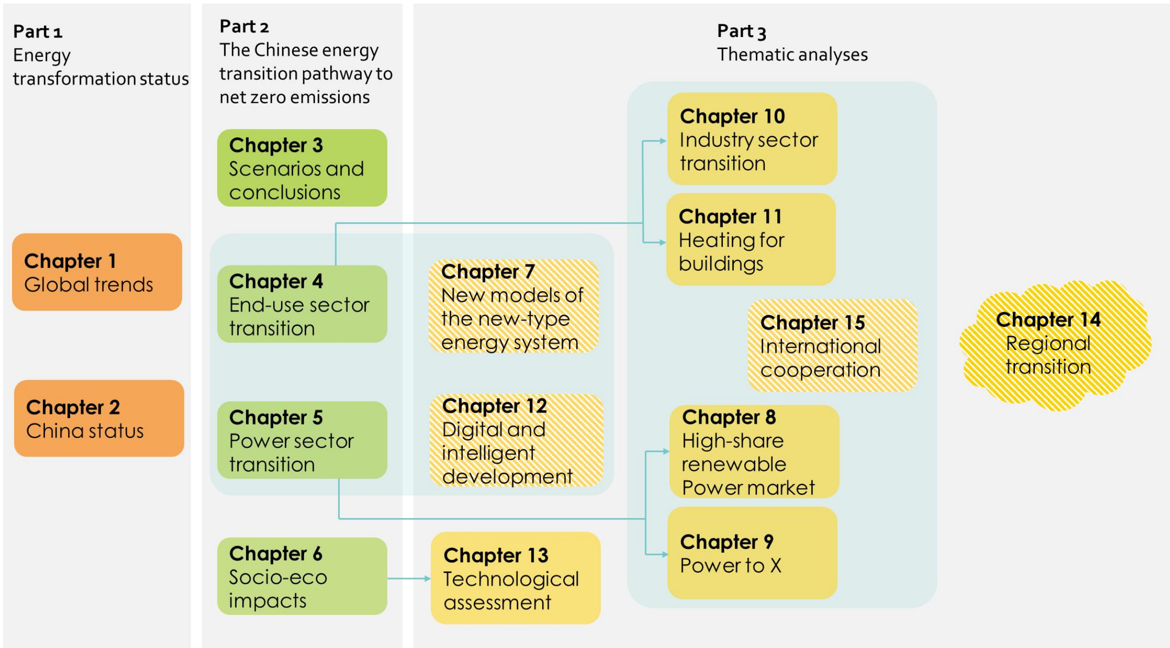
In summary, China's energy transformation is a long-term and challenging societal project. Within less than forty years, China must first surpass its peak carbon emissions and then achieve carbon neutrality. The challenges are immense, and it is a difficult task. This requires policymakers to face these 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.

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 31). The main conclusions of the chapters in Part III are presented below. We recommend reading the full report if you are interested in the details.

Figure 31 Relationships between the chapters of China Energy Transformation Outlook 2024



New models of the new 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 (Photovoltaic, Energy storage, Direct current, Flexibility) 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.

Building electricity markets adapted to a high proportion of renewable energy

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.

Electrically produced synthetic fuels

Electrically produced synthetic fuels, such as hydrogen, ammonia, and methanol, are crucial technological pathways for achieving global carbon neutrality. These fuels represent new energy carriers for the future energy transformation.

Several countries are actively planning the development of synthetic fuels from electricity and reinforcing low-carbon standards. The U.S. National Clean Hydrogen Strategy and Roadmap anticipates that the production of clean hydrogen will reach 10 million tons per year by 2030, increasing to 20 million tons per year by 2040 and 50 million tons per year by 2050. Germany's updated Hydrogen Strategy positions hydrogen and hydrogen-rich fuels (such as ammonia and methanol) as sustainable fuels, aiming to deeply decarbonise the aviation and maritime sectors. Japan's 2023 Hydrogen Strategy expands the application of green hydrogen and green ammonia to "hard-to-abate sectors" like steel, chemicals, aviation, and coal power. At the same time, various countries are enhancing the low- and zero-carbon characteristics of electrically produced fuels, accelerating the formulation and release of carbon emission standards for these fuels, with clean hydrogen emission thresholds ranging between 3-4 kg CO_{2e} /kg H_2.

Domestically, policies for electrically produced synthetic fuels are continuously being optimised, and production capacity is rapidly increasing. In the hydrogen sector, several regions, including Hebei, Guangdong, Liaoning, Anhui, and Xinjiang, have opened market access for hydrogen production through electrolysis and integrated hydrogen production and refuelling stations outside chemical industrial parks. Regions such as Ordos (Inner Mongolia), Karamay (Xinjiang), and Shenzhen (Guangdong) offer subsidies or electricity tariff exemptions for wind and solar hydrogen production projects and integrated hydrogen production and refuelling stations. In 2023, China added about 37,000 tons per year of new electrolytic hydrogen production capacity, bringing the total capacity to approximately 72,000 tons per year. Of this capacity, 63% is concentrated in Xinjiang and Ningxia, and 80% of it is solar-powered hydrogen production. Large green hydrogen projects mainly operate through grid-connected or semi-off-grid systems. **In the green methanol and green ammonia sectors,** China is in the process of constructing 11 green and low-carbon methanol projects, with a combined capacity of about 366,000 tons per year. Additionally, 13 green ammonia projects are under construction, with an announced capacity of around 790,000 tons per year, most of which are scheduled to be completed in 2024 or 2025.

The electrically produced synthetic fuel industry is beginning to take shape, with costs continuously declining. In 2023, China's alkaline electrolysers entered a new phase of technological readiness, with maximum hydrogen production from a single unit reaching 3,000 Nm^3/h. The supply chain for proton exchange membrane (PEM) electrolysers is forming, and the mass production of domestic proton exchange membranes, catalysts, and other components is progressing. Currently, the cost of hydrogen produced directly from solar power is approximately 20 RMB/kg. As the costs of photovoltaic/wind power, electricity used for hydrogen production, and electrolysers continue to decrease, the economic viability of electrically produced fuels is expected to improve significantly.

The economic viability of electrically produced synthetic fuels still needs improvement, and the industry faces multiple challenges. At present, the costs of green hydrogen, green ammonia, and green methanol are about twice that of similar fossil fuel production methods, and the spatial mismatch between supply and demand further complicates the utilisation of these fuels. The immediate priority for the industry's sustainable development is to build an industrial ecosystem for production, storage, transport, and utilisation, overcoming technical bottlenecks in core materials and equipment, increasing the scale of demonstration projects, and enhancing the techno-economic efficiency of the entire value chain.

Low-carbon transformation in the industrial sector

In the global effort to address climate change, the deep decarbonisation of industry has become a common concern of governments and relevant institutions. Research from various organisations has shown that deep industrial decarbonisation faces multiple challenges, such as a large carbon emission base, complex causes and difficulty in reducing emissions. As the world's largest developing and industrialised country, China bears a special responsibility in promoting the low-carbon transformation of its industrial sector.

In recent years, China's industrial sector has made progress in low-carbon transformation. Since 2012, the country's industrial sector has achieved an annual value-added growth of around 5.8%, while energy consumption has increased by only 2.2% annually on average. This sets a "Chinese model" for global industrial low-carbon transformation. Key elements of China's progress include industrial restructuring, rapid adoption of new technologies, the significant improvement of energy conservation and environmental protection, and the accelerated substitution of traditional energy sources with clean, low-carbon alternatives.

Model analyses suggest that with the widespread adoption of energy-saving and low-carbon technologies, the large-scale application of clean energy such as electricity and hydrogen, and the continuous structural adjustments, China can maintain industrial growth while reducing energy inputs and carbon emissions. In both scenarios, energy demand in the industrial sector grows, then stabilises and declines, showing an "inverted U-shaped" trend. China's industrial energy consumption is expected to rise first, then fall, and by 2060, energy demand is projected to decrease to 72%- 75 % of 2020 level, while industrial value-added reaches 3.0 and 3.3 times the 2020 level, and energy productivity improves by more than fourfold.

Four key actions are proposed to facilitate the reduction of carbon emissions in China's industries. First, establish a modern and high-end industrial system while aiming to reduce the output of energy-intensive and high-emission products, such as crude steel and cement, by 40%-60%. Second, build a circular and integrated organisational form, gradually increasing the proportion of recycled materials—such as steel, aluminium and plastics — to over 50%. Third, focus on developing a digital, intelligent and efficient production model by implementing ultra-premium efficiency projects in key industries and leveraging digitalisation for systematic energy efficiency gains. Lastly, reshape the energy structure by enhancing the synergy between electricity and hydrogen, promoting the substitution of traditional fossil fuels with these clean energy sources, aiming for electricity and hydrogen to account for about 70% of industrial energy use by 2060.

Low-carbon transformation in building heating

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 industry.

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.

To promote the low-carbon transformation of heating, the Chinese government has introduced a series of policies that have yielded positive results. These efforts include gradually reducing the heating demand per unit area by raising energy-saving design standards for new buildings, promoting the construction of ultra-low and near-zero energy buildings, and retrofitting existing buildings for energy efficiency. Additionally, through the Clean Winter Heating Plan in Northern China, the government aims to transition the heat source structure toward cleaner, low-carbon alternatives. These actions have led to marked improvements in air quality during the fall and winter months in northern China.

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 will 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.

Digital and intelligent development of the energy sector

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.

Synergistic impact of carbon and pollution reduction technologies in the energy sector

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 transition 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, carbon capture, utilisation, and storage (CCUS) offer significant carbon reduction benefits but also increase water consumption.

Energy transformation practices and achievements in typical provinces

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.

International cooperation on energy transformation

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.

China Energy Transformation Outlook

2024

Executive Summary