China Energy Transformation Outlook 2025

Energy Research Institute of Chinese Academy of Macroeconomic Research

Executive Summary

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

Implementing Unit

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"The world now faces a huge demand for green development. It is important that countries strengthen international coordination in green technologies and industries to address the shortfall in green production capacity and ensure free flow of quality green products globally, so that the benefits of green development can reach all corners of the world."

President Xi Jinping
Remarks at UN Climate Summit
24 September 2025

Preface

Energy serves as the foundation and driving force behind the advancement of human civilisation. Throughout the history of human societal development, every major leap forward in civilisation has been accompanied by transformations in energy utilisation methods and shifts in primary energy sources. The "drilling wood to produce fire" technique initiated the first energy revolution, ushering in the "wood-fuel era" and propelling human society into an agricultural civilisation characterised by slash-and-burn farming and settled communities. The invention of the steam engine and advances in coal mining technology sparked the second energy revolution, marking the "coal era." Machines replaced manual labour across economic and social spheres, catalysing the first industrial revolution and propelling humanity into the industrial age. The invention of the internal combustion engine and the widespread application of electricity launched the third energy revolution, ushering in the "oil and electricity era." This spurred the second industrial revolution, propelling industrial civilisation to a highly developed stage. As a new wave of technological revolution and industrial transformation deepens, green and low-carbon development, digital intelligence, and sustainable growth have become defining themes of our era. A new energy revolution is now surging forward, guiding human society from industrial civilisation toward an ecological civilisation.

China Energy Transformation Outlook 2025 (CETO 2025) examines China's latest development landscape, analysing the nation's path to achieving carbon peak and carbon neutrality goals while exploring the potential impacts of enhanced international cooperation and future technological innovation on China's energy transformation. The report analyses China's energy transformation pathways and prospects under different international cooperation scenarios through two distinct scenarios. Beyond the scenario analysis, CETO 2025 conducts thematic studies on key topics, including enhancing the secure and reliable substitution capacity of renewable energy, applying heat pump technology in the building sector, and developing zero-carbon industrial parks. International institutions such as the Danish Energy Agency (DEA) and Columbia University's Center on Global Energy Policy (CGEP) provided technical support for the model analysis and thematic research.

The Executive Summary of CETO 2025 encapsulates the report's key findings and can be read independently.

CETO 2025 is a think tank research report that is updated annually based on the previous year's development dynamics in China and the latest assessments of future technological advancements. I sincerely hope this report will serve as a valuable reference for formulating energy strategy plans and major policies in China and globally, fostering enhanced cooperation among nations in energy transformation and enabling us to address the challenges of global climate change jointly.

Here, I would like to express my sincere gratitude to all colleagues from the Energy Research Institute project team and other participating Chinese institutions for their tireless efforts in researching and drafting this report.

Special thanks go to the relevant departments (offices) for their valuable comments and suggestions in refining the report.

I also extend my appreciation to the Danish Energy Agency, the Center on Global Energy Policy at Columbia University, and Ea Energy Analysis for their substantial support and insightful contributions to this study.

Finally, I would like to thank our long-term partner, the Children's Investment Fund Foundation (CIFF), for its sustained funding and support over the years in enabling the Energy Research Institute to conduct the research and prepare the reports for the CETO series.

Lyu Wenbin

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Reading guide for China's Energy Transformation Outlook 2025

China Energy Transformation Outlook 2025 (CETO 2025) consists of an executive summary and three main sections. It can be found on https://www.cet.energy.

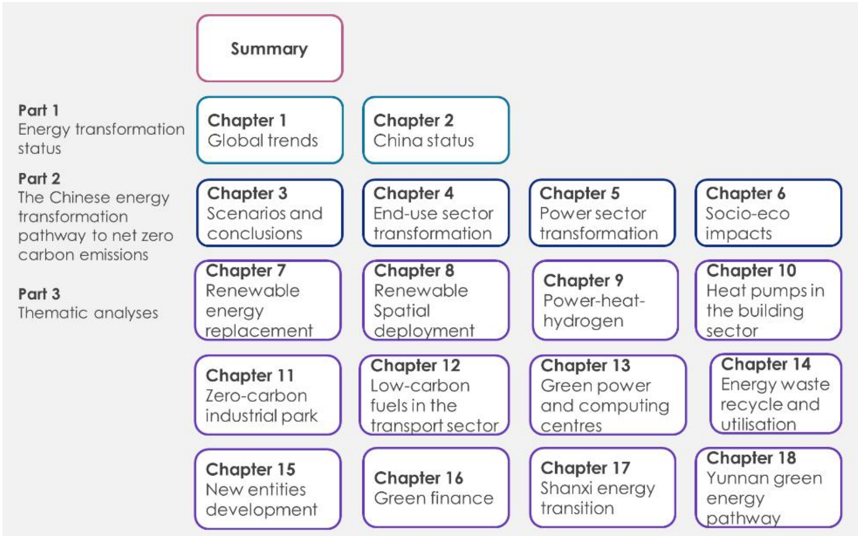
The Executive Summary (this report) gives an overview of the report's key findings and can be read independently.

Part 1 briefly analyses the global climate change and global energy transformation landscape (Chapter 1) and reviews recent changes in China's energy production and consumption system (Chapter 2).

Part 2 presents a scenario-based analysis of China's energy system transformation toward the 2060 carbon-neutrality target. It is primarily divided into four chapters. Chapter III summarizes the outlook for China's energy system transformation, including scenario design and key conclusions; Chapter IV analyses the energy transformation pathways in end-use sectors, primarily covering industry, buildings, and transportation; Chapter 5 examines the energy transformation outlook for the power sector, focusing on the development prospects of renewable energy, grid expansion, and power system regulation capabilities; Chapter 6 evaluates the impacts of China's energy transformation on its economic transformation and social development.

Part 3 primarily covers hot topics that have undergone significant changes in China in recent years and attracted widespread attention, divided into twelve chapters. Chapter 7 analyses how to enhance the secure and reliable substitution capacity of renewable energy; Chapter 8 explores the spatial planning and spatial element safeguards for new energy; Chapter 9 examines the current status and future prospects of electricity-heat-hydrogen coupling development in China and typical countries; Chapter 10 analyses the application of heat pump technology in the building sector in China and typical countries; Chapter 11 outlines China's objectives, tasks, and roadmap for establishing zero-carbon industrial parks; Chapter 12 explores the development prospects of low-carbon and zero-carbon alternative fuels for transportation; Chapter 13 analyses key issues and international practices in advancing the coordinated development of green power and computing power in China; Chapter 14 investigates recycling pathways for new types of waste such as wind power, solar PV materials, and power batteries; Chapter 15 presents typical cases of China's promotion of new business entities in the power sector; Chapter 16 summarizes international progress in leveraging green finance to enable low-carbon transitions; Chapter 17 analyses the achievements and future directions of Shanxi Province's energy transformation through its comprehensive energy revolution pilot program; Chapter 18 introduces Yunnan Province's exemplary practices in achieving comprehensive green transformation of economic and social development through its energy revolution. The analyses in Part III provide more robust policy, information, and technical support for the model construction and transition pathway analysis in Part 2.

Figure 1
China Energy Transformation Outlook 2025 report structure



Readers interested in model analysis may refer to Part 2 for a more comprehensive and in-depth understanding of the analytical processes and specific conclusions across key sectors. Those interested in hot topics may consult Part 3, where each chapter can be read independently.

We hope this report will help 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 the following email address: ceto@cet.energy.

This report reflects solely the research findings of the China Energy Transformation Outlook (CETO) project team. It does not necessarily represent the views or positions of any supporting institutions, nor does it represent official opinions.

Background of the study

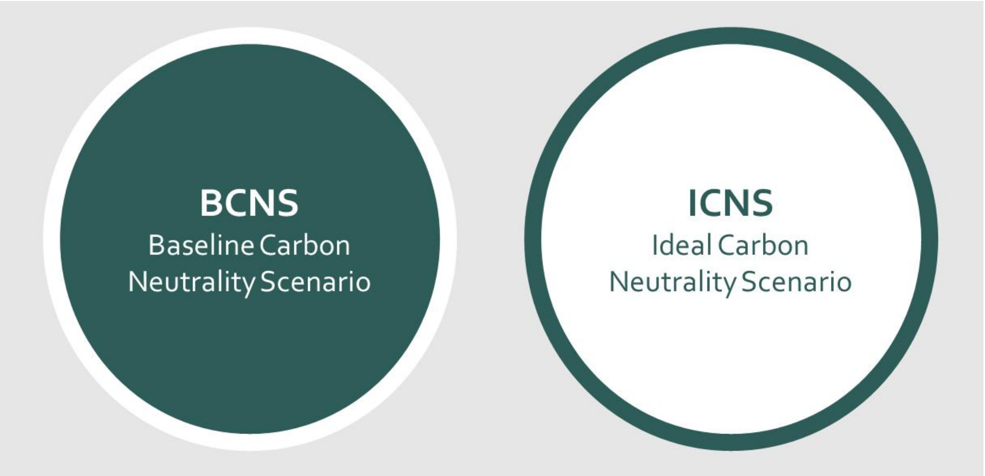
China Energy Transformation Outlook 2025 (CETO 2025) projects the pathways and prospects for China's energy transformation before 2060: During the *15th Five-Year Plan* period (2026–2030), China will achieve its carbon peak target as scheduled and strive to realise carbon neutrality before 2060. Carbon dioxide emissions account for approximately 81% of China's total greenhouse gas emissions. Carbon dioxide emissions from energy production and consumption activities constitute roughly 87% of the nation's total CO_2 emissions. Consequently, energy transformation represents China's primary front in addressing global climate change. Grounded in China's national context, drawing on international experience, and balancing China's socioeconomic development with its carbon-emission goals and vision, this study focuses on the challenge of mapping out a blueprint for China's energy transformation on the journey toward Chinese-style modernisation.

The CETO 2025 report analyses the recent global energy transformations and reviews China's energy transformation achievements over the past few years. It models the prospects for China's energy production and consumption transformation before 2060, focusing on pathways and technical solutions to achieve net-zero carbon emissions in China's energy system under two scenarios. The research team employed the China Energy Demand Analysis Model (ERI-LEAP), the China Electricity and Heat Deployment Optimisation Model (ERI-EDO), and the China Energy Transformation Socioeconomic Impact Assessment Model (CETPA). These models analysed the end-use energy consumption, electricity and heat supply and distribution, and the socioeconomic and environmental impacts of the energy transformation.

The study aims to chart the safest, most feasible, and most economical energy transformation pathway toward achieving the goals of building a modern socialist state by mid-century and reaching carbon neutrality before 2060. This integrated approach advances carbon reduction, pollution control, ecological expansion, and economic growth, ultimately realising the Chinese-style modernisation characterised by harmonious coexistence between humanity and nature.

In analysing China's energy transformation until 2060, the CETO 2025 research team developed two scenarios: a *Baseline Carbon Neutrality Scenario* (BCNS) and an *Ideal Carbon Neutrality Scenario* (ICNS). Both scenarios share the common goal of China achieving a carbon peak before 2030 and carbon neutrality before 2060. Considering the increasingly urgent global climate change situation and the more complex and volatile international political and economic landscape, technological innovation and its potential for widespread application hold significant promise. However, their progress relies on high-level international cooperation.

Figure 2
Two scenarios of the China Energy Transformation Outlook 2025



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The BCNS envisages a future in which, through a series of substantial endeavours, China's medium- to long-term socio-economic development objectives and its carbon peak and carbon neutrality targets are realised as scheduled. However, the international political and economic landscape is becoming increasingly complex, with recurring geopolitical conflicts. Climate change mitigation efforts have been relegated to secondary importance in certain nations or even met with withdrawal from international agreements. Disputes over climate-related trade barriers are proliferating, making consensus-building challenging; collaboration on low-carbon and zero-carbon technology R&D and industrial partnerships proves challenging; and cost reductions for new technologies remain difficult due to global market fragmentation. Against this international backdrop, China should steadfastly pursue its own responsibilities, striving to peak carbon dioxide emissions before 2030 and endeavouring to achieve carbon neutrality before 2060. This will drive China's medium- to long-term energy transformation.

The ICNS envisions a future in which, through a series of monumental efforts, China's medium- to long-term socioeconomic development goals and its carbon peak and carbon neutrality targets are achieved as planned. The severe global climate crisis sparks a heightened awareness among nations to take decisive action, prompting countries to prioritise accelerating their energy transformations as a core element of national development. Although political and economic conflicts may occasionally arise in specific regions or time frames, most nations will prioritise strengthening political, economic, trade, industrial, technological, financial, talent, knowledge, and data cooperation to address climate change. This concerted effort will systematically drive down the R&D costs of low-carbon, zero-carbon, and negative-carbon technologies, enabling all countries to adopt these technologies at scale earlier and at lower cost. Throughout the global green transition, greater emphasis is placed on equity and fairness, with full respect for developing countries' right to development. Nations adhere to the principle of "common but differentiated responsibilities," in which developed countries take the lead in fulfilling their emission-reduction obligations while providing financial and technical support to developing countries. This assistance helps capacity-constrained developing nations enhance their ability to address climate change.

"

Building upon the CETO 2024 study, the CETO 2025 report optimised and adjusted the model in four key areas:

- Firstly, it revised the model's baseline year parameters and future scenario projections based on China's latest advancements in wind power, solar PV, energy storage, and related sectors (which experienced higher-than-expected growth in 2024).
- Secondly, building on last year's model, it incorporates new modules for heat pump analysis in end-use sectors and for building stock turnover analysis, while enhancing provincial-level analysis modules for nuclear and hydropower capacity projections and for electricity/heat supply.
- Thirdly, it adjusts quantitative assessments of future global energy technology development, industrial and supply chain optimisation, and energy product economics under both scenarios, incorporating recent international geopolitical dynamics, global trade conditions, and climate governance trends, with heightened emphasis on energy security and supply considerations.
- Fourthly, incorporating the latest advancements in deep-sea offshore wind power, energy storage, electric heavy-duty trucks, and point-to-point green power supply technologies and business models, the report makes bolder assumptions than last year regarding energy technology innovation and industrial development prospects under the ideal scenario. It explores how technological breakthroughs in specific segments impact the development outlook for those sectors.

Figure 3
Vision for China's energy transformation targets under ICNS

Findings

Energy transformation refers to the process by which, against the backdrop of traditional energy systems struggling to adapt to the demands of the new era, guided by new development concepts, significant transformations in energy production and consumption are driven by enhanced energy science and technology innovation. This, in turn, catalyses major shifts in the energy industry chain and supply chain, energy governance systems, international cooperation frameworks, and even the global climate governance system, progressively establishing a new-type energy system characterised by net-zero carbon emissions.

This signifies that the energy transformation will drive significant changes across five dimensions: energy consumption, energy supply, energy technology and equipment, energy governance, and the international energy cooperation landscape.

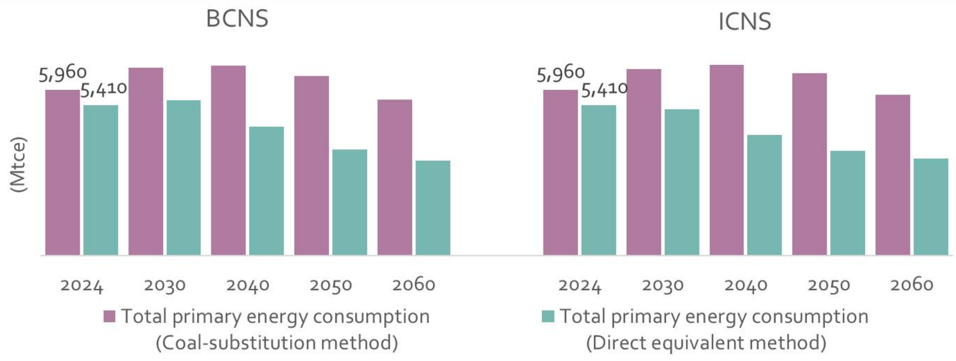
Through model analysis and thematic research, the project team has reached the following key conclusions regarding the long-term pathway for energy transformation and the medium- to short-term tasks for energy development over the next five years (2026-2030).

(I) Energy conservation and efficiency improvements are the prerequisites for energy transformation, and electrification is an effective pathway towards carbon neutrality

Throughout both the fossil fuel and renewable energy eras, we shall consistently prioritise energy conservation. During the fossil fuel era before 2035, energy conservation and efficiency improvements represent the most economical, low-carbon and cleanest form of energy, making them our "primary energy source". After 2050, in an era dominated by non-fossil energy sources, energy conservation and efficiency improvement will help reduce land use, lower reliance on critical mineral imports, ease electricity supply-demand balancing challenges, and lower the overall costs of the energy transformation.

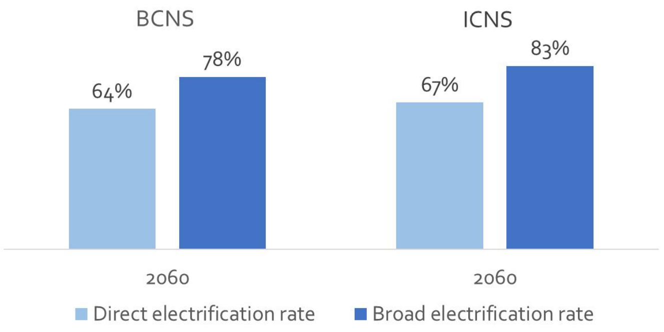
Different convert methods yield different projections for primary energy demand trends. Compared with the direct equivalent method, the peak primary energy demand calculated using the coal substitution method occurs later. It shows a smaller reduction from the peak demand level by 2060 (as shown in Figure 4).

Figure 4
Total primary energy consumption, 2024-2060 (comparison of coal substitution method and direct equivalent method)



Electrification represents a crucial direction for future energy transformations across the industry, building, and transport sectors. In 2024, China's direct and broad electrification rates were both 28.8%. By 2060, China's total electricity consumption is expected to reach 21,200-22,600 TWh, the direct electrification rate is expected to rise to 64%-67%, while the broad electrification rate is expected to increase to 78%-83% (as shown in Figure 5).

Figure 5
End-use direct and broad electrification rates in 2060



Note: Direct electrification refers to the direct use of electricity by end-use energy sectors. Broad electrification encompasses the use of electricity, synthetic fuels produced from electricity, and commercial heat generated from electricity by the end-use energy sectors.

Global energy transformation cooperation facilitates the widespread adoption of energy-efficient technologies and electrification solutions worldwide and in China, accelerating the pace of low-carbon transformation across industry, buildings, and transport sectors.

Regarding the key priorities for the next five years, the research team recommends

- Develop a top-level strategy for energy conservation, establish clear objectives and tasks, and position energy efficiency as a vital component in achieving the 2030 carbon emission intensity control target. Establish energy conservation plans and targets as a crucial component of achieving the 2030 carbon intensity control objectives.
- Strengthen monitoring, early warning and regulation of coal, oil and natural gas, and promote to reach peak consumption of coal and oil.
- Seize opportunities presented by emerging zero-carbon models - such as zero-carbon industrial parks, zero-carbon towns, and PSDF (solar PV-energy storage-DC flexible transmission) buildings - to advance new paradigms including point-to-point green power supply, electricity-heat-hydrogen coupling, low-carbon/zero-carbon transport fuels, and new business entities and business models in the power system. These efforts aim to enhance renewable energy integration and drive zero-carbon demonstrations that can, "from a single spark, start a prairie fire," pushing forward the energy revolution.
- Monitor AI-driven electricity demand and carbon emissions growth during 2025-2030 and promote the integrated development of computing power and green power.

(II) Building a new-type power system centred on wind and solar energy is an inevitable choice for the energy transformation

Strive to develop wind and solar power, while appropriately increasing the scale of nuclear power and conventional hydropower development, 'establish the new before abolishing the old' drives the gradual replacement of fossil fuels with non-fossil fuels. Accelerate the development of wind and solar power, making them the primary power sources. Expedite technological innovation in nuclear and hydropower, enhancing their installed capacity. By 2060, nuclear power generation capacity is targeted to reach approximately 200 GW, while conventional hydropower capacity is aimed to reach 550-590 GW. By 2060, non-fossil energy consumption shall account for over 80% of total primary energy consumption (as shown in Figure 6 and Figure 7).

Figure 6

Total primary energy consumption structure in 2060 (coal-substitution method)

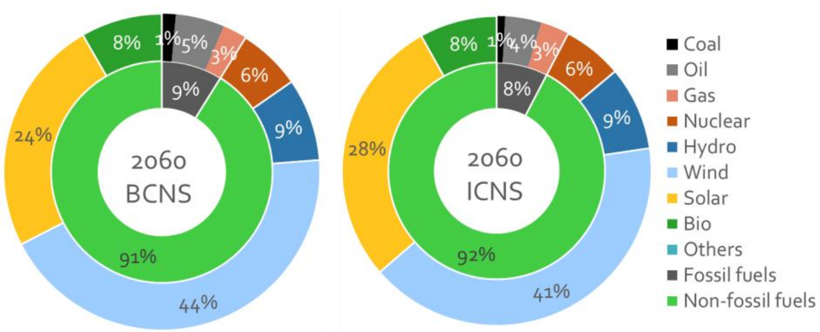
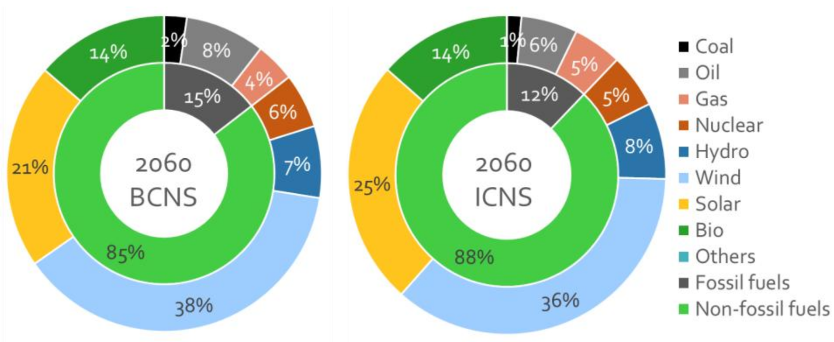


Figure 7

Total primary energy consumption structure in 2060 (direct equivalent method)



Five phases will drive the sustained advancement of wind and solar power to become the primary sources of electricity supply. By 2045, China will have established a new-type power system characterised by renewable energy dominance and high proportions of wind and solar generation. In the long term, the share of wind and solar in electricity generation significantly impacts the security and stability of the power system. Based on the share of wind and solar power in total generation, the development of the power system can be divided into five phases:

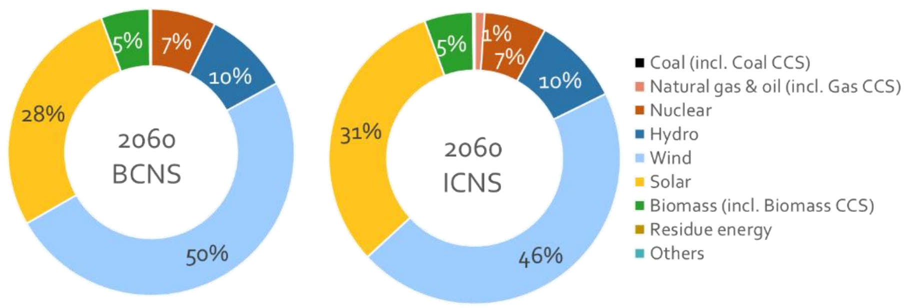
- Phase I <5% (very low share phase),
- Phase II 5%-20% (low share phase),
- Phase III 20%-40% (medium share phase),
- Phase IV 40%-60% (medium-to-high share phase), and
- Phase V >60% (high share phase).

China's power system is transitioning from the Phase II to the Phase III. As of 2024, wind and solar together accounted for 18.2% of China's total power generation, indicating that the power system is currently in the Phase II (low-share phase).

Model analysis suggests China's power system will enter the Phase III (medium-share phase) for wind and solar power generation in 2025, transition to the Phase IV (medium-to-high share phase) after 2030, and reach the Phase V (high-share phase) after 2040.

By 2060, wind and solar power in China will account for approximately 77% of total electricity generation, with renewable energy comprising around 92% of the electricity mix (as shown in Figure 8). In certain regions, the proportion of wind and solar power generation will advance to higher phases earlier.

Figure 8
Total electricity generation mix in 2060



Distributed wind and solar power will become key pillars of the urban and rural energy transformation. The model analysis indicates that China's installed wind power capacity will increase from 520 GW in 2024 to 3,220-3,340 GW by 2060, with distributed wind power accounting for 28%-29% of total wind capacity (as shown in Figure 9). Meanwhile, solar PV capacity will expand from 890 GW in 2024 to 5,500-6,500 GW by 2060, with distributed PV accounting for 50%-55% of total PV installed capacity (as shown in Figure 10). Distributed wind power and distributed solar PV systems, developed and utilised locally, will provide electricity services to an increasing number of urban and rural residents.

Figure 9
Wind power installation capacity structure in 2060

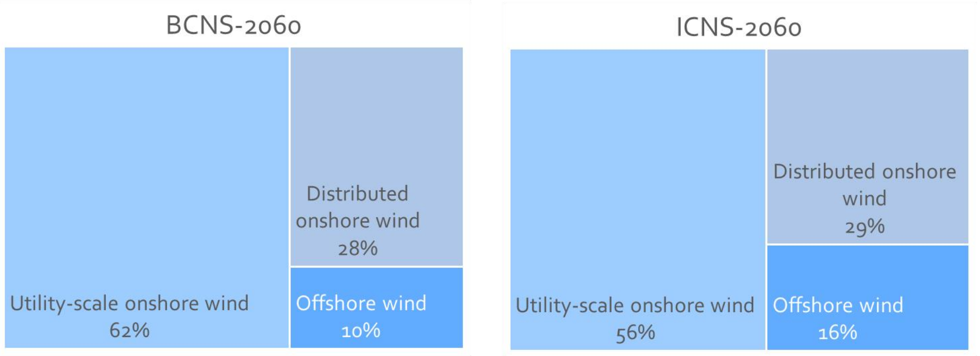
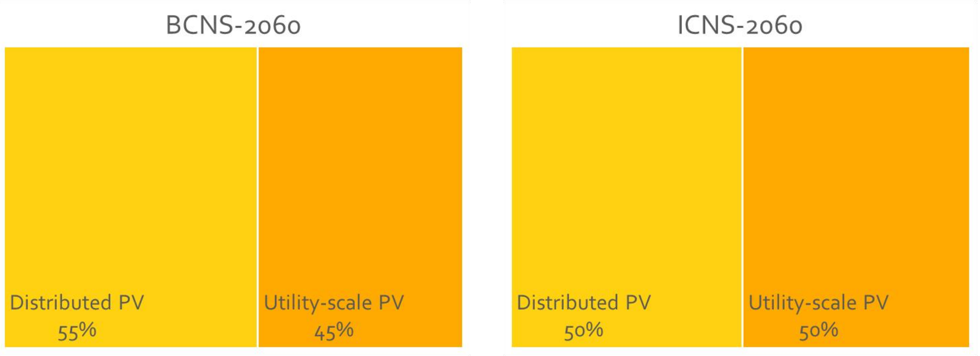


Figure 10
Solar PV installed capacity structure in 2060



The role of coal-fired power generation is gradually being transformed, shifting toward a dual focus on security supply and power system regulation.

Strengthening international cooperation on energy transformation will help China further enhance its non-fossil energy supply capacity and grid security.

Regarding the key priorities for the next five years, the research team recommends

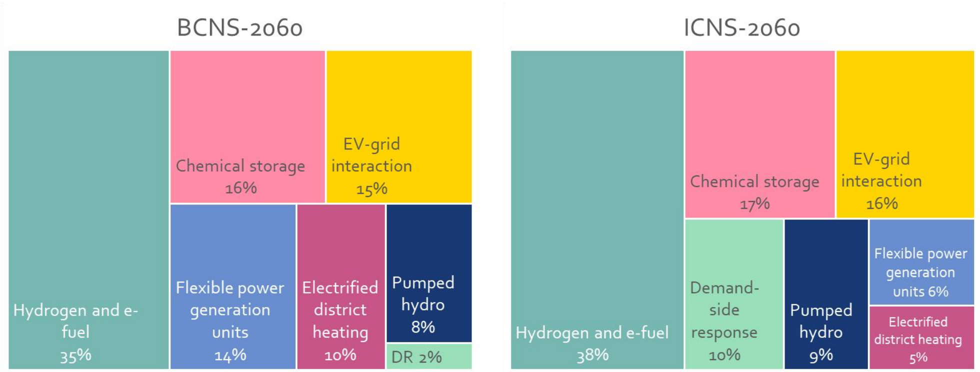
- Construct large-scale wind and solar power bases in desert and gobi areas. Promote the orderly and standardised development of offshore wind power clusters. Fully promote distributed solar PV and rural wind power projects. Accelerate the approval process for nuclear and conventional hydropower projects. Continuously increase the share of wind and solar power generation, as well as non-fossil energy generation.
- Strive to cultivate the green certificate market and stimulate the demand for green electricity consumption.
- The share of wind and solar power generation within provincial electricity production varies significantly across China. It is recommended that the five-phase classification method proposed in the report be utilised to conduct detailed analyses of each province's power system characteristics, thereby guiding provinces in developing tailored power sector development plans. Enhanced guidance should be provided to provinces rich in coal-fired power resources (e.g., Shanxi) and those abundant in renewable energy resources (e.g., Yunnan, Qinghai).

(III) Developing resilient, intelligent energy infrastructure is a crucial pillar in establishing a new-type energy system

The flexibility and regulation capacity of power systems serve as a crucial pillar for enhancing the security and resilience of the power grid. In 2024, China's power system regulation capacity remains predominantly reliant on coal-fired power plants. By 2060, China's power system regulation capacity will further increase to 4,970-5,810 GW, with electrolytic hydrogen and electrolytic synthetic fuels (e-fuels) contributing 1,740-2,180 GW of regulation capacity - accounting for 35%-38% of the total power system regulation capacity. Chemical storage will provide 800-1,000 GW regulation capacity, accounting for 16%-17%; vehicle-grid interaction (intelligent orderly charging and bidirectional charging/discharging (V2G)) will provide 750-920 GW, accounting for 15%-16%; pumped hydro will provide 400-500 GW regulation capacity, accounting for 8%-9% (as shown in Figure 11). Hydrogen, e-fuels, chemical storage, EV-grid interaction and pumped hydro will replace coal-fired power generation, becoming the primary sources of power system regulation capacity in 2060.

Figure 11

Power system regulation capacity structure in 2060



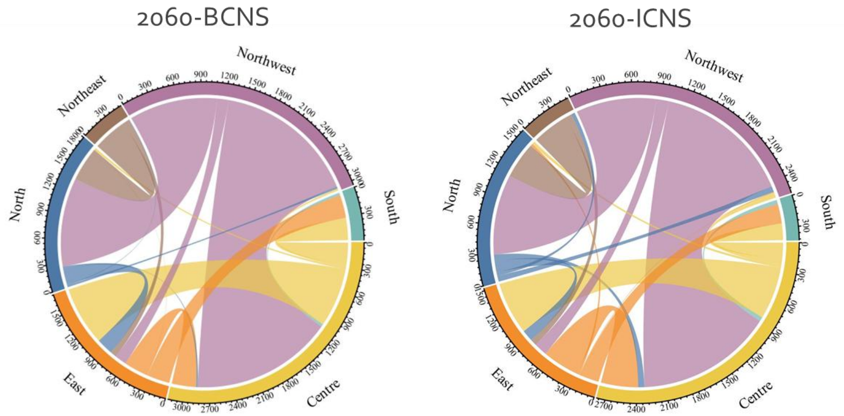
Cross-regional interconnection, self-balancing units, and multi-energy integration are emerging trends in future grid development. These manifest primarily in three aspects.

At the backbone grid level, the national grid will achieve a much higher level of inter-regional complementarity and mutual support. By 2060, the demand for inter-provincial and cross-regional power transmission is expected to reach 4,700-5,400 TWh (as shown in Figure 12), representing a two- to threefold of the current levels.

At the distribution grid and microgrid level, several self-balancing distribution grid units with regional characteristics will emerge, tailored to local renewable resources and demand profiles.

In terms of multi-energy coordination, power system balancing will interact with and couple with heating systems and transport charging/discharging systems.

Figure 12
Cross-regional electricity transmission demand in 2060 (in TWh)



The deep integration of energy and artificial intelligence represents an objective necessity for constructing a new-type energy system. AI will be deployed on a large scale across power grids, wind and solar power generation, hydropower, thermal power, nuclear power, coal, and oil and gas. This will not only enhance the quality of development of the new-type energy system but also stimulate accelerated growth in electricity demand. By 2024, electricity consumption for China's digital infrastructure is expected to account for approximately 3% of total national electricity consumption, with this proportion expected to exceed 10% by 2060.

Regarding the key priorities for the next five years, the research team recommends

- Accelerate the planning and deployment of charging infrastructure, appropriately increase the scale of smart charging/discharging stations to progressively enhance EV-grid interaction capabilities.
- Increase the share of flexible long-distance transmission technologies in planning new interregional transmission lines, enabling a higher proportion of green electricity to be delivered to the central and eastern regions.
- Optimise and expand distribution grid in accordance with local conditions. Aligned with the five-phase classification of power system development, drive the expansion and upgrading of distribution grids while continuously enhancing their capacity to accommodate new energy sources.
- Prioritise the application of artificial intelligence in forecasting and early warning of wind and solar power generation, grid dispatch, and power market transactions to bolster the security of the power system.

(IV) Technological innovation serves as the driving force behind energy transformation, while the industrialisation of energy equipment heralds vast market opportunities

The development of energy technology, equipment, and industries is of significant importance for underpinning China's energy transformation and building a modern socialist country. Achieving carbon peaking and carbon neutrality requires advancements in energy technology and in equipment manufacturing capabilities. The scale of China's clean energy-related industries continues to expand, with output value reaching approximately RMB 10 trillion in 2024, establishing it as a sunrise industry surpassing the real estate sector in scale. By 2060, China's clean energy industry is expected to reach a cumulative scale of RMB 100 trillion, playing a vital supporting role in China's goal of building a modern socialist country.

The energy sector is transitioning from a resource-intensive industry to a technology-driven one, with new technologies and industries emerging from China's energy transformation, offering vast market potential. Energy technology and equipment are the foundation for building a new-type energy system. In the near to medium term, industrial development will focus on technologies such as wind power, solar PV, electric vehicles, energy storage, electrolysers, and heat pumps. By 2060, China's wind power capacity will be over 6 times that of 2024, solar PV capacity over 6 times, stock of electric vehicles over 20 times, energy storage capacity over 9 times, electrolysers capacity over 120 times, and large-scale heat pumps over 36 times.

Plan ahead for the recycling and reuse of waste from retired energy equipment and machinery. After 2030, wind and solar power installations alongside power batteries will reach a peak in decommissioning. To effectively address this impending wave of retirements, coordinated advancement across policy, technology and institutional frameworks is required to foster the healthy and orderly development of the decommissioned equipment recycling industry.

Strengthen international industrial and supply chain cooperation. Encourage countries to collaborate with China on energy R&D and investment, leveraging respective strengths to deepen collaboration across the entire energy value chain and jointly develop regional and third-party markets. Seize the opportunity to jointly build a green Belt and Road to deepen South-South cooperation, support less developed countries in enhancing energy accessibility and low-carbon development capabilities, and jointly advance the global energy transformation.

Enhancing international cooperation on energy transformation will enable China and other nations to jointly reduce the manufacturing, service, and operational costs of new energy transformation technologies, accelerating the achievement of carbon neutrality both globally and in China.

Regarding the key priorities for the next five years, the research team recommends

- Increase investment in major energy R&D initiatives, intensifying research into key technologies such as long-distance flexible transmission, all-solid-state batteries, compressed air energy storage, carbon dioxide capture and storage, hydrogen metallurgy, ultra-low energy buildings, fuel cell vehicles, and nuclear fusion.
- The solar PV, new-type energy storage (e.g. chemical storage), and new energy vehicle industries should urgently address "rat race" competition to foster a market environment conducive to long-term, healthy development.
- Advance equipment renewal for wind power, solar PV systems, and electric vehicles, establishing a long-term mechanism for decommissioned energy equipment and equipment upgrades.
- Accelerate the involvement of green financial institutions in building energy transformation supply and value chains, providing policy and financial support for energy transformation and the development of energy equipment manufacturing.

(V) Deepening institutional reform and strengthening the synergy between energy and carbon policies

In response to new developments and demands in the energy sector, the governance framework should be restructured. This requires adapting to the rapid growth of distributed energy and self-balancing energy supply-demand units, alongside the shift in energy production organisation from centralised, integrated models to decentralised, flat, and distributed approaches. To establish a diversified, unified, open, and orderly competitive energy market system, while better leveraging the government's strategic planning, regulatory, and service functions. Legal frameworks and standards should be continuously adjusted and refined to align with developmental characteristics across different phases, such as the periods before and after carbon peaking and the five phases of power system transformation.

Continue advancing power market reform based on the unified national market framework. Aligned with the five developmental phases of the power system, it is necessary to establish a market framework that accommodates the characteristics of wind and solar power generation, enhances electricity security, and reduces overall carbon emissions. Regarding energy pricing reforms, it is necessary to continue promoting market-based pricing for electricity, coal, petroleum, and natural gas, while progressively making the external costs of fossil fuels explicit through carbon pricing.

Maximise the role of carbon policies in driving energy transformation. Leveraging China's institutional advantages, carbon-management mechanisms should be implemented with more details across multiple levels: "local carbon assessments", "sectoral carbon controls", "enterprise carbon managements", "project carbon evaluations", and "product carbon footprints", thereby accelerating energy transformation. Further enhance the role of the national carbon emissions trading market in advancing energy transformation, and gradually shift carbon market allowances from intensity control to total volume control. Driven by the carbon peaking and carbon neutrality targets, accelerate the green and low-carbon transformation of the energy sector.

Strengthen international cooperation on energy transformation to facilitate in-depth exchanges between China and other nations on legislation, carbon emission strategies and policies, and energy transformation measures, thereby enhancing China's comprehensive capabilities in this transformation.

Regarding the key priorities for the next five years, the research team recommends

- Prioritise establishing a unified national power market, reinforcing policy guidance and regulatory oversight to better leverage the market's role in integrating renewable energy and fostering the development of diverse new market entities. Refine electricity pricing mechanisms to facilitate orderly cost transmission and equitable burden-sharing.
- Expand ETS coverage to include key emission-intensive sectors with rapid development such as petrochemicals and chemical. The allocation method should gradually shift from intensity-based to absolute-cap control.
- Encourage green finance institutions to actively participate in carbon and power markets to provide greater financial support for the energy transformation.

China should advance its energy transformation across five dimensions in parallel: electrification of energy consumption, decarbonisation of energy supply, interaction between supply and demand, modernisation of energy equipment, and scientific energy governance. Concurrently, international cooperation on energy transformation should be strengthened to jointly explore pathways forward. This will ensure China's energy transformation progresses smoothly while strengthening China's role in global energy transformation.

Amidst accelerating global transformations and the escalating climate crisis, it is imperative that nations join hands to uphold multilateralism and deepen international cooperation, translating long-term visions and international commitments into concrete project arrangements and pragmatic actions, work together to save our shared human destiny.

China energy flow charts

Figure 13
China's energy flow chart in 2024

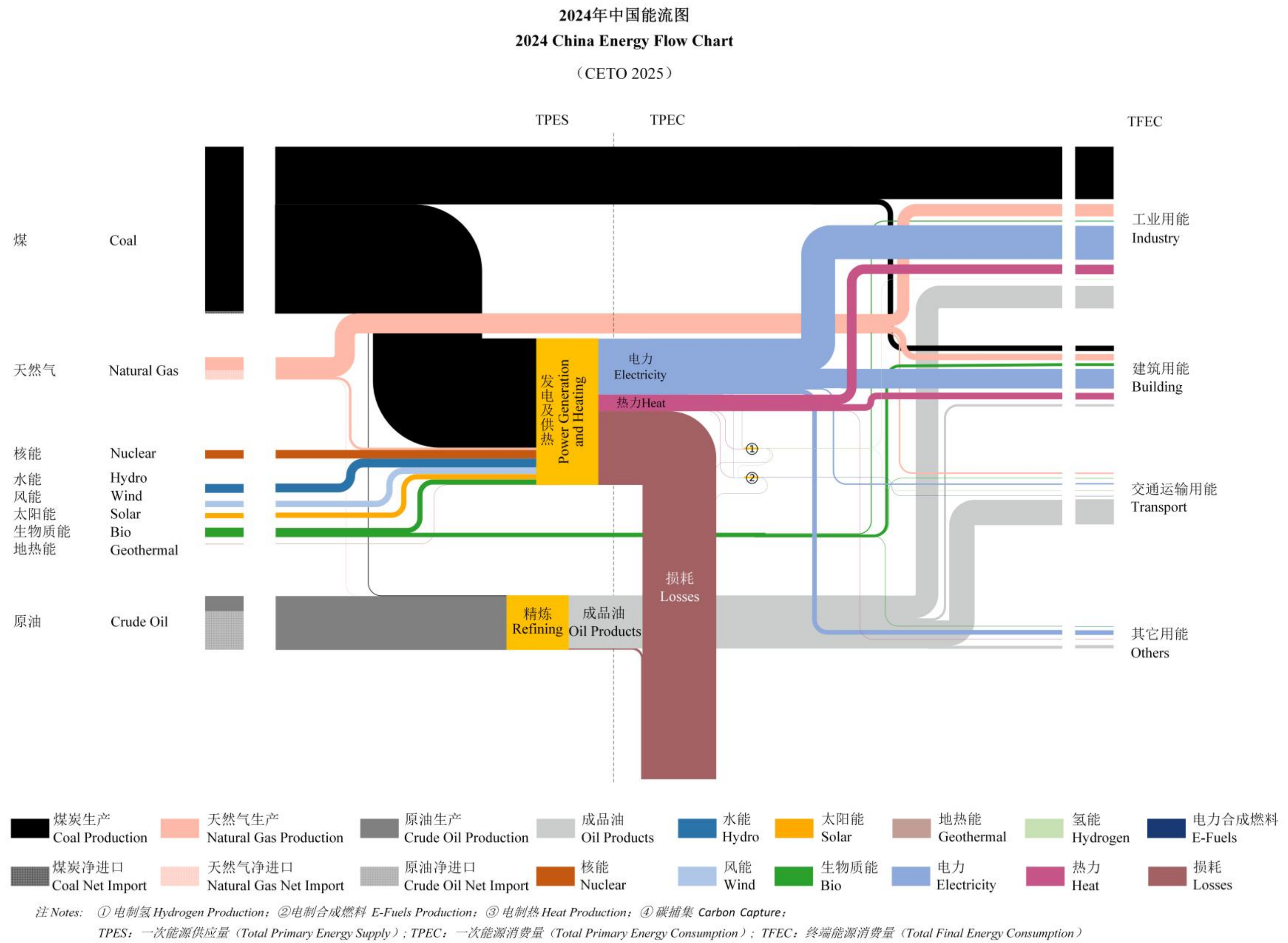


Figure 14
China's energy flow chart in 2030 - BCNS

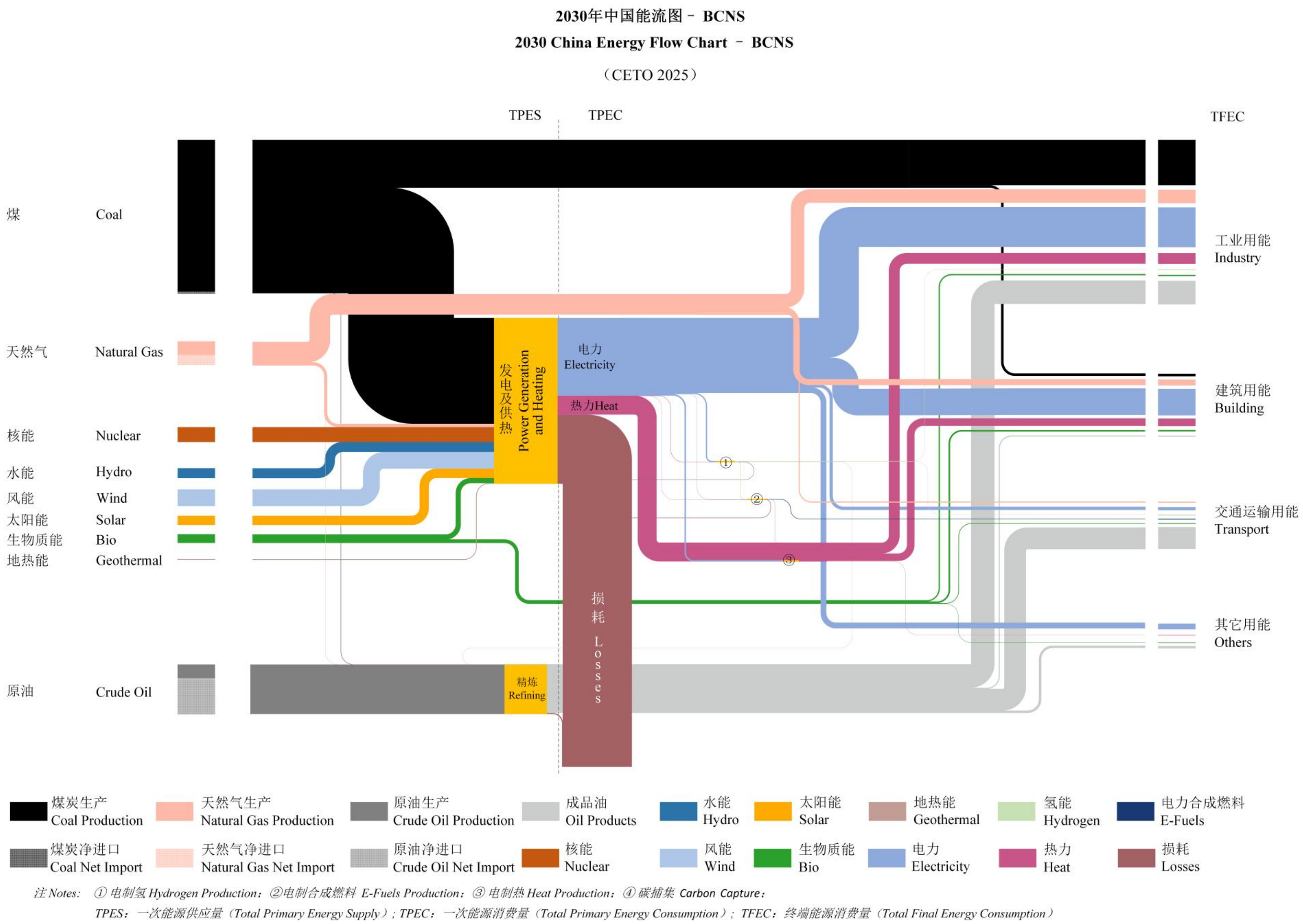


Figure 15

China's energy flow chart in 2030 - ICNS

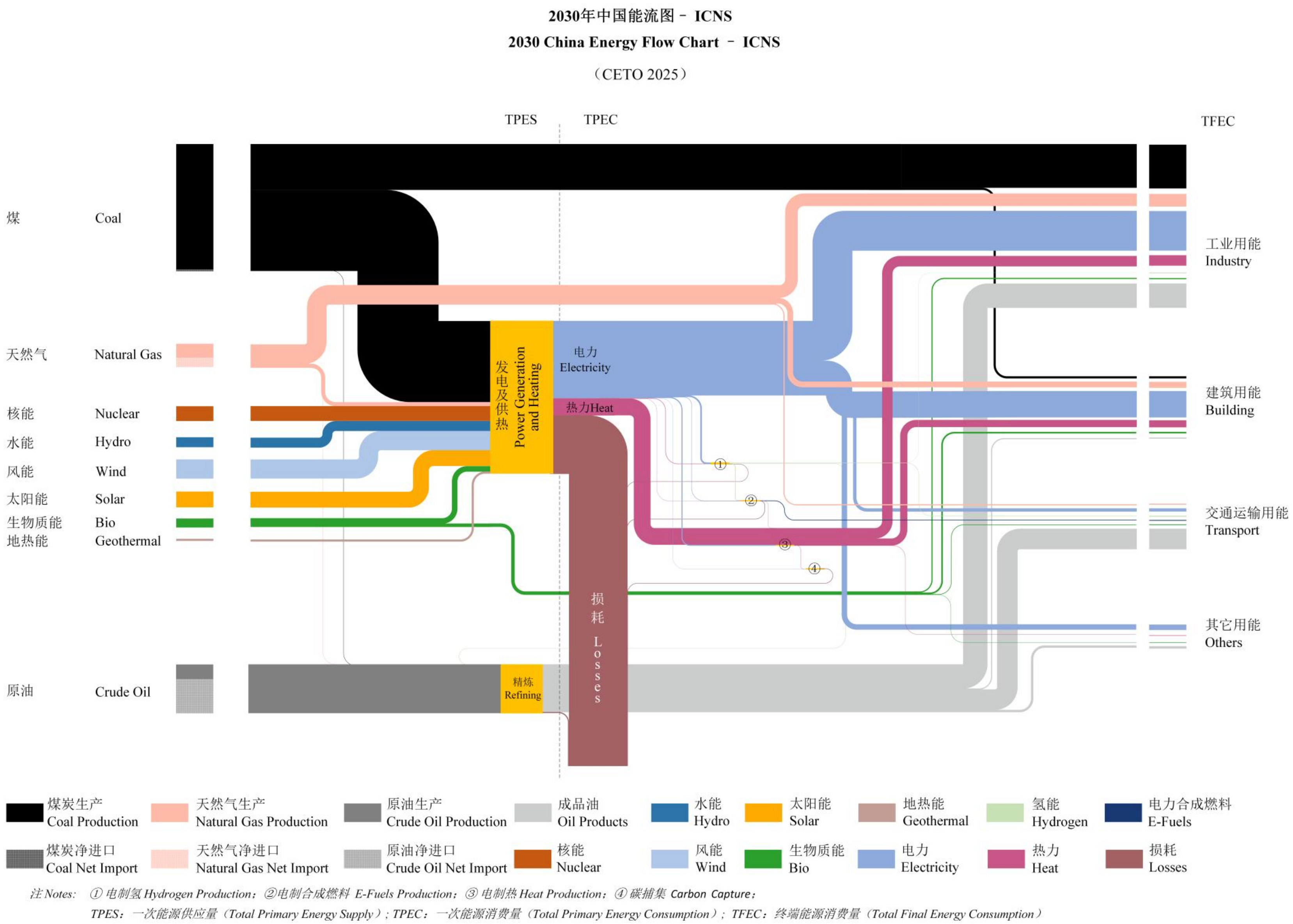


Figure 16
China's energy flow chart in 2060 - BCNS

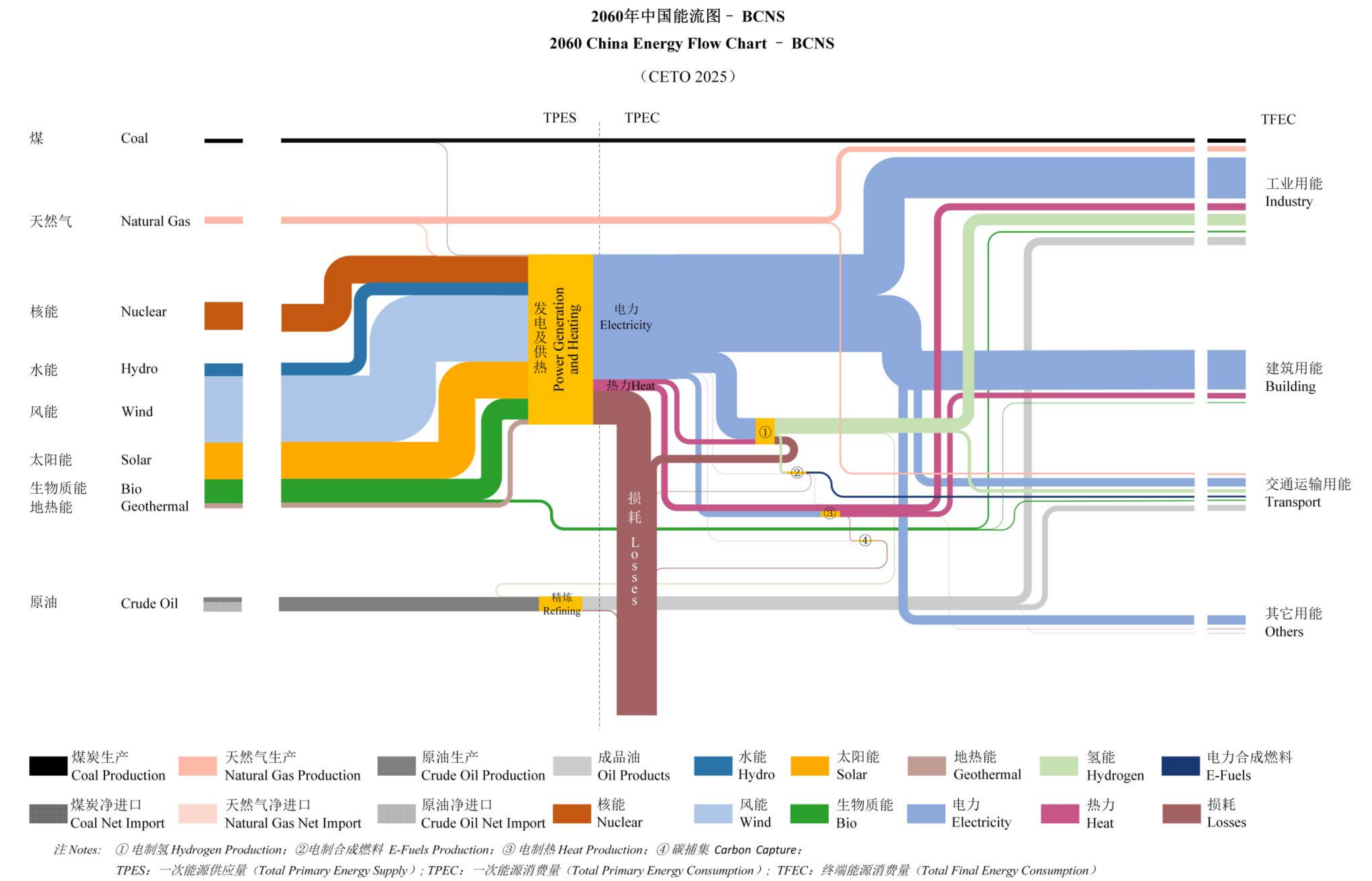
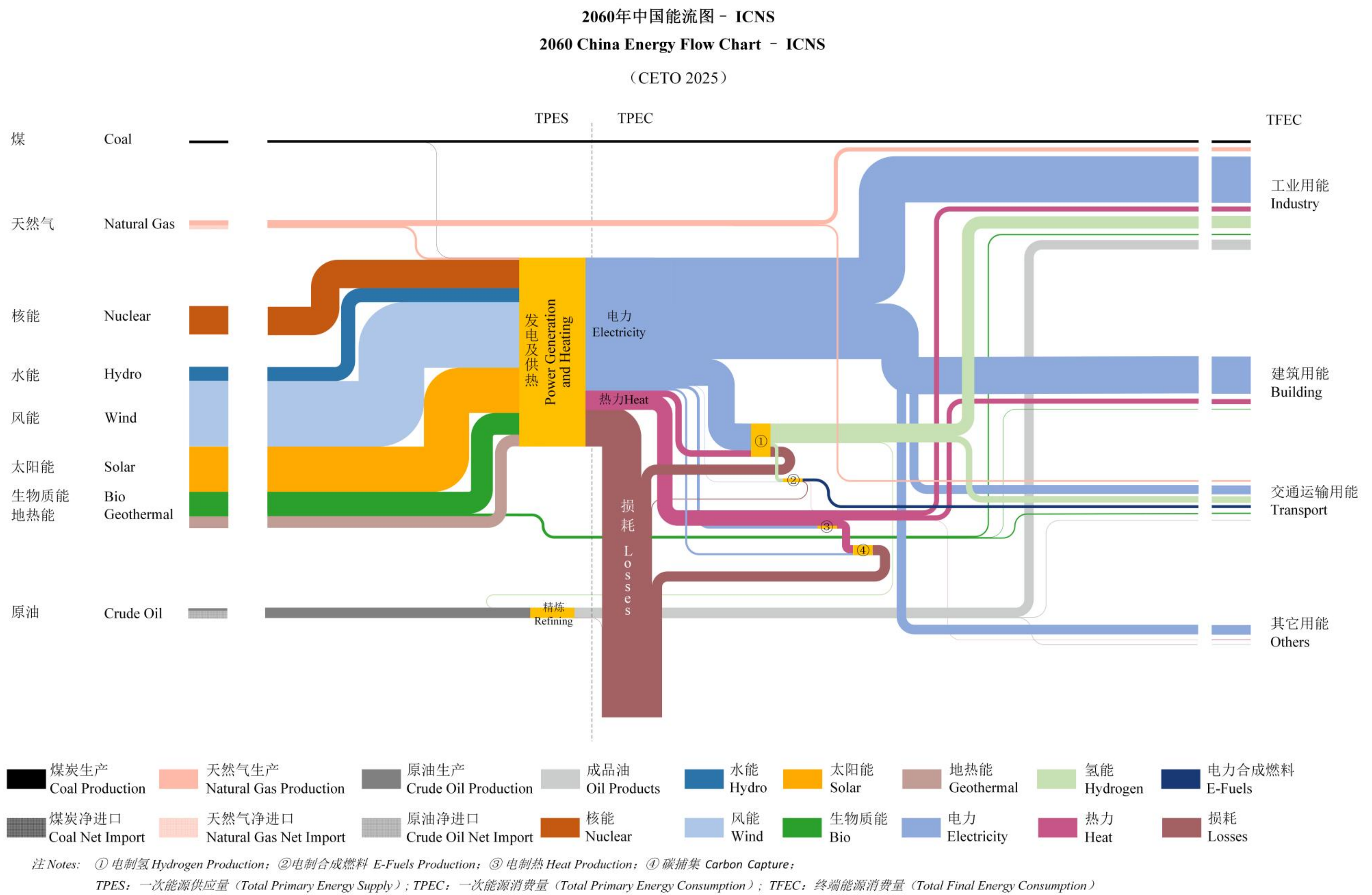


Figure 17
China's energy flow chart in 2060 - ICNS



Key scenario analysis findings

Figure 18

Total primary energy consumption and structure, 2024-2060 (direct equivalent method)

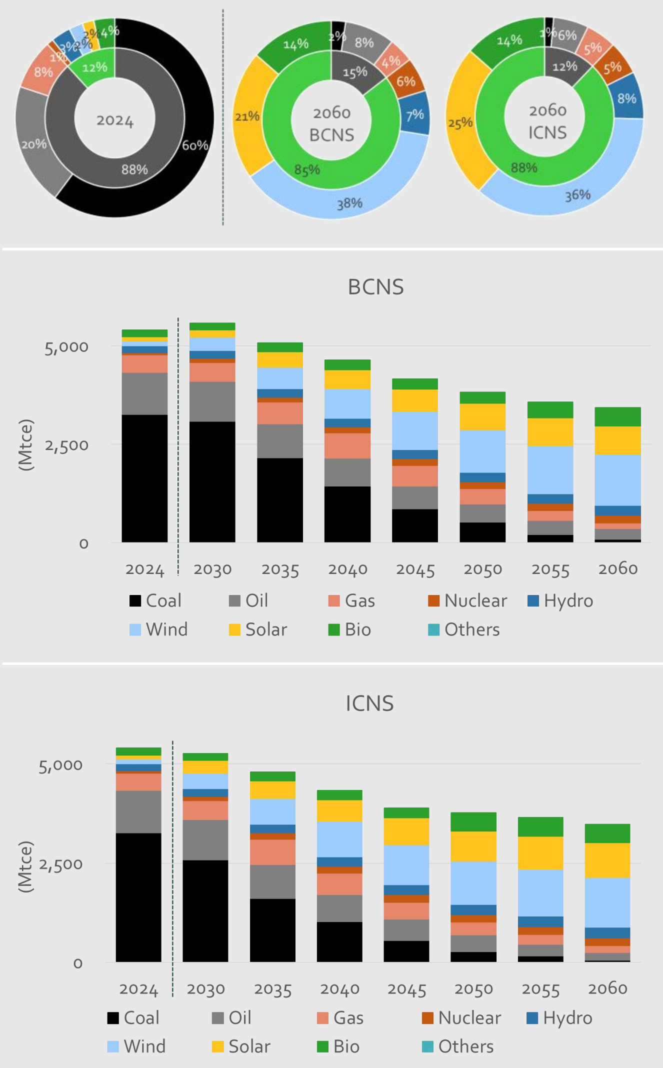


Figure 19

Total primary energy consumption and structure, 2024-2060 (coal substitution method)

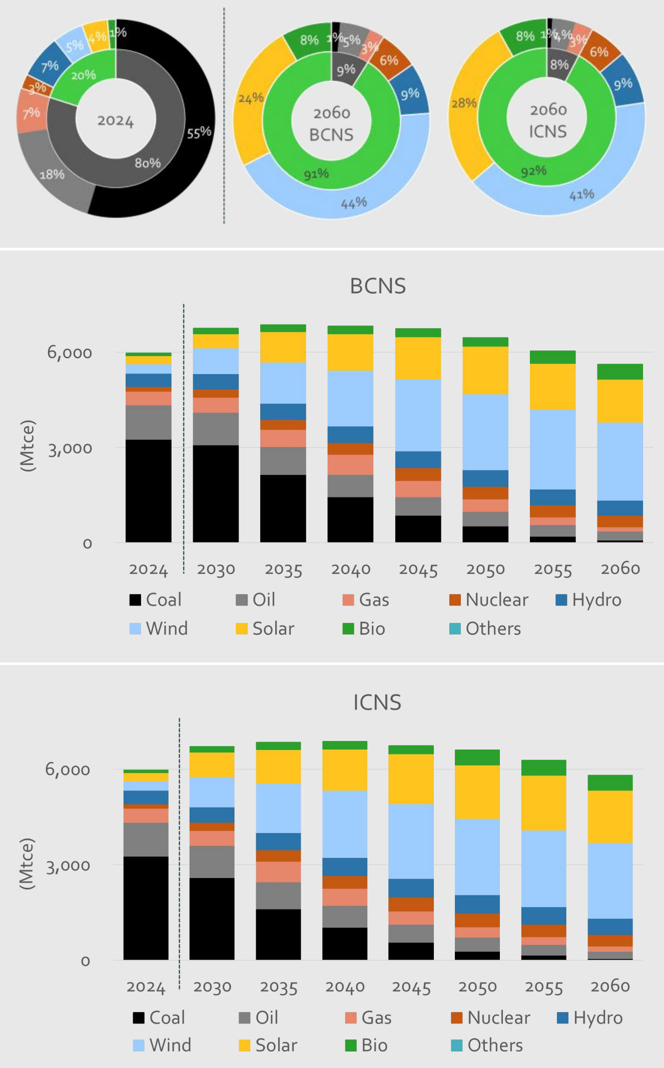


Figure 20

Society-wide electricity consumption and structure, 2024-2060

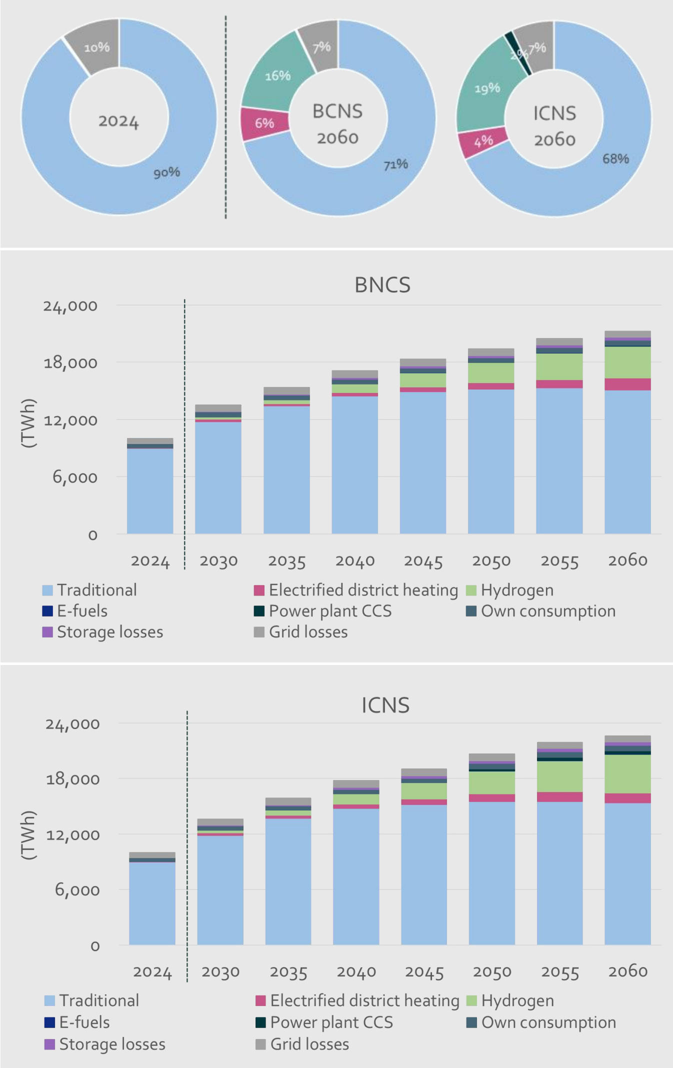


Figure 21
Total final energy consumption and structure, 2024-2060

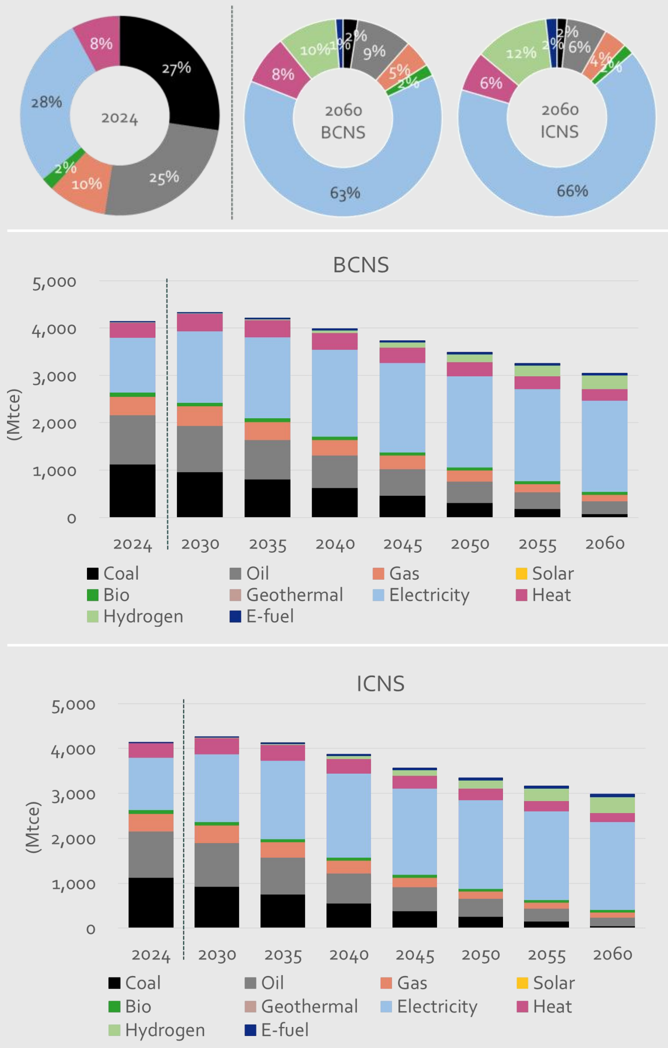


Figure 22
Installed power generation capacity and structure, 2024-2060

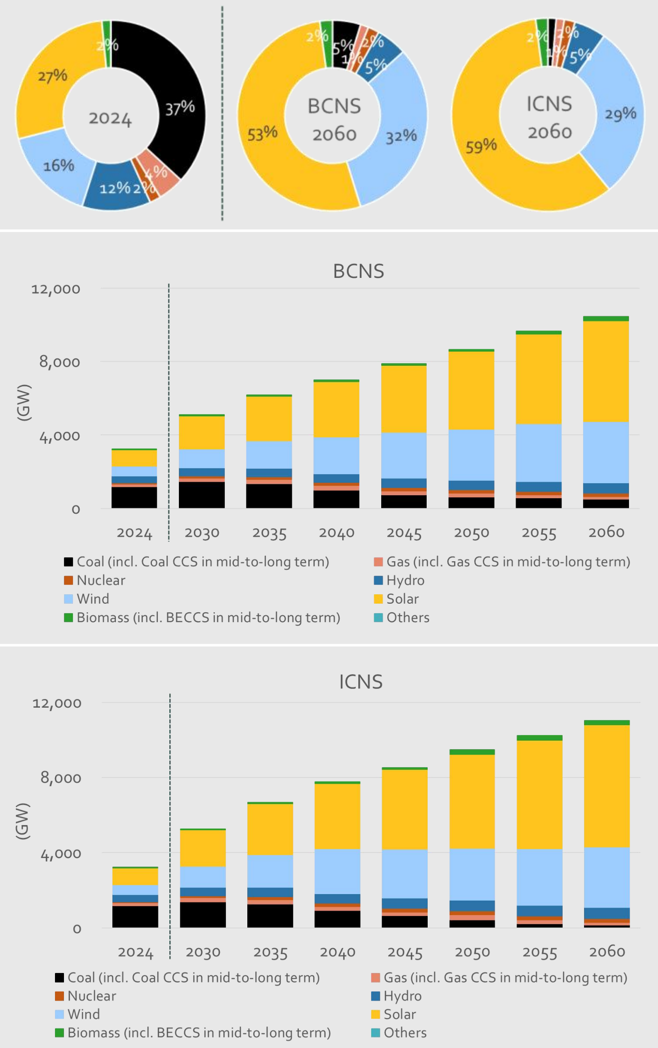


Figure 23
Total power generation and structure, 2024-2060

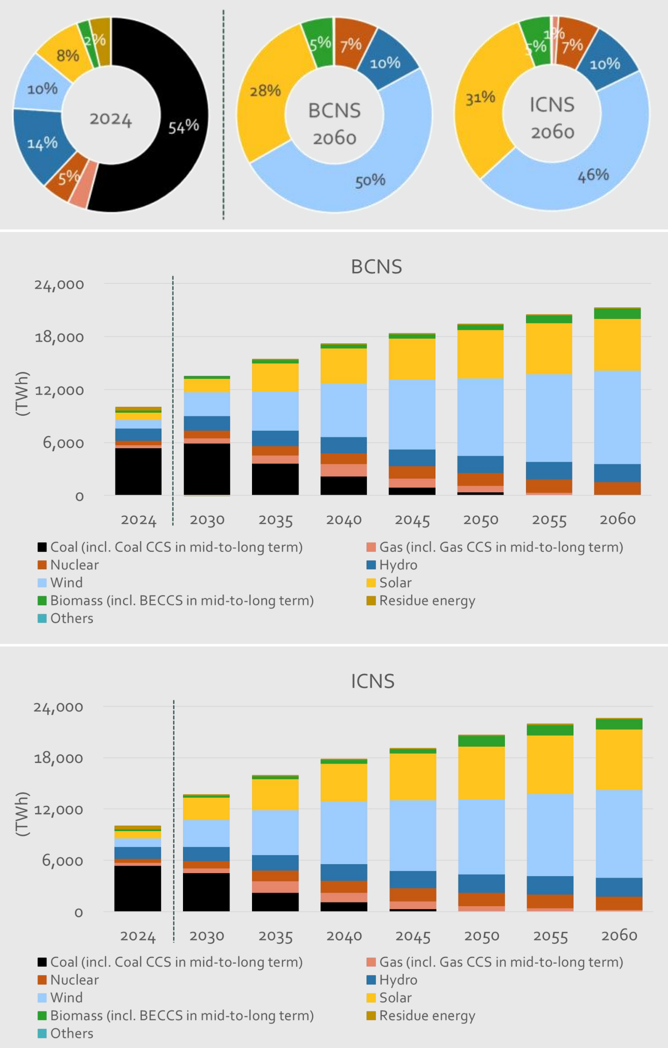


Figure 24
Wind power installed capacity and structure, 2024-2060

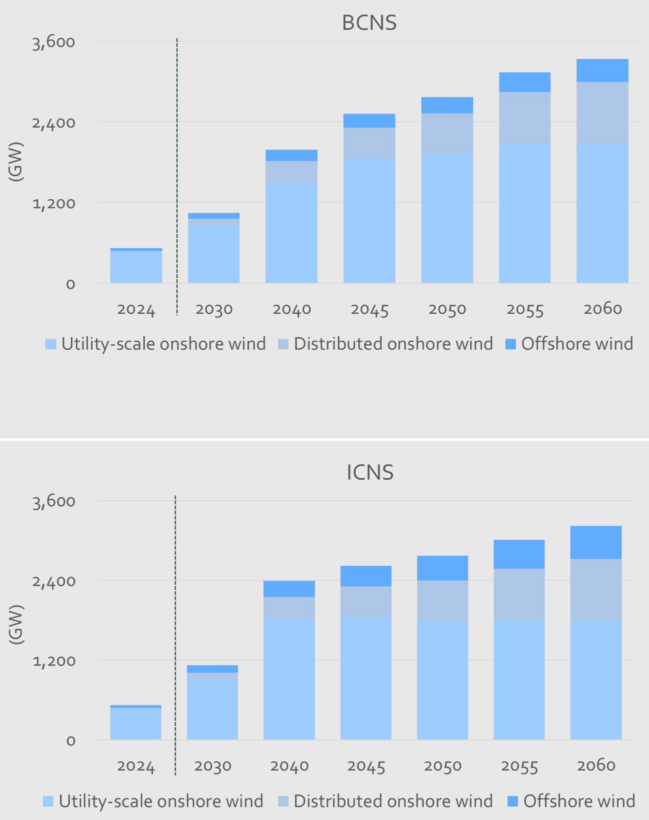


Figure 25
Solar PV installed capacity and structure, 2024-2060

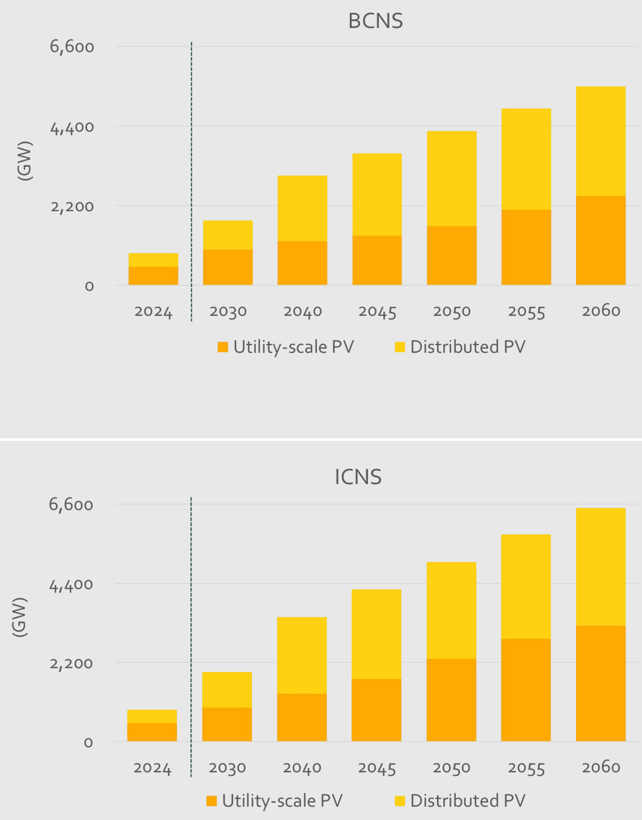
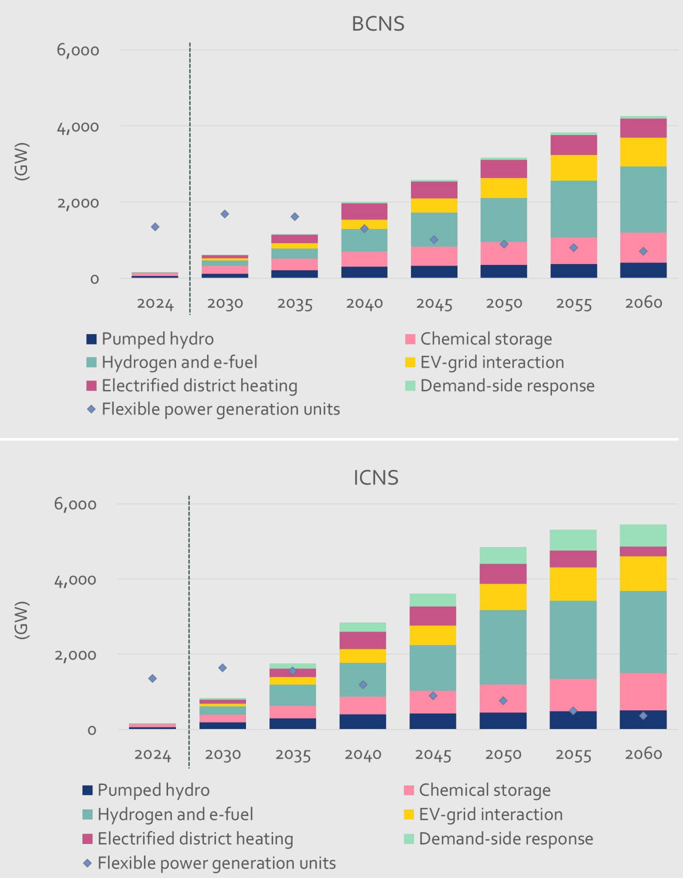


Figure 26
Power system regulation capacity and structure, 2024-2060



Part I A review of the energy transformation

(I) The global climate change situation is becoming increasingly severe, making it imperative to accelerate the energy transformation and deepen international cooperation

The impact of climate change on human survival and development is intensifying. By 2024, the global average temperature had risen by over 1.5°C compared to pre-industrial levels (the 1850-1900 average), precipitating a series of grave risks including frequent extreme weather events, species extinction, sea-level rise, and reduced crop yields. This serves as a stark warning to the international community that unprecedented efforts are needed to advance the low-carbon transition.

Green industries such as wind power, solar PV, energy storage, and new energy vehicles are now entering an era of explosive growth. Major economies are intensifying investments in technological R&D and market cultivation, positioning green and low-carbon industries as the new frontier in international competition and accelerating the pace of energy transformation. Concurrently, the deep integration of digital and intelligent technologies with energy systems is profoundly reshaping energy production and consumption patterns. Applications such as smart grids and virtual power plants have significantly enhanced the capacity for renewable energy integration and system operational efficiency, while also driving substantial growth in green energy demand for data centres.

Presently, the resurgence of unilateralism and protectionism has weakened the collective momentum for global climate governance and energy transformation, severely disrupting the stability of global clean energy industrial and supply chains while hindering the deployment and application of clean energy equipment worldwide. China's new round of nationally determined contributions (NDCs) commits to reducing economy-wide net greenhouse gas emissions by 7% to 10% below peak levels by 2035, injecting greater stability and certainty into the global collective response to climate change. This year marks the tenth anniversary of the Paris Agreement and a pivotal juncture for the submission of new NDCs. As global climate governance enters a critical phase, nations must remain steadfast in their commitment to a low-carbon transition, strengthen international cooperation on green technologies and industries, safeguard the stability and smooth operation of global energy supply chains, and jointly address the challenges posed by global climate change.

(II) China is accelerating its energy transformation, establishing the world's largest and fastest-growing renewable energy system

Over the past two years, despite increasingly complex international circumstances, China's economy has maintained steady development with sustained growth in primary energy consumption. Despite significant pressure to ensure energy supply, China's energy transformation accelerated throughout 2024, with the share of renewable energy in incremental energy consumption rising substantially. Remarkable achievements were made in advancing green, high-quality energy development.

Primary energy consumption continued to grow, while electricity consumption accelerated. In 2024, China's primary energy consumption reached 5,960 Mtce, with per capita energy consumption at 4.2 tce. Industrial consumption accounted for approximately 70% of national energy consumption. Since the beginning of the 14th Five-Year Plan period, the growth rates of China's energy and electricity consumption have markedly accelerated, with both energy and electricity consumption elasticity coefficients at elevated levels (as shown in Figure 27 and Figure 28).

The transformation of energy infrastructure accelerated, with both energy and electricity consumption moving toward greener pathways. By 2024, non-fossil energy accounted for 19.8% of China's primary energy consumption, while coal's share declined to 53.2% (based on the coal substitution method, as shown in Figure 29). In terms of existing capacity, approximately 1 kWh of every 3 kWh of electricity consumed in China originated from green power sources (as shown in Figure 30). In terms of incremental growth, the proportion of new non-fossil fuel electricity consumption relative to total societal electricity consumption has risen from approximately 40% around 2017 to 83% by 2024 (as shown in Figure 31).

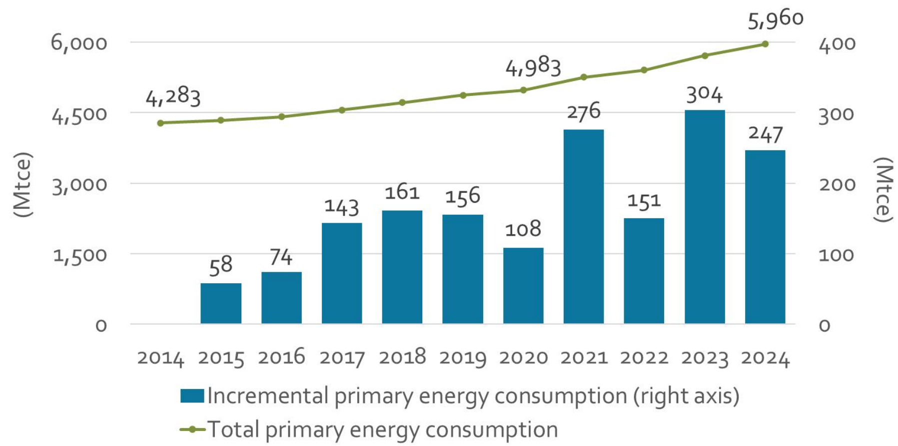
China has established the world's largest power system, constructing the world's most extensive renewable energy generation network in the shortest timeframe. In 2024, China's electricity generation exceeded 10,000 TWh, more than double that of the United States and over three times that of the European Union. With immense electricity demand comes substantial pressure for the power system transformation. Facing formidable challenges, China has actively accelerated renewable energy development, maintaining the world's largest installed wind power capacity for 15 consecutive years and the largest solar PV capacity for 10 straight years. In 2024, China's new wind and solar power installations totalled 360 GW. Cumulative wind and solar capacity accounted for 47% of the global total, while new installations that year represented 63% of the world's additions. By July 2025, China's renewable energy generation capacity expanded to 2,170 GW. Its role in securing supply and driving transformation has become increasingly pronounced. In 2024, China issued 4.73 billion green certificates and traded 446 million green certificates. Since 2020, new energy sources have played an important role in optimising China's energy structure, achieving two '50%' milestones: from 2020 to 2024, the contribution of non-fossil energy to the incremental electricity generation nationwide exceeded 50%, and the supply of non-fossil energy increased by nearly 50%.

New energy storage installations doubled in 2024, while new energy vehicle market share exceeded 40% for the first time. China's total energy storage capacity reached 138 GW in 2024, with new energy storage accounting for 73.8 GW — a doubling of the 2023 installed capacity. China's automobile production and sales volumes reached 31.282 million and 31.436 million units, respectively, in 2024. Within this, new energy vehicle production and sales stood at 12.89 million and 12.87 million units, respectively, representing year-on-year growth of 34.4% and 35.5%. Concurrently, key energy transformation technologies such as compressed air energy storage and heat pump technology accelerated their commercialisation pace, beginning to gain traction in the market.

Power market reforms progressed steadily, with significant achievements in establishing a unified national power market. Firstly, China constructed a "multi-tiered, multi-category, multi-functional" unified national power market system, defining market tasks across spatial, temporal, and trading product dimensions. Secondly, the Chinese government has formulated a fundamentally comprehensive regulatory framework for the unified national power market. Building upon the Basic Rules for Power market Operation, the framework centres on three core trading mechanisms — the medium-to-long-term market, spot market, and ancillary services market — supported by market registration, metering and settlement, and information disclosure, thereby establishing fundamental operational principles. Thirdly, the scale of electricity trading markets has expanded, with an increasingly diverse range of market participants. By 2024, market-traded electricity accounted for over 60% of total national electricity consumption, with active participation from power generation enterprises, transmission and distribution companies, power aggregators, and electricity consumers.

The framework for the dual-control system on carbon emissions has taken initial shape, with the carbon emissions trading market gradually expanding its coverage. Drawing on the experiences of developed countries and building upon China's innovative energy conservation policy system, the General Office of the State Council issued the *Work Plan for Accelerating the Establishment of a Dual-Control System for Carbon Emissions* in 2024, proposed that during the *15th Five-Year Plan* period, carbon emission intensity reduction would be designated as a binding indicator for national economic and social development, replacing energy consumption intensity as the binding metric. Key components include five aspects: "local carbon assessments", "sectoral carbon controls", "enterprise carbon management", "project carbon evaluations", and "product carbon footprints". In 2025, China's carbon emissions trading market will for the first time incorporate the steel, cement, and aluminium smelting industries into its mandatory carbon market. The total emissions covered by this mandatory market will account for over 60% of the nation's total carbon dioxide emissions. Given that the energy activity is China's primary source of carbon emissions, the improvement and enhancement of the dual-control system and carbon trading market policies will undoubtedly speed up the impetus for China's energy transformation.

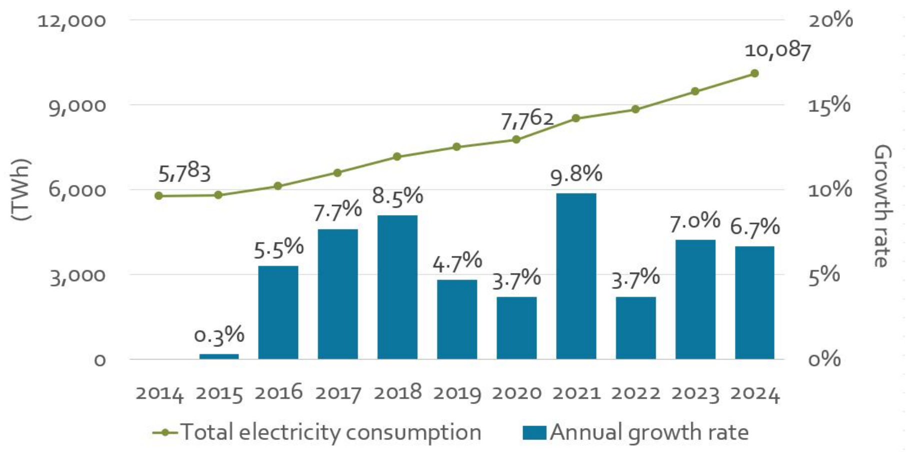
Figure 27
China's total primary energy consumption and growth rate, 2014-2024



Source: China Statistics Press, China Statistical Yearbook 2024 and China Statistical Abstract 2025

Figure 28

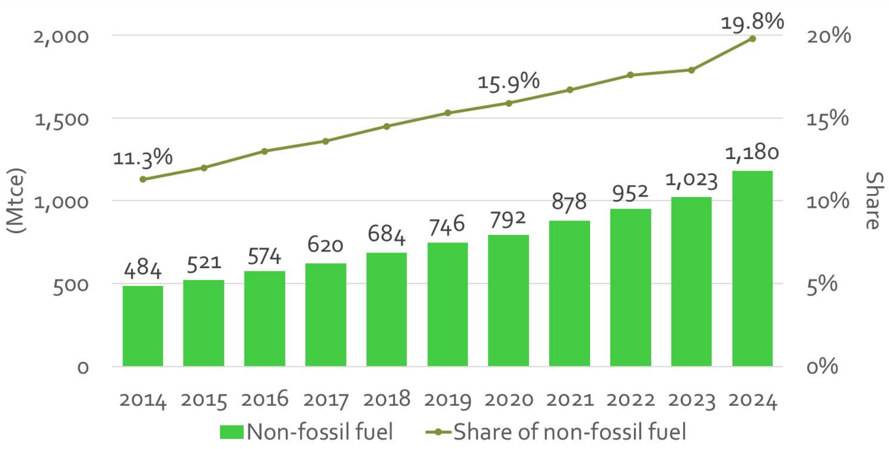
Total electricity consumption and annual growth rate, 2014-2024



Source: China Statistics Press, China Energy Statistical Yearbook 2023, Statistical Bulletin 2024, 2025

Figure 29

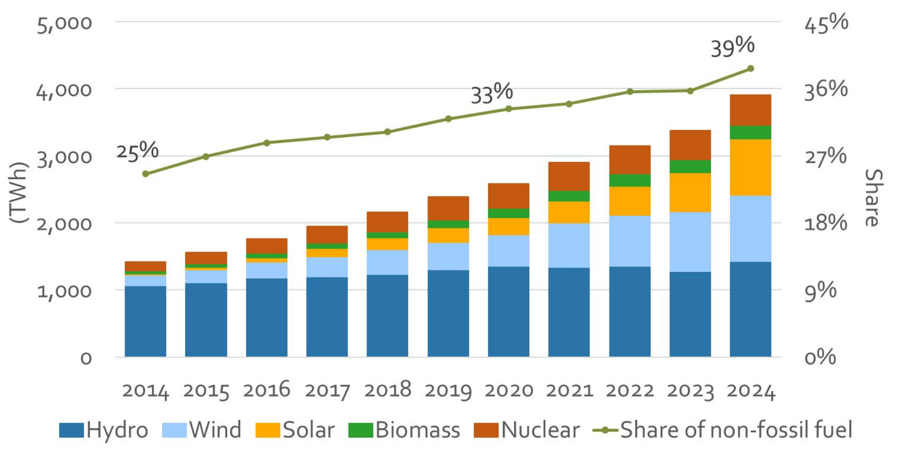
Non-fossil energy sources and their share of primary energy consumption, 2014-2024



Source: China Statistics Press, China Energy Statistical Yearbook 2023, Statistical Bulletin 2025. Coal substitution method used.

Figure 30

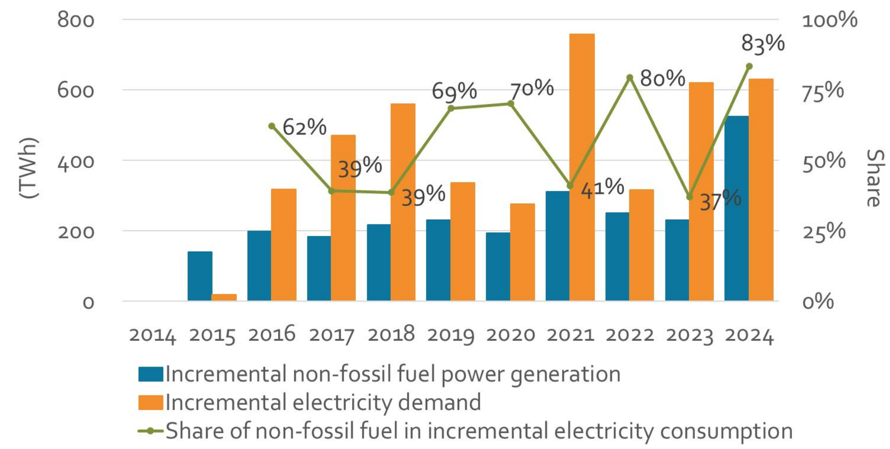
Non-fossil power generation and its share in total power consumption, 2014-2024



Source: National Energy Administration

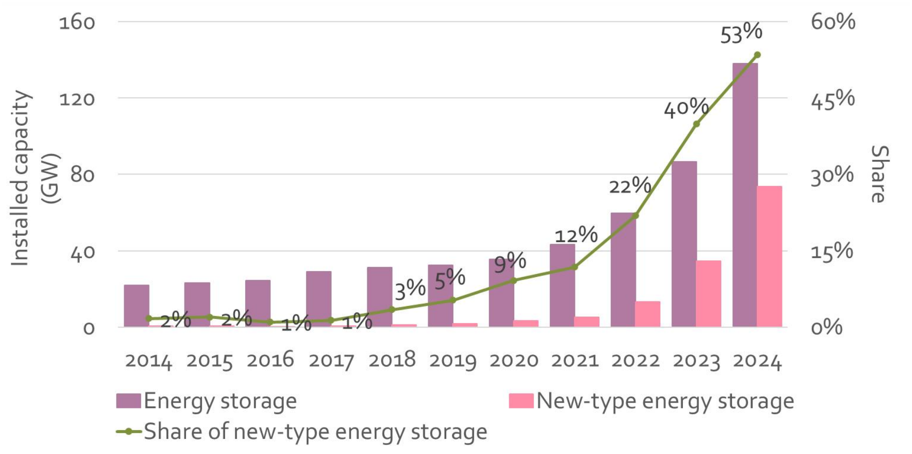
Figure 31

Non-fossil energy electricity generation and its share in incremental electricity consumption



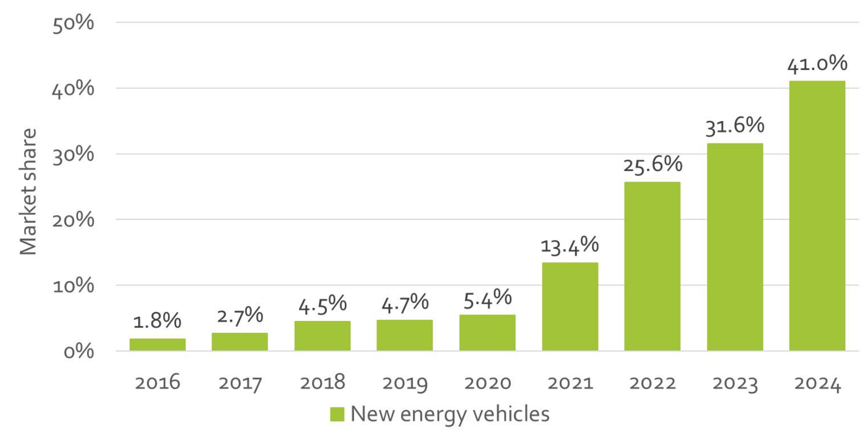
Source: Calculated by the author based on data from the National Energy Administration and the National Bureau of Statistics.

Figure 32
Installed energy Storage capacity, 2014-2024



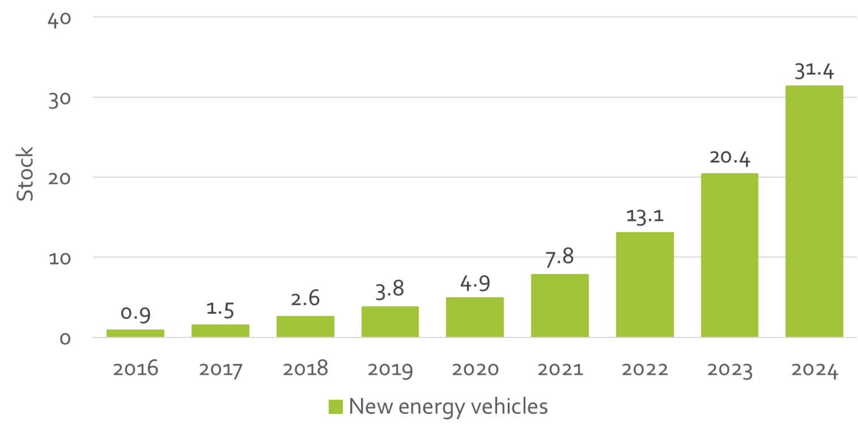
Source: China Energy Storage Association, Energy Storage Industry Research White Paper 2025

Figure 33
Market share of new energy vehicles, 2016-2024



Source: China Association of Automobile Manufacturers

Figure 34
Stock of new energy vehicles, 2016-2024



Source: China Association of Automobile Manufacturers

(III) Despite positive progress in the energy transformation, China's energy development also faces numerous growing pains

Particularly in the past two years, a series of new difficulties and challenges have frequently arisen.

Firstly, integrating wind and solar power generation has become increasingly difficult in certain regions. For a long time, China's wind and solar resources have been primarily located in the northwest, while energy consumption has been concentrated in the eastern and central regions. The distance between these areas ranges from 1,000 to 3,000 kilometres, resulting in a significant mismatch between regional supply and demand. In recent years, while wind and solar generation capacity in the northwest has surged, the inability to transmit 100% green electricity over such vast distances has created substantial local pressure to integrate renewable energy.

Secondly, the power system suffers from insufficient peak-load capacity. The pronounced trend of load "peakification" in recent years, coupled with inadequate generation capacity during peak periods, has become a critical threat to power security. Even when planning new coal-fired power plants near peak-load areas, these facilities face increasingly low annual generation hours and struggle to survive solely on power market revenues. In regions with a high share of renewable energy, wind and solar generation often fail to meet demand during periods of unfavourable weather. Ensuring power security has thus become a dilemma for many areas.

Thirdly, the weakness of distribution grids constrains the localised development and utilisation of wind and solar power. Traditional grid systems, designed for high-parameter, large-capacity, long-distance transmission, have distribution grids that can only supply power to load users. When distributed renewable energy generation from the load side feeds into the grid, it can cause distribution grids to flash "red lights" due to insufficient acceptance capacity.

Fourthly, enthusiasm for using zero-carbon energy sources such as green electricity and green hydrogen on the demand side has yet to be fully mobilised. In recent years, market-oriented power reforms have driven rapid adjustments to pricing policies and profit models, yet stable market expectations remain elusive. Carbon pricing has not fully permeated energy and product pricing systems, the endogenous momentum for energy transformation is insufficient

In the long term, China's energy development faces multiple challenges: immense demand pressure, significant supply constraints, and the arduous task of green transition.

Confronted with these multifaceted challenges, the research team has pooled the expertise and insights of specialists from China, Denmark, the United States, and other nations. Through collaborative model analysis and field investigations, they endeavour to break the traditional energy system's trilemma - simultaneously achieving green, secure, and economical outcomes - and chart a path for China's energy transformation towards net-zero carbon emissions in the medium to long term.

In short, there is still a long way to go in keep advancing China's energy transformation.

Part II Pathways to net-zero carbon emissions for China's energy system

Analysis by the research team indicates that by 2035, when China has essentially achieved socialist modernisation, per capita GDP will at least double relative to 2020, reaching the current level of moderately developed nations (USD 20,000-30,000 per capita). To fully establish itself as a modern socialist power by the mid-21st century, China should quadruple its per capita GDP by 2050 relative to 2020, attaining the average level of developed nations (US$40,000-60,000 per capita). Sustaining stable and continuous economic growth is an intrinsic requirement for China to achieve its modernisation objectives. Against this backdrop, both the expansion of China's economic scale and the enhancement of its development quality will impose higher demands on the scale and quality of China's energy requirements, while also raising greater expectations for the security of China's energy supply.

China's economic development has transitioned from a phase of high-speed growth to one of high-quality development, while urban development is shifting from large-scale incremental expansion to a stage prioritising quality enhancement and efficiency gains within existing stock. Looking ahead, to meet the people's aspirations for a better life and actively develop new productive forces, China will foster a series of new industries and numerous innovative models. This will drive unprecedented transformations in both the scale and patterns of energy consumption across sectors such as industry, construction, and transportation, injecting fresh momentum into China's socio-economic development. Concurrently, traditional industries will maintain a certain scale of development, remaining reliant on substantial energy consumption levels in the near to medium term.

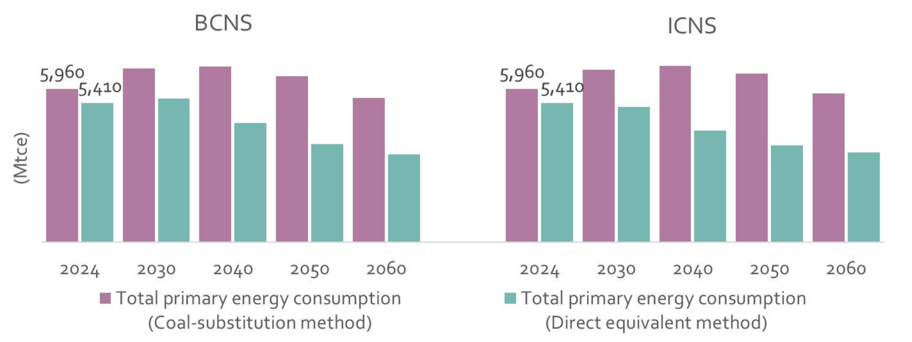
As the vital material foundation and driving force of economic and social development, energy security should be prioritised during the energy transformation. Balancing "reasonable quantitative growth with effective qualitative enhancement" throughout this process is essential to support high-quality economic and social development and the construction of a modernised nation.

Building on projections of China's economic and social development, the research team conducted a systematic analysis of the net-zero carbon emissions pathway for China's energy system by 2060, through an in-depth examination of the Benchmark Carbon Neutrality Scenario (BCNS) and the Ideal Carbon Neutrality Scenario (ICNS). This analysis yielded the following key conclusions.

(I) Primary energy demand first increased, then declined, with the energy structure undergoing a transformative shift

Primary energy demand will continue to grow in the near- to medium-term, with a gradual decline in the long term. Model analysis indicates that, calculated using the coal-substitution method, China's total primary energy consumption in 2060 will range from 5.67 to 5.87 billion tonnes of standard coal equivalent (Btce). Under the BCNS scenario, primary energy consumption will peak around 2035, while under the ICNS scenario, it will peak around 2040. In both scenarios, by 2060, total primary energy consumption is expected to return to 2024 levels. Calculated using the direct equivalent method[1], China's total primary energy consumption in 2060 is expected to range between 3.43 and 3.48 Btce. Under the BCNS scenario, consumption will peak around 2030, whilst under the ICNS scenario, it will peak before 2030[2]. By 2060, total primary energy consumption is expected to fall below 2024 levels (as shown in Figure 35). The differences between the coal-substitution method and direct equivalent method arise because the former converts electricity generation from wind, solar, hydro, and nuclear power to an equivalent amount of coal-fired power plant generation, thereby inflating total primary energy consumption.

Figure 35
Total primary energy consumption, 2024-2060 (comparison of coal substitution method and direct equivalent method)

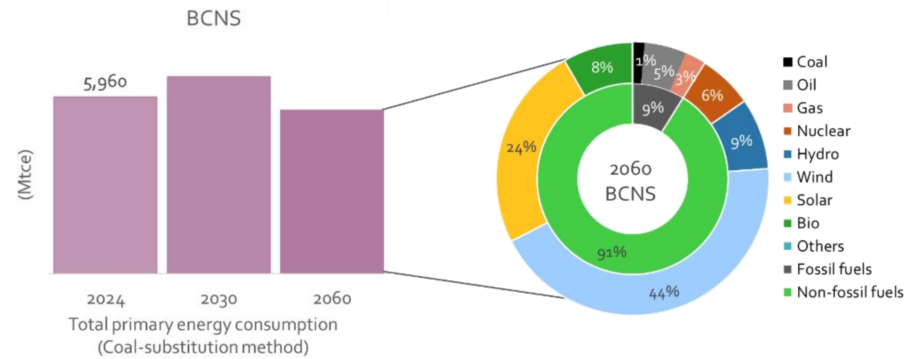


[1] In the *Direct Equivalent* method used by the IPCC, all non-combustible energy sources (e.g. renewables, nuclear) are converted into primary energy equivalents as they appear in the total final energy consumption (i.e. using a 100% efficiency to convert them into primary energy equivalents. IRENA REMAP 2030.
[2] As international institutions and China use different conversion methodologies (i.e. different default conversion methods), this may lead to different conclusions regarding the long-term trends of China's future energy transformation.

The share of non-fossil energy relative to fossil energy demand will change dramatically. Calculated using the coal consumption for power generation method, China's non-fossil energy consumption share stood at 19.8% in 2024. Large-scale development of non-fossil energy such as wind energy, solar energy, hydropower, biomass energy, and nuclear energy will increase the share of non-fossil energy to 90.2%-91.5% by 2060 (as shown in Figure 36). As coal-fired power generation is expected to be minimal by 2060, the coal-substitution method will no longer be applicable in that scenario. Therefore, calculated using the direct equivalent method, the share of non-fossil energy in 2060 will be 85.4% to 87.8% (as shown in Figure 37). Enhanced international cooperation will result in higher primary energy consumption and a higher share of non-fossil energy for China by 2060.

Figure 36

Total primary energy consumption and structure, 2024-2060 (coal-substitution method)



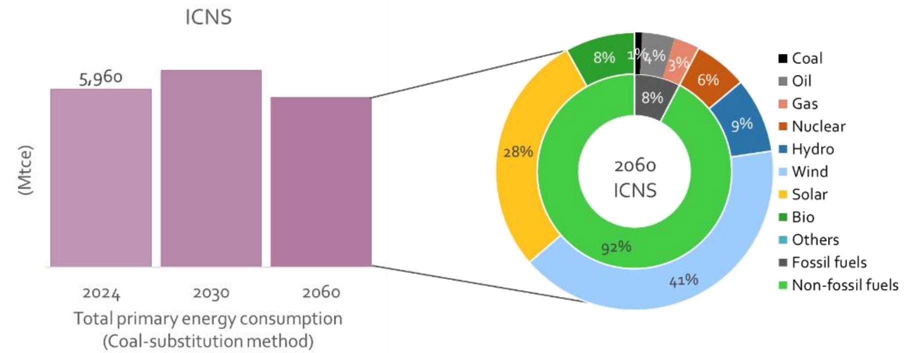
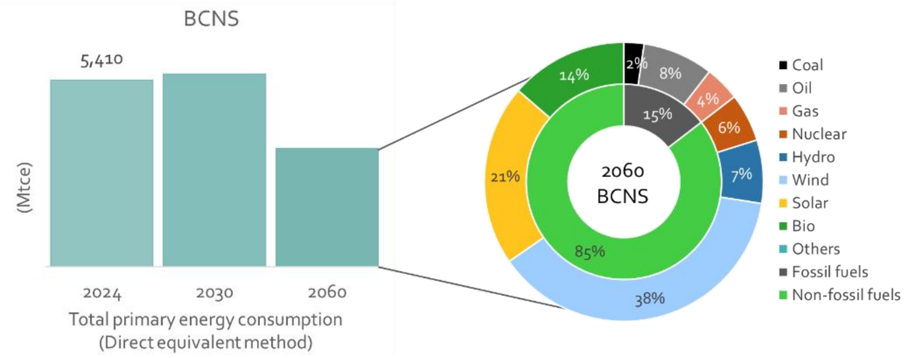
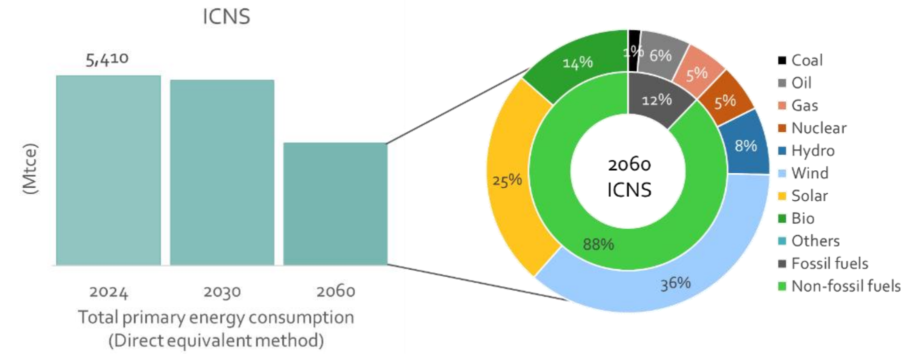


Figure 37

Total primary energy consumption and structure (direct equivalent method), 2024-2060





For the next five years (2026-2030), China's primary energy consumption will continue to grow, with the share of non-fossil energy steadily increasing. The model analysis based on the coal-substitution method confirms an ongoing upward trend. The share of non-fossil energy within primary energy consumption is expected to rise from 19.8% in 2024 to around 25% by 2030. Calculated using the direct equivalent method, primary energy consumption will stand at 5.41 Btce in 2024 and remain largely stable over the subsequent five years.

(II) By adopting a threefold approach of reducing consumption, exploiting non-fossil energy sources and removing emissions, the energy system is poised to achieve net-zero carbon emissions ahead of other sectors

From a long-term perspective, the energy system should pursue three pathways in a coordinated manner: reducing consumption, exploiting non-fossil energy sources, and removing emissions. In 2021, carbon emissions from China's energy activities accounted for 87% of the nation's total CO_2 emissions (excluding forest carbon sinks), making energy transformation the decisive factor in reaching peak carbon and carbon neutrality. Analysis indicates three primary pathways for reducing CO_2 emissions within the energy system: first, implementing energy conservation and improving energy efficiency to reduce consumption; second, accelerating the development of non-fossil energy sources to increase supply; and third, deploying carbon capture, utilisation and storage (CCUS) technologies to remove emissions.

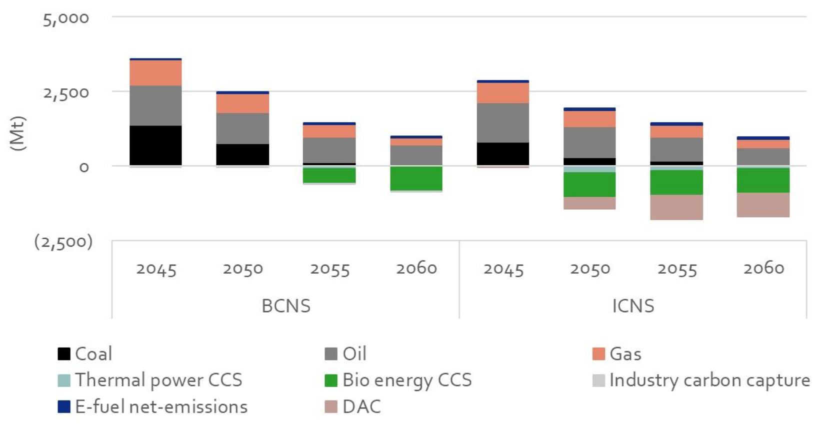
Model analysis indicates that, constrained by technological and economic factors, carbon removal technologies such as CCUS are unlikely to play a significant role before 2045. Sustained efforts to curb excessive energy demand growth through energy efficiency are essential, keeping per capita energy consumption below 5.1 tonnes of standard coal equivalent (tce). Concurrently, the scale of renewable and nuclear energy development shall be continuously expanded to achieve a comprehensive and deep substitution of fossil fuels with non-fossil energy sources.

Beyond 2045, large-scale deployment of CCUS across thermal power generation, biomass power, and industrial processes will be essential, alongside the exploration of Direct Air Capture (DAC) technologies. As shown in Figure 38, CCUS accounts for 7% of total carbon reductions by 2050 under the BCNS scenario and 52% under the ICNS scenario. By 2060, CCUS deployment will reach 1,240-1,410 million tonnes of CO_2 ($MtCO_2$) per annum. Under the BCNS scenario, carbon reduction relies primarily on CCUS, with the contribution of DAC being almost negligible; under the ICNS scenario, CCUS accounts for 54% and DAC 46%, indicating that DAC technology can play a more significant role. Supported by carbon removal and negative-carbon technologies, the energy sector achieves net-zero carbon emissions before 2060.

Under the BCNS scenario, China's energy system could achieve net-zero carbon emissions between 2058 and 2059. Under the ICNS scenario, this milestone could be brought forward to 2052-2053. Consequently, energy transformation can play a decisive role in enabling China to realise its carbon-neutrality target before 2060.

Through enhanced international cooperation, the ICNS scenario demonstrates greater intensity and effectiveness in China's approach of "reducing consumption, exploiting non-fossil energy sources, and removing emissions".

Figure 38
Energy activity-related carbon dioxide emissions, 2045-2060



Looking ahead to the next five years (2026-2030), reducing carbon emissions will primarily rely on "reducing consumption" and "exploiting non-fossil energy sources", with "removing emissions" reducing no more than 1% of energy-related carbon dioxide emissions. Regarding "reducing consumption", calculated using the coal-substitution method, China should continue to strengthen energy efficiency efforts, aiming to keep primary energy consumption below 7,400 Mtce by 2030 - a figure lower than that expected under a linear development trajectory. Regarding "exploiting non-fossil energy sources", the share of non-fossil fuels in total primary energy consumption reaches around 25% by 2030, through actively developing non-fossil fuel energy and replacing fossil fuel energy, to promote reaching peak consumption of coal and oil. Regarding "removing emissions", the scale of CCUS projects within the energy system is expected to reach 5.1 to 7.3 $MtCO_2$ by 2030, accounting for less than 0.1% of energy-related carbon dioxide emissions.

(III) Regardless of the era of fossil fuels or the era of renewable energy, it is required to prioritise energy conservation consistently

From a long-term perspective, energy conservation should remain a consistent priority throughout both the fossil-fuel and renewable-energy eras. Model analysis indicates that under the BCNS scenario, during the era dominated by fossil fuels, efforts should continually enhance the efficiency of fossil fuel utilisation and reduce energy costs. While during the era dominated by non-fossil fuels, the principle of prioritising energy conservation should also be upheld. Given current technological capabilities, prioritising energy conservation in a renewable-dominated era stems from four primary reasons:

- Firstly, it reduces demands on territorial space. The inherent characteristics of non-fossil energy sources, such as wind and solar power, result in lower energy density. Enhancing energy efficiency helps minimise land and maritime use requirements, rooftop space, noise pollution, and impacts on natural landscapes, thereby fostering harmonious coexistence between humanity and nature.
- Secondly, it reduces reliance on imports of critical minerals such as nickel, cobalt, and lithium. Equipment for solar PV, chemical storage, and wind power relies on these minerals, yet China faces scarcity in such resources. Lowering import dependency safeguards national security.
- Thirdly, it eases the challenge of balancing the energy system. As the share of wind and solar power increases on the supply side and the share of electricity demand from end-use sectors, such as the service sector, continues to rise on the demand side, future electricity demand will exhibit higher seasonal peak loads and lower troughs. Daily load curves will shift towards a "duck curve" or even a "canyon curve" (as shown in Figure 43), necessitating robust emergency safeguards during extreme weather events. Energy conservation and efficiency improvements help reduce peak electricity demand, thereby safeguarding the power system's security.
- Fourthly, it reduces the cost of energy transformation. Expenses related to securing land resources, importing critical minerals, and addressing peak load challenges will all increase, thereby raising transition costs. Consequently, as one of the world's most populous nations, China should consistently prioritise energy conservation to facilitate a smoother energy transformation.

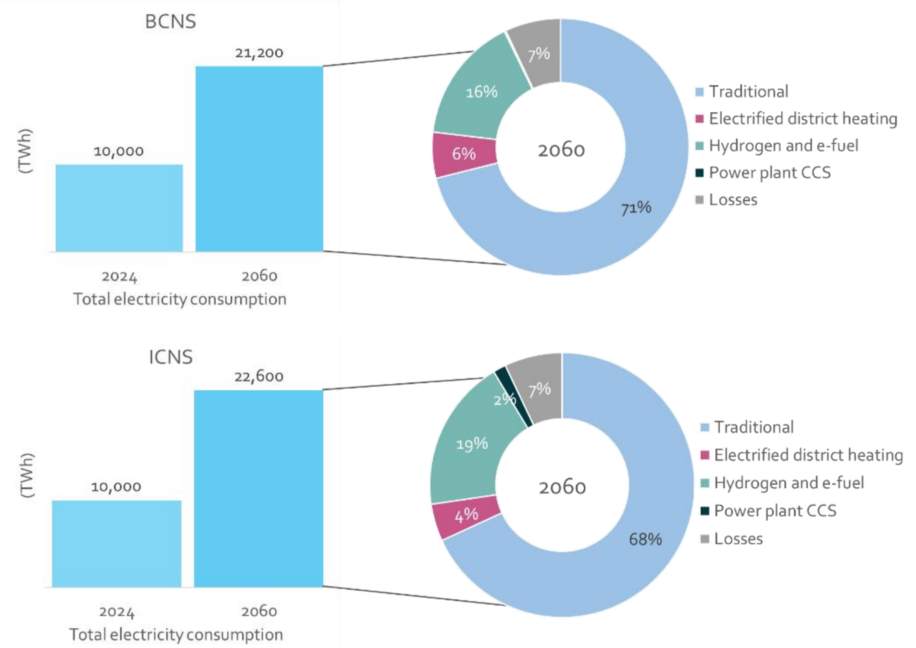
Looking ahead to the next five years (2026-2030), sustained efforts are required to enhance energy efficiency across society steadily. Model analyses indicate that from 2024 to 2030, the comprehensive energy consumption per tonne of steel, cement, and AC power consumption for electrolytic aluminium will decrease by 3%-5%, coal consumption per kilowatt-hour of electricity generated by thermal power plants will decrease from 302 grams of standard coal equivalent (gce) in 2024 to below 300 gce by 2030, while the power usage effectiveness (PUE) of data centres will fall from 1.48 in 2023 to below 1.3 by 2030.

(IV) The integrated development of end-use electrification and renewable energy will reshape energy consumption patterns

From a long-term perspective, the integrated development of renewable energy and highly electrified end-use energy systems at the local level represents the predominant form of future energy consumption. In terms of electrification, China's total electricity consumption is expected to reach 21,200-22,600 TWh by 2060 (as shown in Figure 39). End-use sectors such as industry, buildings, and transport will gradually shift from predominantly direct fossil fuel combustion to secondary energy sources and zero-carbon energy such as electricity, hydrogen, and biomass (as shown in Figure 40), with accelerated advancement of both mandatory and voluntary renewable energy consumption policies. In 2024, electricity accounted for 28.8% of final energy demand, while hydrogen accounted for a negligible share. By 2060, the direct electrification rate is expected to rise to 64%-67%, with hydrogen's share increasing to 10-12% (as shown in Figure 41).

Regarding integrated renewable energy development, models such as zero-carbon industrial parks, point-to-point green power supply, and PSDF (solar PV-energy storage-DC flexible transmission) buildings deeply integrate wind power, solar PV, and environmental energy sources (e.g., air-source and water-source heat pumps) with energy consumption in industry, buildings, and transport. This "local generation, local utilisation" approach will maximise the utilisation of renewables while reducing reliance on large-scale power grids and heating networks. Novel zero-carbon models — including zero-carbon industrial parks, zero-carbon towns and villages, and PSDF buildings — will create scattered "sparks of zero-carbon" across the landscape. These sparks, gathering momentum like "from a single spark, start a prairie fire," will inject new vitality into China's energy revolution, ultimately achieving a comprehensive energy transformation.

Figure 39
Total electricity consumption and structure, 2024-2060



Note: Total electricity consumption for 2024 was calculated based on the "2024 National Power Industry Statistical Data" and the "2024 Statistical Bulletin on National Economic and Social Development".

Figure 40
Total final energy consumption and structure (direct equivalent method), 2024-2060

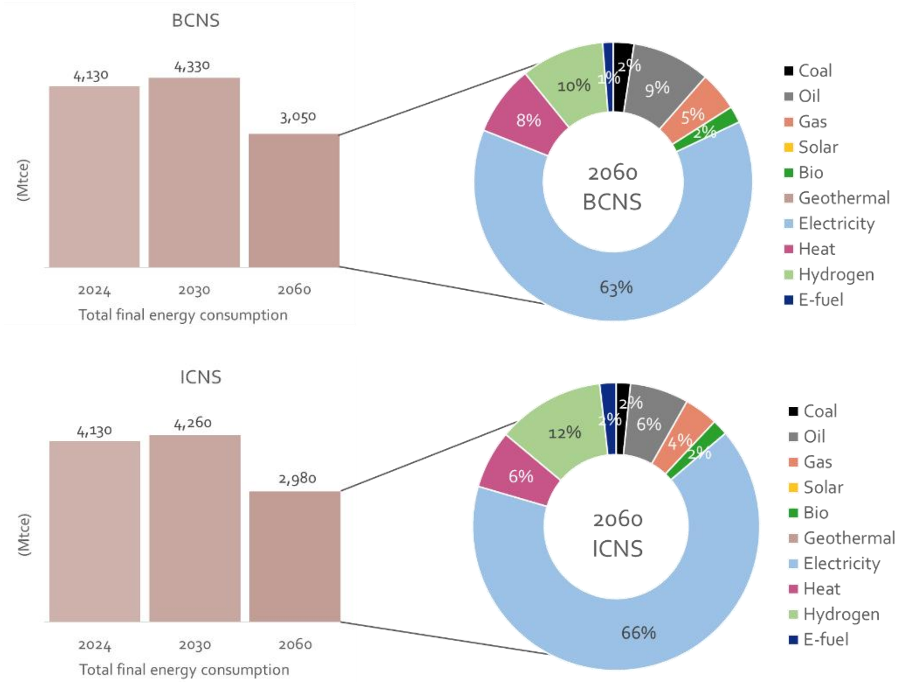
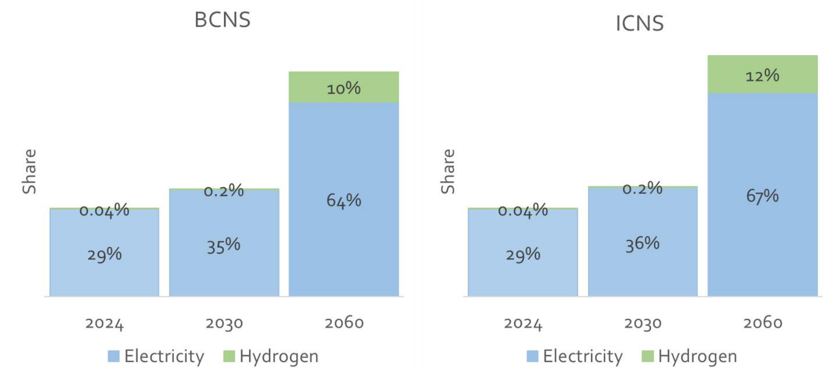
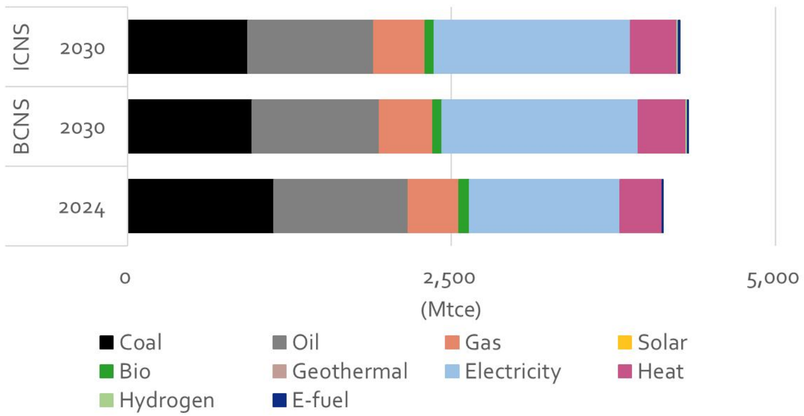


Figure 41
Share of electricity and hydrogen in total final energy consumption, 2024-2060



Looking ahead to the next five years (2026-2030), the electrification drive will enter an accelerated phase, with green hydrogen consumption continuing to rise. Model analysis indicates that as the level of synergy between wind, solar, storage and hydrogen technologies improves, electricity's share of China's final energy consumption will increase to 35%-36% by 2030 (as shown in Figure 42). Green hydrogen demand across end-use sectors will grow from approximately 0.1 million tons in 2024 to around 1.5-2.2 million tons. New models, such as on-grid and off-grid hydrogen production from renewables, will accelerate development. The integrated bases for green hydrogen, ammonia, and methanol, along with inter-provincial transmission facilities, are being planned and constructed, driving a steady increase in market demand for green hydrogen. The advancement of national and provincial zero-carbon industrial parks will continue, synergising pollution reduction and carbon mitigation within industrial zones. Accelerating the localised development and utilisation of green electricity to achieve a higher degree of "green-to-green" production is anticipated. By 2030, an integrated energy system in end-use sectors is expected to become a key approach for advancing renewable energy.

Figure 42
Total final energy consumption and structure for 2024 and 2030 (direct equivalent method)



(V) Five-phase strategy to sustainably advance wind and solar power as the primary sources of electricity supply

International experience[3] indicates that as the share of new energy generation continues to rise, while electricity generation costs decrease significantly, the operational costs of the power system will increase markedly, and the difficulty of maintaining grid security will gradually increase. Using the combined share of wind and solar power generation as a benchmark indicator, and with the primary focus on comprehensively enhancing the power system's regulation capabilities, the transformation of China's power system can be divided into five phases:

The Phase I represents a very low share of wind and solar generation (nationally averaged, wind and solar output constituting <5% of total generation). During this phase, the impact of wind and solar power on the national grid remains limited, with conventional power sources retaining dominance. Coal-fired power and other conventional sources feature mature technology and stable output, exerting minimal pressure on grid connections. System regulation primarily relies on coal-fired power's capacity, with new regulatory resources accounting for a small proportion. Operational costs remain highly susceptible to fluctuations in fossil fuel prices, such as those for coal and natural gas.

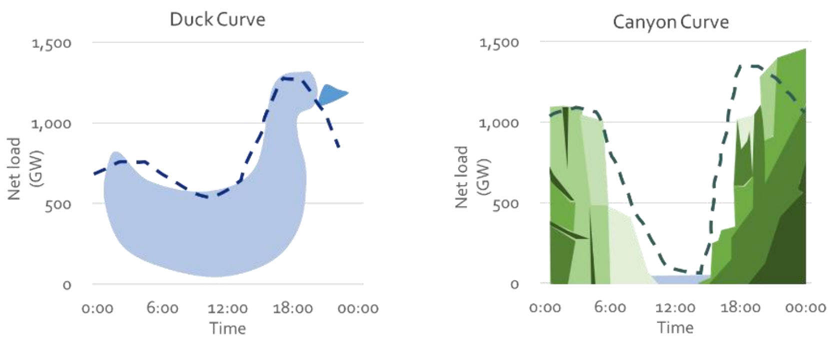
The Phase II represents a low share of wind and solar generation (nationally averaged, wind and solar output constituting 5%-20% of total generation). During this phase, the impact of wind and solar power generation on grid operations becomes evident (e.g., requiring faster and more frequent unit ramping). The discrepancy between net load (load minus wind/solar output) and actual load demand grows increasingly pronounced, with some regions developing a "duck curve" (as shown in Figure 43). Grid security can be maintained by enhancing forecasting accuracy and optimising the utilisation of existing system resources, such as flexible coal-fired power plants.

The Phase III represents the medium share for wind and solar power generation (nationally averaged, wind and solar output constituting 20%-40% of total generation). During this phase, large-scale wind and solar generation dictate the power system's operational mode. The impact of wind and solar intermittency and volatility on system uncertainty intensifies further, with the net load curve becoming increasingly steep. In some regions, net load curves transform into "canyon curve" (as shown in Figure 43), with spot power markets beginning to exhibit zero and negative prices. The growing variability

[3] IEA, Integrating Solar and Wind, 2024

on both the supply and demand sides requires a comprehensive strengthening of the power system's regulation capabilities, as traditional generation assets and conventional operational control methods alone can no longer ensure power system security. Power dispatch now imposes stricter requirements on thermal units regarding regulation depth, ramping speed, and start-stop timing, while simultaneously heightening demand for investment in diverse power system regulation resources.

Figure 43
Schematic diagram of the "Duck Curve" and "Canyon Curve"



The Phase IV represents a medium-to-high share of wind and solar power generation (nationally averaged, with wind and solar output constituting 40%-60% of total generation). During this phase, wind and solar power installations in various regions exceed local demand, enabling them to fully meet load demands during certain periods. This presents entirely new challenges for the planning and operation of power systems. Coal-fired power generation undergoes a comprehensive transition to become a regulating power source, exploring the use of low-carbon and zero-carbon fuels. Gas-fired power generation participates more frequently in grid regulation, with demand for new regulating resources growing rapidly. Flexible electricity-to-heat and electricity-to-hydrogen technologies are being developed at scale. During this phase, electricity energy costs continue to decline. However, this is accompanied by rising costs for ancillary services and reserve capacity, alongside significantly increased difficulty in controlling grid voltage and frequency. Consequently, power system operational costs rise, necessitating the comprehensive establishment of a new-type power system and a corresponding new power market framework.

The Phase V represents a high share of wind and solar power generation (nationally averaged, with wind and solar output constituting >60% of total generation). During this phase, wind and solar become the absolute mainstay of installed capacity and generation output, far exceeding load demand. Coal-fired units are entirely repurposed as regulating or emergency reserve capacity, with some converted to zero-carbon fuels. This necessitates large-scale deployment of new regulating resources such as energy storage. Measures including large-scale electrolytic hydrogen production, electrolytic synthetic fuels, and electrolytic heating convert electricity into zero-carbon secondary energy sources —such as green hydrogen, green synthetic fuels, and green thermal energy —addressing wind and solar surplus and long-duration storage challenges. During this phase, generation-side costs continue to decline, potentially approaching 'zero cost'. However, ancillary service costs, capacity mechanism/market costs, and power system operational expenses constitute significant components of electricity costs. Electricity prices will dynamically interact with green hydrogen, green synthetic fuels, and green heat prices. A new-type power system characterised by net-zero carbon emissions is fully established. Concurrently, the power and heating systems achieve deep coupling through heat and electric storage and electric-heat conversion, achieving an exceptionally high level of integrated energy system security.

From a long-term perspective, establishing a green energy supply system centred on wind and solar power represents a core measure for achieving net-zero carbon emissions. In 2023, the combined share of wind and solar power generation in China's total electricity output stood at 15.8%, rising to 18.2% in 2024. During the first seven months of 2025, this proportion reached 25%, indicating China's entry into the Phase III (medium share phase) for wind and solar power generation. Under the BCNS scenario, China will enter the Phase IV (medium-to-high share phase) for wind and solar power generation after 2030, progressing to the Phase V (high-share phase) after 2040.

In terms of electricity generation, national output in 2060 will reach 21,200-22,600 TWh, with renewable energy accounting for around 92% of this total and wind and solar power contributing approximately 77% (as shown in Figure 44). By 2060, nuclear power generation would reach approximately 1,600 TWh, hydropower generation would be 2,100-2,200 TWh, wind power generation would be 10,300-10,600 TWh, solar PV power generation would be 5,900-7,100 TWh, and biomass power generation would be around 1,200 TWh.

In terms of installed capacity, China's total power generation capacity in 2060 is expected to reach 10,450-11,040 GW, approximately three times that of 2024. Renewable energy sources will account for 92%-95% of this capacity, with combined wind and solar installations totalling 8,840-9,720 GW. Projections indicate that by 2060, China's nuclear power capacity will stand at approximately 200 GW, conventional hydropower capacity at 550-590 GW, and wind power capacity at 3,220-3,340 GW (with offshore wind accounting for 10%-16% of this total). Solar PV capacity will reach 5,500-6,500 GW, and biomass power generation capacity (including both CCS-equipped and non-CCS variants) will stand at 220-230 GW.

Figure 44

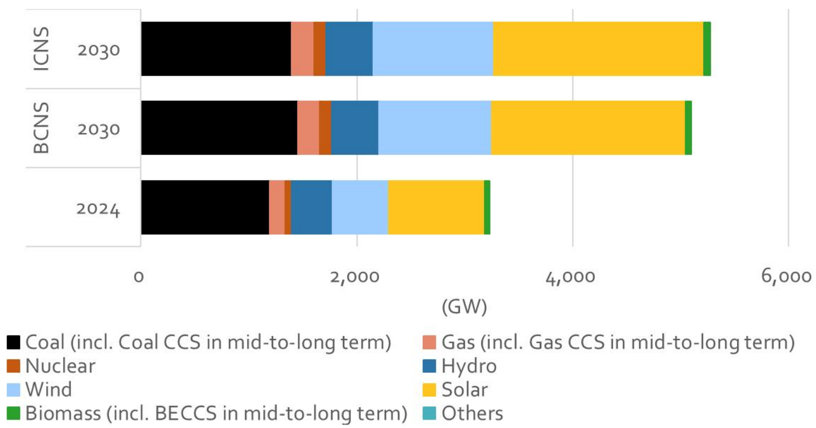
Installed power generation capacity and electricity generation in 2060

Looking ahead to the next five years (2026-2030), China will enter the Phase III (medium share) for wind and solar power generation, with certain regions advancing to the Phase IV (medium-to-high share phase). Maintaining power system stability will present greater challenges. Model analysis indicates that after 2030, the characteristics of medium and higher share levels for wind and solar power generation become more pronounced, making the need to enhance the power system's regulation capacity more urgent.

In terms of installed capacity, by 2030, the installed capacity of wind power and solar PV is expected to double compared to 2024, while thermal power capacity (including coal and natural gas) will see moderate growth to provide "peak generation capacity" for the power system (as shown in Figure 45). Nuclear power capacity will continue to expand, with operational nuclear capacity securing China's position as the world leader. Technological iteration and innovation in nuclear power will advance, with fast reactors and high-temperature gas-cooled reactors poised for large-scale application. Nuclear energy safety, economic viability, and resource utilisation efficiency will steadily improve. Application scenarios will broaden, with nuclear power increasingly providing power system regulation capabilities and regional heating solutions, thereby enhancing the comprehensive utilisation of nuclear energy.

Figure 45

Installed power generation capacity and structure for 2024 and 2030



(VI) Distributed wind power and distributed solar PV are key pillars of the energy transformation in both urban and rural areas

From a long-term perspective, distributed wind power and distributed solar PV will account for half of China’s wind and solar power development, becoming a key resource for local sustainable energy supply in towns and rural areas. Model analysis indicates that, on a scale basis, China's wind power installed capacity will increase from 520 GW in 2024 to 3,220-3,340 GW by 2060. Within this, distributed onshore wind power capacity will rise from under 20 GW in 2024 to approximately 920 GW by 2060, accounting for 28%-29% of total wind power generation capacity (as shown in Figure 46).

China's solar PV installed capacity will increase from 890 GW in 2024 to 5,500-6,500 GW by 2060. Within this, distributed solar PV capacity will rise from 370 GW in 2024 to 3,040-3,280 GW by 2060, accounting for 50%-55% of total solar PV installed capacity (as shown in Figure 47). By this time, both urban and rural areas will universally achieve "electricity from nearby sources", enabling on-site and local consumption and utilisation of wind and solar power. Distributed wind power and distributed solar PV systems, developed and utilised locally, will provide electricity services to an increasing number of urban and rural residents.

Figure 46

Installed wind power capacity and structure, 2024-2060

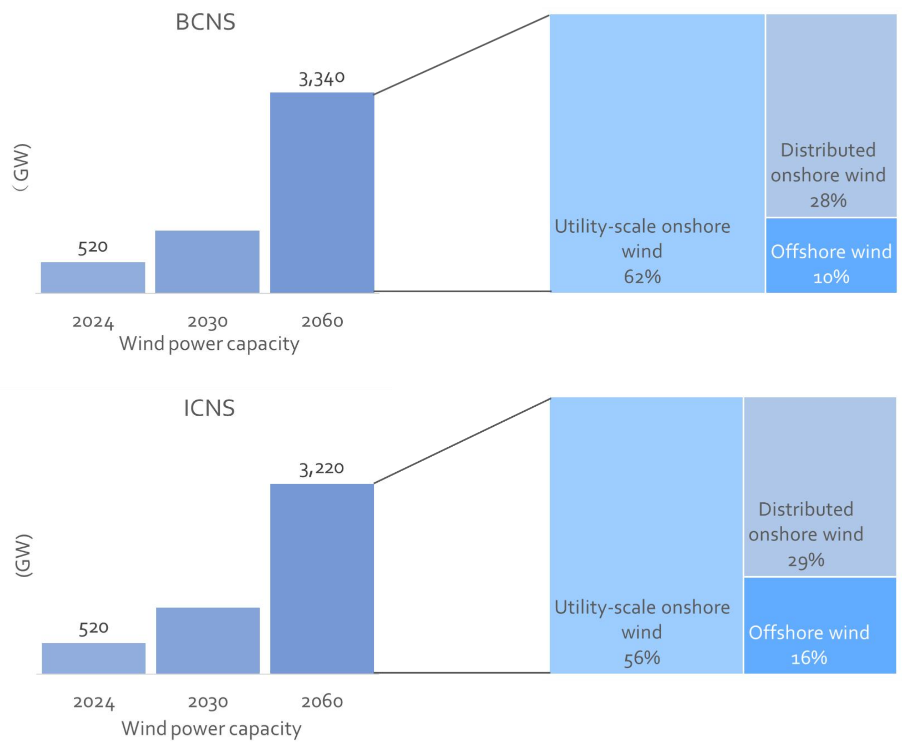
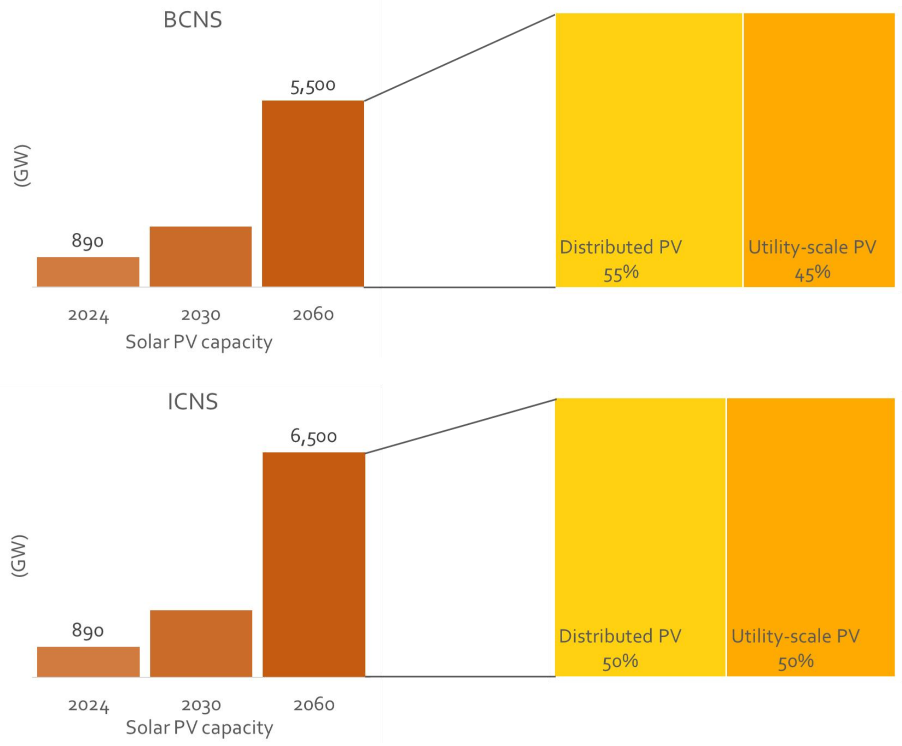


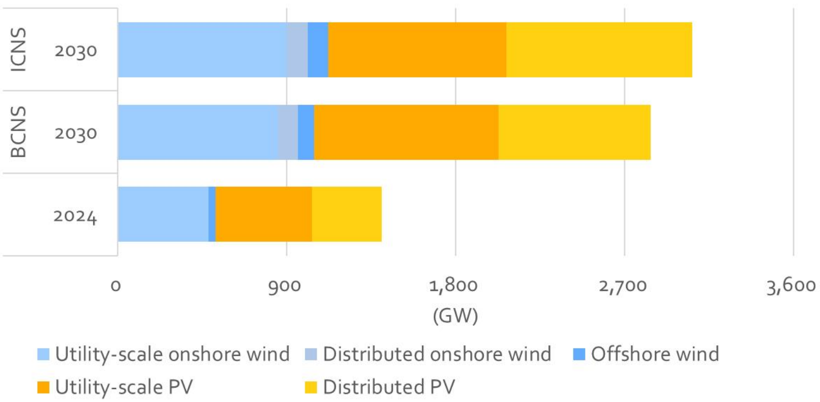
Figure 47

Installed solar PV capacity and structure, 2024-2060



Looking ahead to the next five years (2026-2030), distributed wind power and distributed solar PV will enter a period of rapid development. Model analysis indicates that in terms of scale, China's distributed wind power capacity is expected to reach 100-110 GW, and distributed PV capacity is expected to reach 810-990 GW (as shown in Figure 48). Accelerating the development of distributed PV and distributed wind power over the next five years will require overcoming a series of challenges, including project management, grid integration, integrated development, resource allocation, and participation in power markets.

Figure 48
Installed wind and solar PV capacity and structure for 2024 and 2030



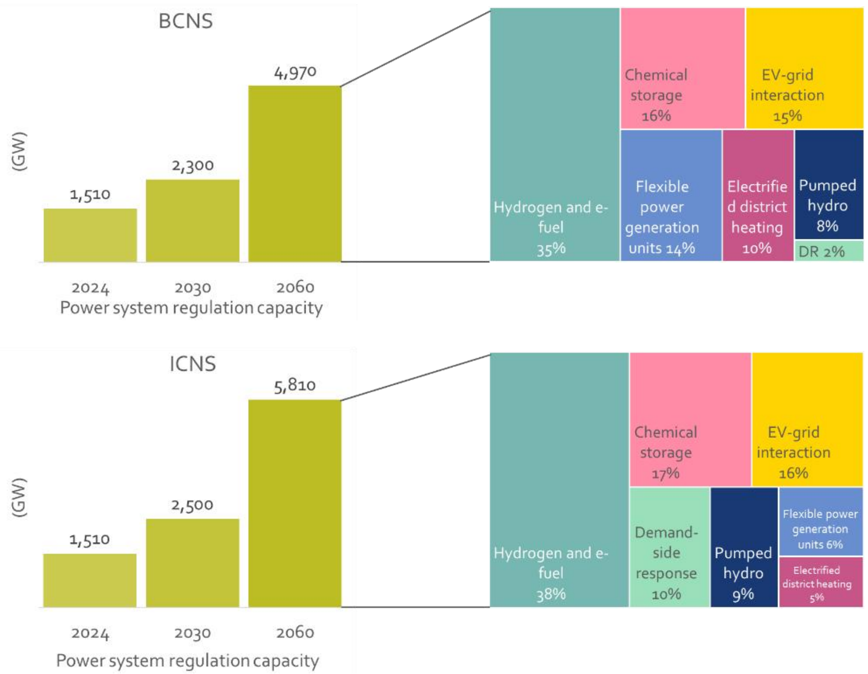
(VII) Regulation capability is a key enabler for enhancing the safety and resilience of power systems

Achieving power system balance in a future Chinese energy system with a high renewable energy share requires meeting diverse demands through a diversified supply of energy sources. Model analysis indicates that to ensure power system security, China's power system regulation capacity must be further enhanced to 4,970-5,810 GW by 2060. Electrolyser-based hydrogen production, electrolyser-based synthetic fuels, chemical storage, EV-grid interaction and pumped hydro will become primary regulation resources, significantly reducing the power system's reliance on traditional regulation sources such as coal-fired power generation (as shown in Figure 49).

By 2060:

- Electrolytic hydrogen and electrolytic synthetic fuels will provide 1,740-2,180 GW of regulation capacity, accounting for 35%-38% of the power system's total regulation capacity. While participating in real-time power balancing, electrolytic hydrogen and electrolytic synthetic fuels will also undertake "cross-seasonal regulation".
- Chemical storage facilities will be widely deployed across the generation, transmission, and consumption sectors. Chemical storage capacity will reach 800-1,000 GW, accounting for 16%-17% of total regulation capacity.
- The electric vehicle fleet will reach 480-540 million vehicles, with EV-grid interaction (intelligent orderly charging and bidirectional charging/discharging (V2G)) providing 750-920 GW of regulation capacity, accounting for 15%-16% of total regulation capacity.
- Pumped hydro storage will provide 400-500 GW of regulation capacity, accounting for 8%-9% of the total regulation capacity.

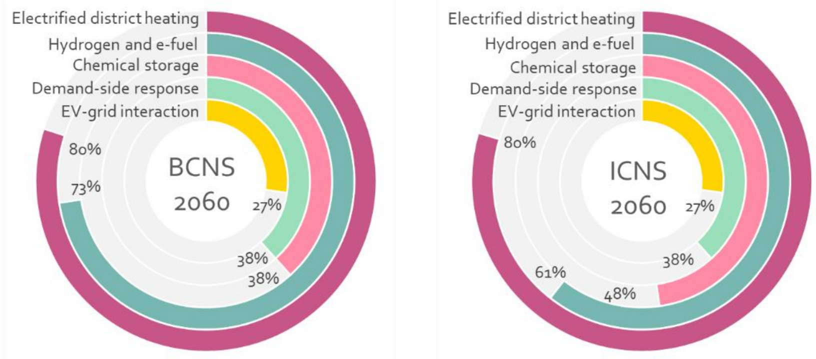
Figure 49
Power system regulation capacity outlook, 2024-2060



In regions with higher proportions of wind and solar power generation, local power system regulation capacity development requires further enhancement (as shown in Figure 50).

Figure 50

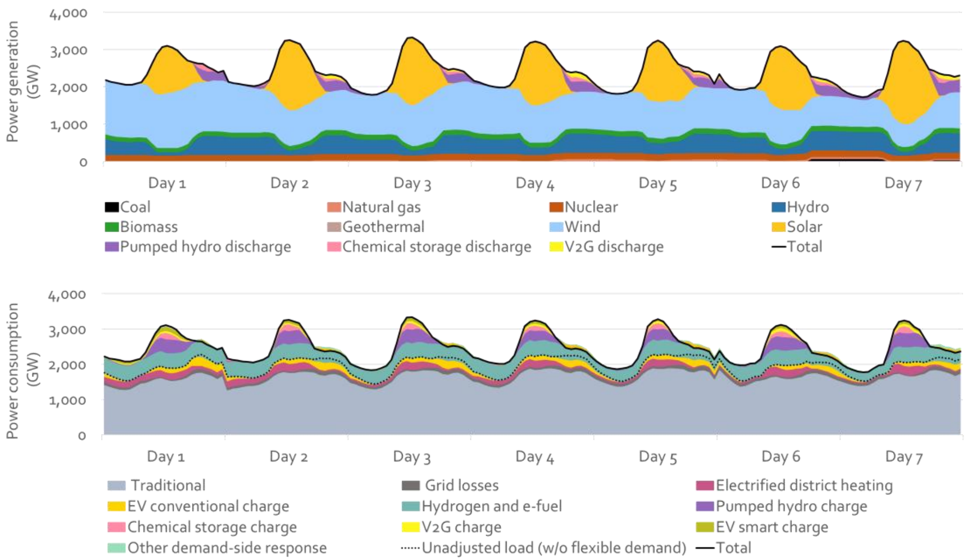
Share of new-type power system regulation resources in the Three North (Northwest, North and Northeast) in 2060



Hourly dispatch has also been simulated and optimised. Taking a typical winter week under the BCNS scenario as an example: during daylight hours with ample sunshine, solar PV output rises rapidly; at night, solar PV output drops to zero while wind power output remains substantial. During the daytime, when generation output exceeds the non-flexible electricity load, pumped hydro, chemical storage, electrolytic hydrogen production, electrolytic synthetic fuel production, EV-grid integration, and demand-side response resources begin to activate. Taking Day 7 as an example, at peak times, the combined regulation capacity provided by these resources can account for up to 37% of the peak load during the week (as shown in Figure 51). At nighttime, when wind power generation increases (e.g., Day 1 in Figure 51), electricity consumption for electrolytic hydrogen production and synthetic fuels rises, accounting for approximately 20% of total electricity demand. During periods of lower wind power generation (e.g., Day 6 in Figure 51), pumped hydro, chemical storage, and V2G commence significant discharges, with their combined output accounting for around 18% of total electricity demand.

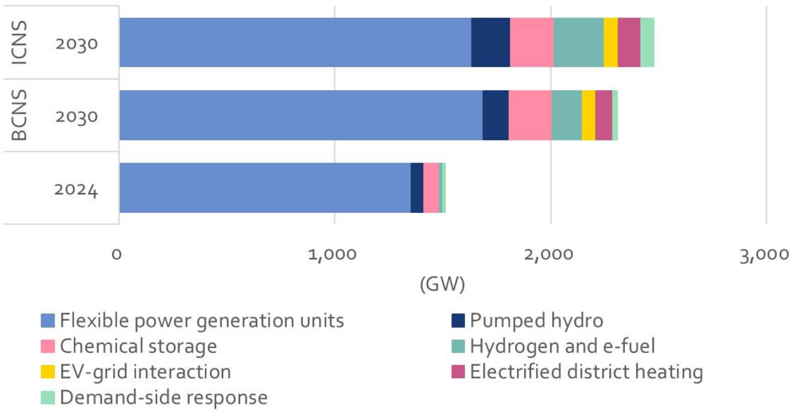
Figure 51

Hourly power balance for a typical week in China's power system in BCNS - winter 2060



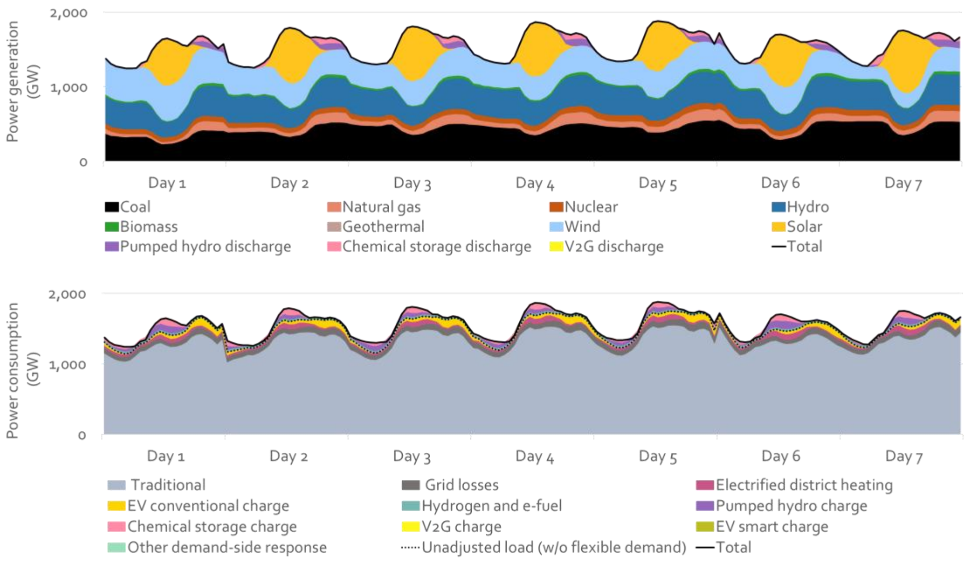
Looking ahead to the next five years (2026-2030), although pumped hydro capacity will steadily increase and chemical storage will develop rapidly, the relatively swift growth in electricity demand will necessitate continued reliance on coal-fired power to provide robust grid regulation as a significant supporting pillar of the system. Model analysis indicates that by 2030, China's power system will possess a total regulation capacity of 2,300-2,500 GW. Among these, coal-fired power, gas-fired power, etc., will contribute approximately 1,600 GW, collectively accounting for 65%-71% of total regulation capacity. Chemical storage installations will reach approximately 200 GW, representing 8%-9% of total regulation capacity; Electrolytic hydrogen production and electrolytic synthesis fuels will provide 140-230 GW of regulating capacity, accounting for 6%-9%; pumped hydro will have an installed capacity of 140-180 GW, representing 6%-7%; and vehicle-grid interaction will contribute 60-70 GW, constituting approximately 3% (as shown in Figure 52).

Figure 52
Power system regulation capacity in 2024 and 2030



Analysing hourly dispatch in 2030 can help paint a picture of how the energy system behaves. Taking a typical winter week from the ICNS scenario as an example, as the sun rises in the early morning, generation output gradually exceeds the unflexible demand. On day 7, in Figure 53, for example, coal-fired units commence downward regulation, with cumulative coal-fired generation approximately 32% lower between 8:00 and 12:00. In the evening on the same day, as the sun sets. Peak electricity demand occurs, while wind and solar generation fall and coal-fired units increase output, resulting in cumulative coal-fired generation rising by approximately 30% between 4:00 pm and 8:00 pm. During periods of low wind power generation in the evening, pumped storage, chemical storage, and V2G systems discharge, collectively accounting for approximately 10% of total electricity demand on day 7, for example. By appropriately enhancing peak capacity in thermal power generation within specific regions, regional electricity security is ensured. Particularly during extreme conditions characterised by good wind and poor solar conditions, coal-fired power plays a crucial role in providing foundational support for the security of the electricity system.

Figure 53
Hourly power balance for a typical week in China's power system in ICNS - winter 2030



(VIII) Cross-regional interconnection, unit self-balancing, and multi-energy integration represent the future development trends of power grids

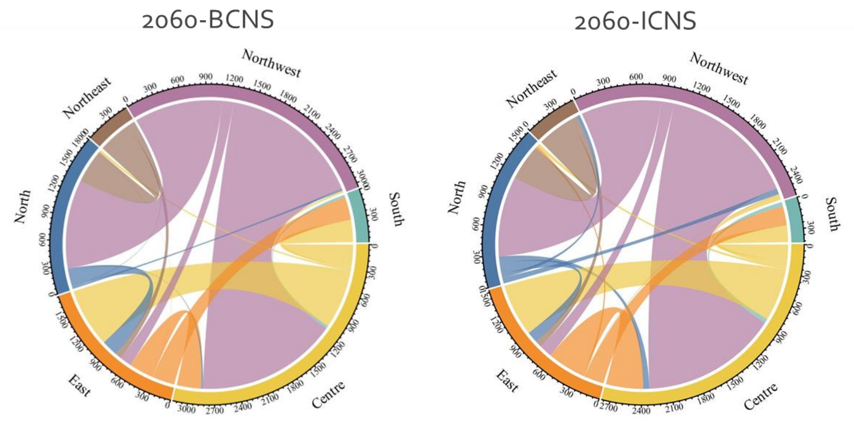
From a long-term perspective, cross-regional interconnection, unit self-balancing, and multi-energy integration will become new imperatives for future grid development. To address the increasingly pronounced unpredictability of wind and solar power generation, the intrinsic logic of China's grid development is undergoing a profound transformation, manifested primarily in three aspects:

First, at the backbone grid level, efforts should be intensified to enhance the complementary and mutual support capabilities of national-level power grids. By establishing a nationwide interconnected grid framework characterised by "West-to-East power transmission with inter-regional mutual support, North-to-South power transmission with inter-regional mutual support," China aims to resolve the regional imbalance between wind and solar generation resources in the northwest and electricity demand centres in the central and eastern regions. Model analysis indicates that by 2060, the demand for inter-provincial and inter-regional power transmission will reach 4,700-5,400 TWh (as shown in Figure 54), representing a two- to threefold of the current levels.

Second, at the distribution and microgrid level, the focus will be on the refined development of self-balancing distribution units with distinct characteristics. To accommodate the large-scale deployment of distributed energy in the future, self-sufficient units in villages, industrial parks, and commercial zones will be developed, forming new local balancing mechanisms that jointly safeguard power supply security.

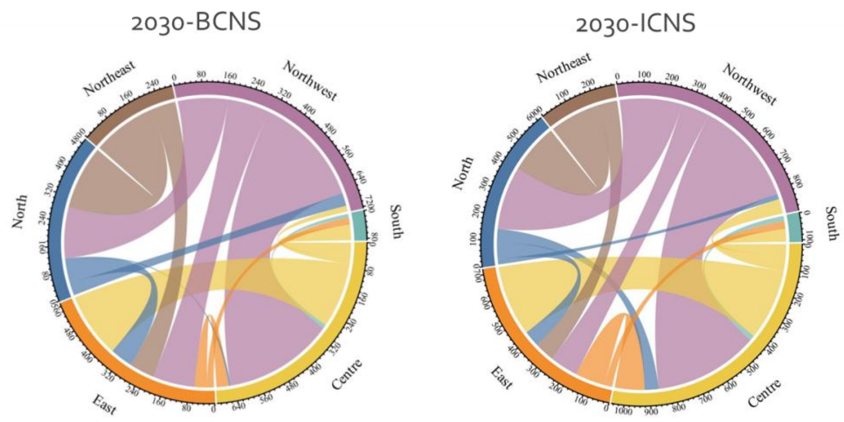
Third, in terms of multi-energy coordination, stronger coupling between the power system and thermal and transport sectors will be promoted. Looking toward a future of integrated multi-energy development, technologies such as electrical heat storage, electrolytic hydrogen production, and EV-grid interaction will play a key role. These solutions will enable deep integration between grid operations and the functioning of electrical heating equipment, district heating, and heat storage systems. They will also link the grid to hydrogen-ammonia-methanol production, storage, and transportation, as well as charging and discharging infrastructure for electric vehicles and heavy-duty trucks. This will ultimately lead to a new, fully integrated network ecosystem including electricity, heat, and transport systems.

Figure 54
Cross-regional electricity transmission demand in 2060 (TWh)



Looking ahead to the next five years (2026-2030), the most critical tasks for grid development remain the sustained advancement of cross-regional transmission corridor construction and the upgrading of distribution grids. Model analysis indicates that China's demand for inter-provincial and cross-regional power transmission will continue to increase, with the scale of "West-to-East" and "North-to-South" transmission set to expand further (as shown in Figure 55). By 2030, the grid will possess approximately 910 GW of distributed renewable energy integration capacity and 60-70 GW of vehicle-to-grid interaction capability. New technologies – such as grid-forming renewables, grid-forming energy storage, and vehicle-to-grid – will be deployed rapidly. The flexible, intelligent, and digital transformation of distribution grids will be largely completed, achieving multi-level coordination across transmission, distribution and microgrids, as well as large-scale resource aggregation and interaction, and plug-and-play access for diverse users. This will effectively promote the integration of distributed smart grids with the transmission grid, supporting the growth of distributed generation, new energy storage technologies and various new business models.

Figure 55
Cross-regional electricity transmission demand in 2030 (TWh)



(IX) Energy and artificial intelligence will become deeply integrated, accelerating the coordinated development of computing power and green electricity

From a long-term perspective, energy and artificial intelligence (AI) will undergo deep integration and development. Electricity is a core factor influencing the scale and efficiency of computing power, while AI development requires support in terms of electricity availability, affordability, and quality. From the perspective of electricity demand, the widespread adoption of digital technologies, such as AI, will drive a sustained growth in power requirements for intelligent computing power infrastructure. It is estimated that in 2024, China's computing infrastructure will consume 200-300 TWh, accounting for approximately 3% of total national electricity consumption, positioning it among the largest energy-consuming sectors. From a cost perspective, the proportion of energy and electricity costs in the computing industry's operational expenses has risen from about 30% five years ago to around 60% today, and is expected to increase further. The rising share of energy and power costs will drive the migration of computing power facilities to regions with lower electricity prices ("energy price basins"). From an emissions-reduction perspective, expanding computing power requires green electricity to reduce greenhouse gas emissions associated with AI applications. Meanwhile, AI technologies in the energy sector will be widely applied across multiple domains — power grids, renewable energy, hydropower, and thermal and nuclear power. This will enable cross-domain, cross-industry, and cross-business integration, contributing to the construction of a new-type energy system.

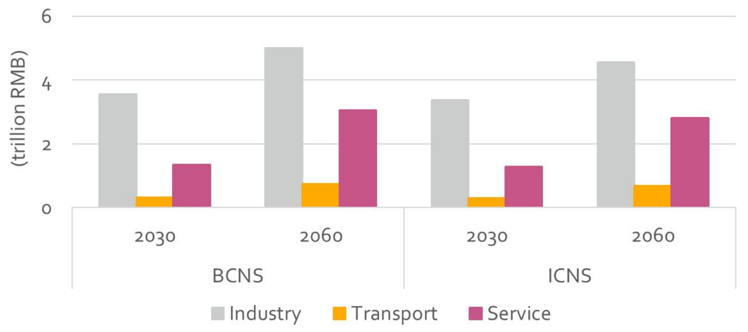
Looking ahead to the next five years (2026-2030), strong efforts should be made to promote the coordinated development of computing power and green electricity. Driven by the rapid expansion of intelligent computing power infrastructure, China's additional demand for computing power capacity development could reach 600 TWh or more by 2030. Promoting the coordinated development of computing power and green electricity and fostering green computing power characterised by a high share of renewable electricity constitutes a key measure for ensuring the high-quality development in the computing industry and a vital pathway to accelerate the decarbonisation of the energy sector, providing robust support for the comprehensive green transition of the economy and society.

An integrated approach should be adopted to account for the timing, scale, spatial distribution, and quality requirements of power demand arising from computing-power development, ensuring close alignment between power-development planning, renewable-energy-development planning, and computing-power-development planning during the *15th Five-Year Plan* period. Efforts should be accelerated to develop new green-power supply models, such as integrated generation-grid-load-storage systems, to reduce electricity costs while ensuring reliable supply to data centres. Energy conservation, efficiency improvement, and comprehensive energy utilisation should be further deepened, leveraging data centre load flexibility to participate in demand response. With the main objective of expanding the application scenarios for deep integration between AI and the energy sector, breakthroughs should be achieved in areas such as intelligent power regulation, smart exploration of energy resources, and renewable energy forecasting. Emerging forms of artificial intelligence, such as embodied and scientific intelligence, should be deployed in key application areas to support the high-quality development of the energy sector.

(X) The energy transformation will underpin high-quality economic development and improved employment

China's energy transformation facilitates an accelerated and smart transformation and upgrading of the national industrial system. As the transition progresses, the share of high-quality energy — represented by electricity — continues to rise, providing both the material foundation and operational environment for the smart development of Chinese industries driven by artificial intelligence applications. Model analysis indicates that under both scenarios, electricity consumption as an intermediate input in the value-added formation of China's industrial, transport, and service sectors exhibits sustained growth (as shown in Figure 56). Taking the BCNS scenario as an example, by 2030, electricity inputs in industry, transport, and services will be 1.2, 2.2, and 2.2 times the current levels, respectively. By 2060, these figures will reach 1.7, 4.9, and 4.9 times the present levels, providing a reliable energy guarantee for the large-scale adoption of artificial intelligence across these sectors. Furthermore, China's energy transformation will also drive technological progress across various industries. Model analysis shows that, under both scenarios, the contribution of technological progress to economic growth remains high and accelerates after 2050, becoming one of the key drivers of China's economic growth.

Figure 56
Inputs of electricity as intermediate use in sectoral output for 2030 and 2060



The development of energy technologies, equipment, and industries is of significant importance for underpinning China's energy transformation and building a modern socialist country. Under the carbon peaking and carbon neutrality goals, the energy transformation depends on innovation in energy science and technology as well as on the enhancement of equipment manufacturing capacity. China's clean energy-related industries continue to expand in scale, with output value reaching approximately RMB 10 trillion in 2024, establishing it as a sunrise industry surpassing the real estate sector in size. By 2060, the cumulative output value of China's clean energy industry is expected to exceed RMB 100 trillion, playing an essential supporting role in building a modern socialist country.

The development of new energy sources and the construction of a new-type energy system will also help address challenges such as workforce relocation from traditional energy sectors. During the energy transformation, conventional fossil fuel industries, such as coal and thermal power generation, face transformation pressures. Reduced job opportunities increase the burden of workforce transition and resettlement. At the same time, the capital stock of traditional energy industries gradually diminishes in the medium- to long-term (as shown in Figure 57). However, overall investment in new energy industries will increase rapidly, leading to fast growth in capital stock (as shown in Figure 58), particularly in wind and solar power, which will experience remarkable expansion in both growth rate and scale. The sustained rapid development of wind and solar power generation will continuously create new employment opportunities (as depicted in Figure 59), providing alternative positions for workers from coal, oil, natural gas, and thermal power sectors and thereby mitigating employment pressures associated with the energy transformation.

Figure 57
Capital stock in the fossil energy sector, 2030-2060

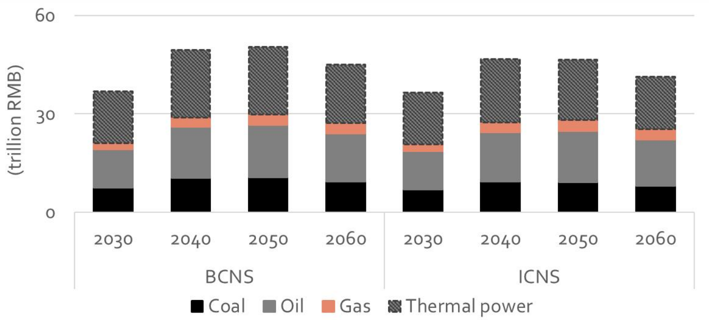


Figure 58
Capital stock in the new energy sector, 2030-2060

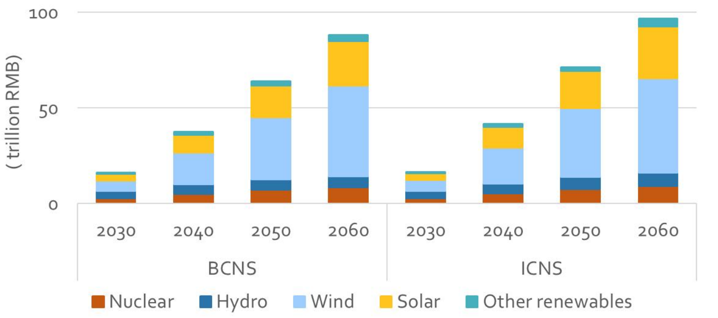
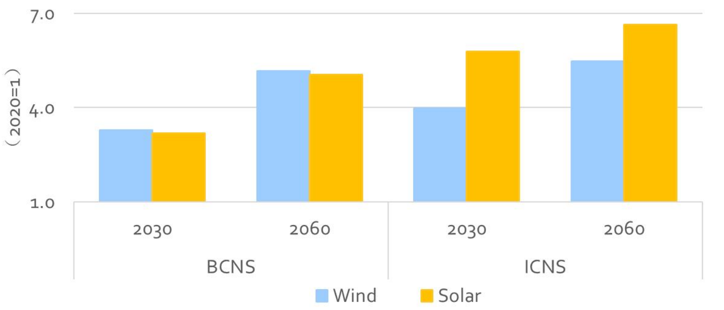


Figure 59
Employment trends in the wind and solar power sectors for 2030 and 2060



Difficulties and challenges faced

China's energy transformation is by no means an effortless endeavour. The international landscape for energy transformation is complex and fraught with challenges, while domestically, the nation faces formidable pressures, including substantial demand pressures, numerous supply constraints, and the arduous task of achieving a green and low-carbon transition.

Internationally, the cooperative framework for global energy transformation is growing increasingly intricate. The global energy transformation represents a long-term strategic realignment involving politics, economics, trade, and the international order, exerting profound, far-reaching systemic impacts on all nations. In recent years, heightened geopolitical conflicts, intensifying great power rivalry, and the resurgence of unilateralism and protectionism have increased instability and uncertainty in international energy markets. Environmental and climate issues have become increasingly politicised, while green trade barriers have multiplied, potentially disrupting the global energy transformation.

Domestically, China's energy development continues to face significant challenges: substantial demand pressures, numerous supply constraints, and arduous tasks in achieving a green and low-carbon transition.

These manifest in three key aspects:

Firstly, sustained growth in energy consumption. In recent years, digital industries, including artificial intelligence, big data, and 5G, have driven rapid expansion in electricity demand, resulting in higher-than-expected energy consumption growth. Compared with developed nations, where energy consumption has reached saturation and is gradually declining, China faces greater practical challenges in balancing energy demand growth with secure supply, while proactively adopting low-carbon technologies to underpin energy development and drive energy transformation.

Secondly, energy supply faces multiple constraints. Although China possesses abundant coal resources, the low-carbon transition limits the full exploitation of this resource advantage. While China possesses abundant renewable energy resources, the large-scale supply and integration of wind and solar power face significant constraints. These include limitations in securing land and maritime space for infrastructure, challenges in power system dispatch capabilities, and the inherent physical characteristics of renewables — fluctuating production, randomness, volatility, and low energy density. Hydropower and nuclear projects encounter difficulties such as complex surrounding natural environments, stringent safety requirements, and lengthy construction cycles, making it challenging to establish adequate supply in the short term, while costs remain relatively high.

Thirdly, implementing the energy transformation presents substantial challenges at the corporate, technological, institutional, and organisational levels. The energy sector is burdened by extensive legacy assets, high investment demands, entrenched development inertia, and protracted transition cycles, rendering the transformation task arduous. For enterprises, traditional energy companies grapple with operational difficulties and innovation barriers, while the pillar industries of fossil-energy-rich regions face severe disruption. Technologically, certain core energy technologies and materials remain constrained by unresolved fundamental theoretical challenges and high import dependency for critical equipment. Even in areas currently holding technical advantages, accelerated global iteration of new energy technologies may soon render them obsolete. Institutionally, increasing renewable generation shares elevates power system regulation costs, rendering traditional electricity pricing mechanisms ill-suited to new realities. Organisationally, emerging energy models such as point-to-point green power supply and local consumption of renewable energy impose new demands on grid security and power market regulation. Standards, management frameworks, and pricing mechanisms urgently require synchronised adaptation.

In short, for any nation, energy transformation is a long-term, arduous societal endeavour. For China — a populous, developing nation historically reliant on coal — this transition presents greater difficulties, more formidable challenges, and more demanding tasks.

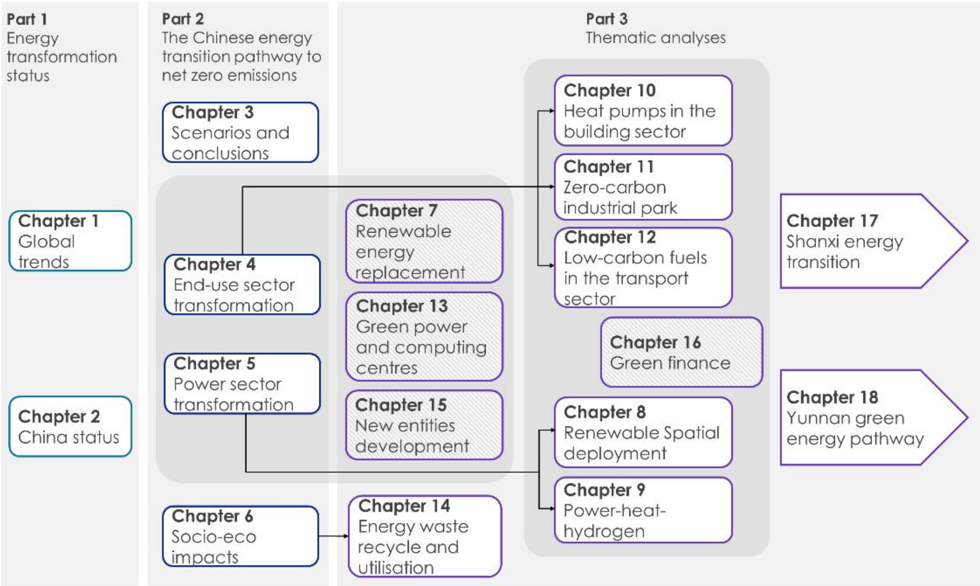
Looking ahead, green and low-carbon development has become an unstoppable trend of our times. Regardless of international developments, China's resolve to advance its energy transformation remains unwavering, its actions unceasing, and its commitment undiminished.

China seeks to strengthen collaboration with nations worldwide on green technologies and industries, jointly driving global energy transformation to achieve harmonious coexistence between humanity and nature, thereby safeguarding our shared planetary home.

Part III Thematic analyses

Part III of the CETO 2025 report comprises twelve thematic analysis chapters, including specialised studies on enhancing the secure and reliable substitution capacity of renewable energy, the application of heat pump technology in the building sector, and the development of zero-carbon industrial parks. These twelve thematic analysis chapters mutually reinforce the model analyses presented in Part II (as shown in Figure 60). The following outlines the principal conclusions of each chapter within Part Three. Should you wish to explore the detailed content, we recommend consulting the full report.

Figure 60
Relationship diagram of chapters in China Energy Transformation Outlook 2025



Chapter 7: Enhancing the reliable substitution capability of renewable energy

New energy serves as the cornerstone for achieving energy transformation and large-scale replacement of fossil fuels, while also providing a new fulcrum for safeguarding energy security. A systematic approach should be upheld to coordinate the development of new energy with national energy security in mind, continuously expanding new energy supply capacity while proactively addressing risks to system security and stability, as well as extreme event risks, thereby enhancing the resilience of the energy system while ensuring economic and social development.

The large-scale deployment of new energy requires enhancing secure, reliable substitution capabilities. Substitution capability refers to the ability to replace fossil fuel energy. Efforts should persistently strengthen comprehensive new energy supply capacity across all regions, accelerate the construction of large-scale wind and solar PV power bases, promote the orderly and standardised development of offshore wind power clusters, coordinate the integrated development of hydro-wind-solar bases, and advance the scaled development of concentrated solar power. During the buildout of this new energy supply, supporting the development of distributed renewable energy locally is key, and actively fostering new models such as point-to-point green power supply projects. At the same time, the continued steady development of biomass power generation and the further development of green fuels such as biogas, biodiesel, and biojet fuel, according to local conditions, remain important, as does the active and orderly development of green hydrogen, ammonia, and methanol from renewable energy. The promotion of the rational and efficient utilisation of geothermal resources also deserves effort, as does the advancement of large-scale application of wave and tidal energy. Furthermore, there is a need to establish a flexible heating system that can synergistically integrate renewable and traditional energy sources.

To enhance the substitution capacity of new energy, there is a growing need for integrated development. Integrated development requires strong collaboration and communication among interdisciplinary stakeholders, including the entire supply chain and local governments. To promote integrated development, broader participation by end-use energy consumers in the development and utilisation of new energy needs to be encouraged, shifting from singular efforts to coordinated group efforts. Integrated development helps coordinate projects that synergise well (so-called "source-grid-load-storage" projects), all of which help integrate new energy production across the entire system via supply, transmission, storage, and demand response projects. National-level coordination on large-scale development of new energy is essential to optimise the national effort to continue encouraging the accelerating deployment of new energy and regulation capacity. National-level leadership is needed to strategically pursue the coupled development of new energy with the industrial, transport, building, and data centre sectors. This will enable new energy to be fully integrated into various industrial economies, urban and rural infrastructure development, and an optimal spatial distribution, achieving a higher level of continuity between green, economic, and secure development.

China aims to strengthen holistic, long-term thinking about its energy transformation, with a focus on building a secure and resilient "new-type power system." As renewable energy grows, the stability of the entire system becomes more interdependent, making it essential to transform how power and energy systems are structured. This new system should handle high levels of renewable generation — both large-scale and distributed — by creating a hybrid grid in which large, interconnected AC/DC transmission grids work with smaller, flexible local grids. These local grids should increasingly become distributed smart grids, capable of self-balancing and coordinating with neighbouring grids, thereby enhancing the system's stability. Distributed smart grids will require new standards and regulations, as well as further development of the power market to send signals to project developers which encourage both new energy and regulation capacity.

Chapter 8: Large-scale new energy deployment and territorial spatial planning support

The forms of energy development and utilisation across different stages of human civilisation have shaped distinct patterns of land-use. Following the transition from an agricultural to an industrial society, the core elements of energy production shifted from land to underground mineral resources. New energy sources, represented by wind and solar power, are now re-establishing the land surface as the primary medium for energy production. Distributed renewable energy systems are increasingly integrated into diverse production, living, and ecological spaces.

China possesses abundant wind and solar resources, and a dual development model combining utility-scale and distributed systems will persist in the long term. Through GIS spatial analysis, and by comprehensively considering multiple factors such as energy resources, land use, topography, geomorphology, and ecological protection, the suitable construction areas for onshore wind power and utility-scale solar PV systems would exceed 600,000 and 200,000 square kilometres, respectively, with approximately two-thirds concentrated in western and northern regions such as Xinjiang, Inner Mongolia, and Gansu, demonstrating strong potential for green development. By 2060, the ratio of utility-scale and distributed wind power capacity is expected to be 66% to 34%, and 85% of installations will be concentrated in the Three North regions. Offshore wind power capacity is expected to reach 500 GW, mainly located in the coastal provinces of Fujian, Guangdong, and Shandong. Utility-scale and distributed solar PV capacity is expected to be equal in scale. Over 90% of utility-scale PV installations will remain in the Three Norths, while distributed PV will see more nationwide adoption and balanced development.

The deployment and utilisation of wind and solar power will profoundly shape the national power flow pattern of the "West-to-East and North-to-South power transmission" corridors, while promoting widespread localised green energy production and consumption. It is estimated that by 2060, more than one-third of national electricity demand will rely on optimal inter-provincial and inter-regional power transmission. By coordinating regional development, optimising new energy base layouts, and strategic productivity planning, the spatial re-organisation of power flows can be effectively improved, potentially reducing inter-regional transmission demands by over 10%. This will support a secure, efficient, and green energy system integrated at a national level across urban and rural land areas.

To advance the high-quality development of new energy sources, the guiding role of territorial spatial planning should be strengthened. It is recommended to comprehensively integrate large-scale new energy bases, major transmission corridors, and typical distributed utilisation scenarios into a unified spatial planning map for China. This will enhance the resource monitoring and evaluation system, promote planning coordination and optimise approval processes, clarify comprehensive land-use policies and technical standards, and ultimately ensure the land and maritime resource requirements for major wind and solar projects. Such measures will provide robust spatial support for achieving national energy transformation and carbon-neutrality goals. Furthermore, urban energy infrastructure planning should be optimised by integrating distributed renewable energy supply systems into land-use planning and implementation schemes, and by including their use in the design review process for new residential and public buildings.

Chapter 9: Key issues in the development of electricity-heat-hydrogen coupling

Electricity, heat, and hydrogen are the most significant energy carriers for future end-use consumption, with their production processes becoming increasingly interconnected due to many synergies.

The electricity-heat-hydrogen coupling integrates these three energy sectors through technical collaboration, leveraging synergies by interconnecting input-output streams, enabling efficient, flexible, and secure integrated energy systems. To ensure these integrated systems are sustainable, electricity is generated from non-fossil, zero-carbon sources, particularly variable renewable generation. Hydrogen is produced via flexible electrolysers or nuclear-coupled iodine-sulphur thermochemical cycles, serving as fuel or industrial feedstock. Heat is supplied by flexible electrothermal systems, high-temperature steam from nuclear plants, waste heat from hydrogen fuel cells, and residual heat from green hydrogen production, all of which can be used for space heating and low-temperature industrial processes.

Research indicates that electricity-heat-hydrogen coupling enhances renewable energy integration, strengthens power system regulation capabilities, and offers potential for reducing overall system costs. The synergistic optimisation of electricity, thermal energy, and hydrogen enables co-benefits between these sectors. For example, electrolyser units operating flexibly produce hydrogen during periods of lower electricity prices (which occur during hours of high solar and wind production), while their residual heat can substitute for other heat sources for space heating, thereby helping integrate renewable energy while also producing hydrogen and heat. Triple coupling offers multiple pathways for integrating renewable electricity: electrolyser units absorb surplus renewable power, producing hydrogen for industrial use and residual heat for district heating systems. The complementary storage capacities and response times (rapid for electricity, moderate for thermal energy, and long-duration for hydrogen) form an integrated regulatory resource portfolio, facilitating the development of more efficient, flexible energy systems. This multi-energy approach is especially critical for managing seasonal variability and periods of low renewable energy output.

Based on case studies from China and Denmark, a comparative analysis suggests several priority areas for China to successfully replicate and scale electricity-heat-hydrogen coupling projects. Regarding integrated system planning, electricity, thermal energy, and hydrogen systems should be treated as a unified portfolio to leverage synergies and enhance value, rather than being managed in isolation. For deployment and operational mechanisms, electrolyser and fuel synthesis facilities should be promoted in regions where renewable energy and thermal demand align, alongside the establishment of flexible operational frameworks that respond to grid requirements. Regarding market and contractual frameworks, energy producers should be incentivised to engage in contracts covering thermal energy, hydrogen, and grid services, thereby adding additional value through cross-product and cross-system support. Within the regulatory framework, approvals and policies should be adjusted to support sector coupling projects, grid integration, and new business models. Particularly in regions with large-scale district heating systems, long-duration thermal energy storage can provide cost-effective power system regulation capabilities.

Chapter 10: Applications of heat pump technology in the building sector

Heat pumps are highly efficient energy conversion devices that transform low-grade thermal energy into high-grade thermal energy by consuming minimal electricity, thereby significantly enhancing energy efficiency. In line with the trend towards electrification of end-use sectors, heat pumps are considered the optimal solution for advancing low-carbon heating. Both domestic and international institutions widely acknowledge that heat pumps will contribute 15%-22% to carbon reduction by 2060. The International Energy Agency ranks heat pump technology alongside solar PV, wind power, and electric vehicles as one of six major clean energy technologies. Global installed heat pump capacity is expected to grow by 3.3 to 4.3 times the 2023 level by 2050.

As a major producer, consumer, and exporter of heat pumps, China leads globally in manufacturing capabilities. China has established a comprehensive heat pump industrial chain and is the world's largest producer of air-source heat pumps, accounting for approximately 58% of global production in 2024. The nation actively promotes clean winter heating in northern regions and building-integrated heat pump applications, with heat pump sales achieving an average annual growth rate of more than 17% since 2014.

To accelerate high-quality development in the heat pump sector, China introduced the 2025 *Action Plan for Promoting High-Quality Development of the Heat Pump Industry*. The document mandates that, by 2030, the energy efficiency of key heat pump products should improve by more than 20%. The action plan calls for breakthrough innovations in core technologies, including high-temperature heat pumps, high-efficiency compressors, and novel refrigerants. The plan also emphasises expanding heat pump applications in buildings and increasing installed capacity. It outlines primary tasks for enhancing the quality and upgrading the heat pump industry from a lifecycle perspective, covering design and R&D, manufacturing, equipment renewal, and end-of-life disposal.

Within the building sector, heat pumps have broad application potential, including individual heating/cooling systems, district heating/cooling networks, waste heat utilisation, domestic hot water provision, and potential steam supply for buildings, indicating a significant market outlook. Recommendations to accelerate adoption include refining incentive policies, strengthening technological R&D, diversifying application scenarios, and standardising energy consumption measurement and statistics for heat pumps to promote their adoption in the building sector.

Chapter 11: Objectives, tasks and roadmap for zero-carbon industrial park construction

China hosts over 80,000 industrial parks of various types, serving as key hubs for resource aggregation to support economic growth. These parks account for around 50% of the nation's direct and indirect carbon emissions. Developing zero-carbon industrial (ZCI) parks represents a strategic and innovative initiative to upgrade decarbonised manufacturing and products, and to improve synergy within the energy transformation. It also constitutes an inevitable pathway toward deep decarbonisation within the Chinese industrial sector.

In developing zero-carbon parks, China emphasises the implementation of pilot demonstrations tailored to local conditions and focuses on integrating renewable energy resources within modern manufacturing processes, while leveraging technological innovation and institutional reform, to establish a cost-effective, efficient, and competitive zero-carbon development pathway. Establishing zero-carbon industrial parks is a long-term, complex, and systemic endeavour that requires transforming development models, process technologies, and energy systems. Regarding development models, efforts will focus on the industrial ecosystem, particularly in urban-park system integration, development paradigms, and inter-park connectivity. This will involve fostering high-end industrial clusters, promoting integrated industrial-urban development, leveraging agglomeration effects, and establishing ecological linkages to advance the decarbonisation and upgrading of industrial structures and organisational forms within parks. Process technology transformation will comprehensively implement ultra-high-efficiency measures, advance electrification 2.0, and promote low-carbon/zero-carbon power generation. It will also involve establishing low- and zero-carbon heating systems, scaling green hydrogen applications, and reshaping flexible manufacturing production systems. These efforts will drive intensive, electrified, hydrogen-based, and intelligent transformations in park energy consumption. Regarding energy system transformation, efforts will focus on three key areas:

1. Developing distributed renewable energy generation within and around industrial parks;
2. Constructing smart grids and microgrid systems;
3. Achieving synergy between generation, grid, load, and storage.

Together, these actions will establish a new industrial park energy supply system that combines green energy provision, intelligent, efficient and flexible transmission and distribution systems, and resilient regulation.

China's development of zero-carbon industrial parks should follow an implementation pathway of "pilot demonstration - scaled rollout - full carbon neutrality". This approach will advance proactively, tailored to different park types and developmental stages, progressing "from the simple pilots to more complex models" and "from individual cases to nationwide coverage". In the short term, driven by China's proactive promotion of enterprise relocation to industrial parks and the rapid expansion of emerging industries alongside petrochemical sectors, energy demand and carbon emissions in these zones will continue to rise. Energy demand is expected to peak around 2035, while carbon emissions are expected to peak before 2030. By 2030, approximately 100 representative zero-carbon demonstration parks will be established nationwide. After 2030, the development of zero-carbon parks will accelerate significantly. Parks dominated by emerging industry sectors will achieve comprehensive zero-carbon status around 2040, while those centred on traditional low-energy-intensive industries will reach this milestone around 2050. Highly energy-intensive industrial parks, particularly those dominated by the petrochemical and steel sectors, are expected to achieve comprehensive zero-carbon status around 2055.

Chapter 12: Low-carbon and zero-carbon alternative fuels for transport

Achieving carbon neutrality in the transport sector presents challenges in certain hard-to-abate modes such as shipping, aviation, and heavy-duty vehicles, where electrification cannot be directly applied. Consequently, ongoing exploration continues into the technological application of low-carbon and zero-carbon fuels, including hydrogen, ammonia, methanol, and sustainable aviation fuels.

International transport organisations and several developed nations have set targets for net-zero emissions or low-carbon/zero-carbon fuels in the transport sector. Within shipping, the International Maritime Organisation (IMO) aims to reduce annual greenhouse gas emissions from international shipping by 20% from 2008 levels by 2030, by over 70% by 2040, and to achieve net-zero emissions by 2050. The European Union requires shipping companies to reduce their average annual fuel greenhouse gas intensity by 2% from 2020 levels by 2025, ultimately achieving an 80% reduction by 2050. In aviation, the International Civil Aviation Organisation (ICAO) has set a net-zero target for 2050. It aims to increase the blending ratio of Sustainable Aviation Fuels (SAF) in international flights to 5% by 2030. The EU mandates that SAF blending at EU airports should reach 2% by 2025, with a target of 70% blending by 2050 at the latest. For new heavy-duty trucks, the EU aspires to achieve a 45% reduction in the average CO_2 emissions by 2030 compared to a mid-2019/20 baseline. Japan has proposed that new hydrogen fuel cell commercial vehicles should achieve a penetration rate of 20%-30% by 2030.

The Chinese government has also introduced a series of policies in recent years to support the development of low-carbon and zero-carbon fuels. The *Guiding Catalogue for Adjusting Industrial Structure (2024)* includes alternative-fuel-powered vessels powered by methanol, hydrogen, and biofuels among the projects encouraged for development. The Guiding Opinions on Vigorously Implementing the Renewable Energy Substitution Initiative propose supporting pilot operations in eligible regions for biodiesel, biojet fuel, biogas, and green hydrogen-ammonia-methanol in the shipping and aviation sectors. The "14th Five-Year Plan Special Programme for Green Development in Civil Aviation" targets cumulative sustainable aviation fuel consumption reaching 50,000 tonnes during the 14th Five-Year Plan period.

China has made significant strides in developing low-carbon and zero-carbon fuels for the transport sector, with their share expected to rise steadily in the future. In practical applications, China's 10,000-tonne methanol dual-fuel cargo vessel has been formally launched. A fleet of domestically manufactured ammonia-fuelled/dual-fuel vessels has also been successfully delivered and commissioned. The domestically produced fuel cell-powered vessel "Three Gorges Hydrogen Boat No. 1" completed its maiden voyage through the Three Gorges on the Yangtze River. Hydrogen-powered aircraft are currently deployed for unmanned aerial vehicle cargo transport, while 200kW-class hydrogen-powered heavy-duty trucks are progressively entering service. Regarding future development trends, projections indicate that by 2060: green methanol will account for 20% of shipping energy consumption; green ammonia will constitute 40% of shipping energy consumption; hydrogen-powered heavy-duty trucks will achieve a penetration rate of 20%-50%; hydrogen will represent 15%-30% of energy consumption within the transport sector; and sustainable aviation fuels will exceed 50% of aviation fuel usage.

Chapter 13: Key issues in the synergistic development of green power and computing power

Computing power constitutes a vital component of critical new infrastructure and new-quality productive forces, with electricity serving as the core factor influencing its scale and efficiency. Developing green computing power, characterised by a high share of green electricity supply, is a key measure for advancing the high-quality development of the computing power industry. It also constitutes an important pathway for accelerating the energy transition toward low carbon, providing robust support for the comprehensive green transformation of the economy and society.

The development of computing power urgently requires the safeguarding and support of "more robust electricity". According to International Energy Agency data, global data centre electricity demand reached 415 TWh in 2024, accounting for 1.5% of total global electricity consumption, and is expected to rise to 3% by 2030. Public data indicates that China's data centre electricity consumption exceeded 3% of total national consumption in 2024, and is expected to double by 2030 compared to 2024 levels.

Vigorously promoting synergistic development of computing power and green electricity. China has introduced multiple policies to encourage green and low-carbon development in data centres, driving coordination between computing power and green electricity. Currently, data centres utilise green electricity through two primary methods: physical direct connection and market transactions. Physical direct connection includes models such as distributed renewable energy deployment, integrated source-grid-load-storage systems, and independent microgrids. Market transactions encompass participation in green electricity trading and the purchase of green power certificates. Concurrently, from a technical perspective, data centres themselves possess inherent flexibility for load regulation. From a policy standpoint, both national and local authorities actively promote data centre participation in electricity demand-side management.

Advancing industrial development through computing power-electricity synergy. Firstly, further strengthen the coordination between electricity planning and data centre planning. Holistically consider the temporal sequence, aggregate volume, spatial distribution, and quality requirements of energy and electricity demand driven by computing power growth. This will facilitate deep integration between the *15th Five-Year Plan* period's electricity development blueprint, new energy development strategy, and computing power development roadmap. Secondly, accelerate the development of novel green electricity supply models such as "integrated generation, grid, load and storage". Seize the opportunity presented by green electricity direct supply pilot demonstrations to research new benefit-sharing mechanisms among renewable energy power stations, the grid and users. Explore cost-sharing mechanisms for peak shaving and reserve capacity arising from the grid's backstop supply function, thereby further reducing electricity costs while ensuring reliable power supply to data centres. Thirdly, deepen energy conservation, reduce consumption, and promote integrated energy utilisation. Promote the application of liquid-cooling technology in data centres, tailored to local conditions, to reduce overall energy consumption, and pilot the construction of a batch of advanced, energy-efficient data centres with low PUE values. Fourthly, advance the coordinated scheduling of computing power and electricity. As key entities in future electricity demand-side management, data centres can leverage their load regulation capabilities to participate in electricity demand response. The cross-regional transfer of data centre operations enables the coordinated scheduling of computing power and electricity.

Chapter 14: Recycling pathways for new types of waste in the energy sector

As the global energy transformation continues to advance, new forms of waste in the energy sector are expected to increase substantially. Research indicates that after 2030, the decommissioning of wind and solar power equipment and power batteries will reach its peak, creating significant opportunities for the circular economy. Wind turbine towers and generators contain large quantities of base metals, such as steel and copper, as well as rare earth elements, such as neodymium. Panels are rich in critical resources, including silicon, silver, and aluminium, making their recycling economically valuable. The recovery of end-of-life power batteries can substantially reduce reliance on primary lithium, cobalt, and nickel resources, mitigating external dependence on these minerals and holding strategic importance for safeguarding national resource security.

At present, the circular utilisation of decommissioned equipment still faces multiple constraints, including technical and economic viability, sustainable business models, and carbon emissions accounting. Simultaneously, it is urgent to address severe challenges, such as international green trade barriers. To support the sustainable development of the industry, it is necessary to identify circular utilisation pathways for decommissioned wind and solar power equipment and power batteries, promoting a shift from linear extension to dynamic circularity. Specifically: - Decommissioned wind turbines should adopt a tiered utilisation model encompassing reuse, remanufacturing, and resource recovery. - Retired solar PV equipment should adopt a graded approach combining reuse and high-value regeneration. - End-of-life power batteries should establish a closed-loop utilisation system centred on cascading deployment and resource recovery. Additionally, integrating Internet of Things (IoT) technologies into recycling systems will facilitate digital transformation and enable intelligent, high-efficiency recovery networks.

To effectively manage the upcoming wave of decommissioning, it is imperative to strengthen top-level design and coordinate progress across policy, technology, and mechanisms to foster a healthy, orderly development of the end-of-life equipment recycling industry. Specific measures include: First, strengthen the top-level design of policy, technologies and institutions for standardised recycling and regeneration to ensure coverage across the entire industry chain. Second, enhance innovation in low-carbon recycling technologies and promote the application of new technical achievements. Third, accelerate the implementation of extended producer responsibility mechanisms to clarify the obligations of all stakeholders along the industry chain. Fourth, establish stable, long-term support mechanisms and build a diversified funding security system. Fifth, develop cross-regional recycling networks to enable efficient matching of supply and demand.

Chapter 15: Promoting the innovative development of new entities in the power sector

With China's renewable energy capacity now accounting for over half of total installed power generation, the electricity system is accelerating its transition from a "source-following-load" model to a "source-load interaction" paradigm. Against this backdrop, new operational entities such as distributed power sources, novel energy storage systems, and virtual power plants are becoming pivotal forces in constructing the new-type power system. Drawing upon domestic and international practical experience, this report proposes policy recommendations to foster the innovative development of these new entities, forming the following key conclusions:

While China has established an initial policy framework for new entities, core institutional barriers remain to be overcome. These entities primarily encompass single-technology providers, such as distributed solar PV and energy storage, as well as resource aggregation models, such as virtual power plants and smart microgrids. Their defining characteristics include small-scale, dispersed operations; distribution grid integration; and integrated generation-consumption. Although national policies such as the "Guiding Opinions on Supporting the Innovative Development of New Business Entities in the Power Sector" have been introduced, these entities still face challenges, including difficult market access, limited revenue streams, and inadequate infrastructure. For instance, distributed generation encounters transmission fee barriers in local trading; new energy storage does not benefit from capacity compensation mechanisms and faces market access barriers; while virtual power plants are constrained by insufficient infrastructure and imperfect market pricing mechanisms.

International policy frameworks and market designs advance synergistically, emphasising equitable access and digital empowerment. The EU's Clean Energy Package establishes a policy framework for new market participants, while the US promotes distributed resource market participation through regulations like FERC Order 2222. Core experiences include: establishing clear legal status and market access rules; developing multi-tiered market systems to support revenue stacking; and advancing digital infrastructure development.

Policy design and technological innovation should be leveraged to unlock the market value for new market participants, thereby facilitating the paradigm shift in power systems. Firstly, enhancing wholesale power market mechanisms, improving spot market price signals, expanding ancillary service categories, refining capacity compensation, and establishing cost-sharing mechanisms encompassing all entities — generation, grid, and load. Secondly, advancing local transactions at the distribution grid level, improving transmission tariff pricing mechanisms, establishing the operational status and system responsibilities of self-balancing units, and refining retail electricity pricing mechanisms. Furthermore, one should accelerate technological innovation by encouraging the development of virtual power plant platforms, enhancing distribution grid digitalisation, and promoting the application of new technologies such as artificial intelligence and grid-forming/long-duration energy storage.

Chapter 16: International progress in green finance empowering low-carbon transition

Green finance has provided robust support for advancing the global low-carbon transition. In 2024, global green bond issuance exceeded 600 billion USD, while green loans reached 272.5 billion USD, propelling clean energy to become the primary driver of investment growth in the energy sector. Nearly 300 institutions have signed the Principles for Sustainable Insurance and launched multiple innovative products, effectively mitigating uncertainty risks in transition projects. Globally, 38 carbon trading systems have been established, covering 19% of greenhouse gas emissions with a combined market size exceeding 4 trillion USD. China's carbon market ranks largest in scale, while the EU carbon market boasts the strongest liquidity. International bodies, including the G20 Sustainable Finance Working Group and the OECD, have prioritised transition finance within global net-zero strategies, thereby advancing energy-justice transitions in developing nations.

Leveraging green finance to power low-carbon transitions has become a key strategy for most nations. Developed economies focus on establishing standards and institutional frameworks. The United States and the European Union have respectively enacted the Inflation Reduction Act and the REPowerEU initiative to create unified green classification standards, introduce financial instruments such as green bonds and credits, and establish specialised green banks. Developing nations place greater emphasis on advancing green finance tailored to their specific needs. Countries such as China and Brazil have incorporated green finance into national strategies, establishing cross-departmental coordination mechanisms. Aligning with their developmental stages and resource endowments, they are gradually scaling up successful regional pilot initiatives. These efforts actively channel government resources, market capital and international funding towards collaborative solutions for low-carbon transition challenges.

Global green finance cooperation to empower the low-carbon transition is advancing steadily but requires further deepening. Developed nations, including the US, EU, and Japan, are driving the formulation of international green finance standards to steer global capital flows. China is strengthening practical green finance collaboration within the Belt and Road Initiative, assisting partner countries in overcoming funding bottlenecks for green transitions. Multilateral development banks and international climate funds are actively issuing green bonds and providing innovative tools such as risk guarantees and joint financing. Currently, the scale of green finance cooperation falls significantly short of the energy transformation demands of most developing nations. Standards set by developed countries risk becoming green barriers, while existing funding volumes remain far short of what developing nations need. Many countries still lack the expertise to apply green finance instruments, underscoring the urgent need to deepen international cooperation in this field.

Opportunities and challenges coexist in international cooperation for green finance. Amid the global momentum for a low-carbon transition, international green finance cooperation presents significant opportunities. Firstly, the global green policy framework is increasingly robust, with International Sustainability Standards Board (ISSB) guidelines adopted by multiple nations. Secondly, technological innovation continues to diversify transition pathways, while digital technologies reduce the costs of the low-carbon transition. Thirdly, green investment volumes surge alongside sustained growth in ESG awareness.

On the other hand, deepening low-carbon transition financing cooperation faces persistent obstacles and challenges as international competition in low-carbon initiatives intensifies and protectionist barriers escalate. The United States' renewed withdrawal from the Paris Agreement has also heightened global uncertainties regarding the low-carbon transition. Moreover, innovation in green financial products and services has thus far failed to fully meet the demands of the industrial low-carbon transition. Lastly, there also remains a mismatch between industrial needs and financial supply, with gaps persisting in the alignment of international standard details.

Within the global climate governance framework, advancing green finance to support this low-carbon transition necessitates active efforts and close cooperation among nations, specifically across the following five key areas. First, a robust global green finance standards system should be established. Building upon the China-EU and multilateral taxonomies, a unified framework should be developed to advance mutual recognition of standards, refine ESG disclosure and carbon accounting rules, and support capacity-building in developing nations. Second, national incentive and constraint mechanisms require further development. Governments should provide increased legislative and fiscal policy support, while markets should guide diverse stakeholders' participation. The financial sector should innovate financing solutions, strengthen performance evaluation, and foster risk-sharing mechanisms. Thirdly, green financial product innovation should be intensified; central banks should develop structural instruments, financial institutions should deepen cooperation and integrate investment with lending, and dedicated funds should be established alongside the development of carbon finance products. Fourthly, supervision and information sharing should be modernised through a global regulatory system that leverages digital technology to build information platforms for risk prevention and transparency. Fifthly, international cooperation should be strengthened; multilateral platforms should be leveraged to advance governance through concerted action and shared development, thereby supporting the development of green finance in emerging economies.

Chapter 17: Deepening the comprehensive reform pilot for the energy revolution to accelerate Shanxi's energy transformation

Shanxi Province has been designated by the Central Committee of the Communist Party of China as the pilot region for comprehensive reform of the energy revolution. Since commencing the pilot programme in 2019, Shanxi has made steady progress across all assigned tasks and achieved notable results. This has yielded a range of advanced practices and exemplary cases that are replicable and scalable. For instance, the Taigu District Heating Project's long-distance heating model characterised by high temperature difference has become a benchmark for clean urban heating; green and intelligent coal mining has set a national standard; the Jin Hua furnace has developed independent intellectual property rights for resolving challenges in utilising low-grade coal; the clean and renewable polar energy system has commenced operation at the Qinling Station in Antarctica; Shanxi Province has become home to China's first officially operating electricity spot market; and the Taiyuan Energy Low-Carbon Development Forum has evolved into a high-level international cooperation platform for energy transformation. Nevertheless, Shanxi's coal-dominated energy structure and resource-based economic characteristics remain fundamentally unchanged. As China accelerates its comprehensive green transformation of the economy and society while constructing a new-type energy system, Shanxi needs to clarify its role, leverage its comparative strengths, and develop a distinctive pathway for energy transformation and economic upgrading.

As an important national energy base, Shanxi will, for the foreseeable future, continue to shoulder the responsibility of supplying thermal coal to the entire nation and ensuring electricity supply to the Beijing-Tianjin-Hebei region.

To accelerate the energy revolution, the priority is promoting green and safe coal production. This entails continuous development of green mining technology, combining source reduction with comprehensive resource utilisation to mitigate solid waste issues; extensively applying intelligent technologies to enhance the intrinsic safety of coal mines; and promoting the coordinated extraction of coal together with associated resources such as pyrite, bauxite, and coalbed methane.

Efforts should focus on integrating coal-fired power into the national power market and unlocking the new potential of flexible grid resources. It is required to intensify flexibility upgrades, integrate new energy storage technologies, and establish carbon capture, utilisation, and storage (CCUS) at the power plant. These measures will create a new generation of flexible, intelligent, clean, and low-carbon coal-fired units. Meanwhile, leveraging the advantages of transmission corridors, Shanxi Province should proactively integrate into the unified national power market, transforming coal-fired power from a mere "electricity supplier" into a valuable "provider of regulatory services" to achieve a leap in value.

It is required to keep pace with technological advancements in energy transformation to encourage the development of new energy models and business formats. This entails establishing industrial hubs for high-end carbon materials and carbon-based synthetic materials, enabling coal to explore new and untapped markets in the renewable energy and advanced materials sectors. Furthermore, we should leverage industrial by-product hydrogen to actively promote diversified applications, such as coke-oven gas-based methanol, fuel ethanol, LNG, and "blue hydrogen." Thereby, using low-cost "blue hydrogen" to drive the development of the entire hydrogen energy value chain. Furthermore, it is required to vigorously advance the use of AI in energy development, employing digital and intelligent technologies to foster new models and business formats such as virtual power plants, green electricity parks, smart microgrids, energy self-balancing units, and vehicle-to-grid interaction. This will enhance the user-friendly capabilities of distributed energy systems. Consequently, through green and intelligent energy and power services, we will attract more high-quality industries — including data centres and computing services, new-energy heavy-duty trucks, and specialised metal processing — to establish operations in Shanxi, thereby cultivating and strengthening new drivers of the province's economic growth.

Chapter 18: Yunnan's green energy development paves innovative pathways for high-quality development

Yunnan Province has continuously enhanced its green energy development capabilities, accelerating the construction of a new-type power system that has significantly boosted green energy supply capacity. Firstly, it has advanced the development of large-scale hydropower bases and pumped-storage power stations, conducting thorough feasibility studies and steadily progressing with the harnessing of remaining hydropower resources. Secondly, by leveraging the cascade hydropower stations along the Lancang and Jinsha rivers, it has accelerated the establishment of integrated "wind-solar-hydro-storage" bases, while utilising hydropower's regulation capabilities to smooth fluctuations in renewable energy generation. Thirdly, the province has refined its power market design, supporting new market participants, such as virtual power plants, to engage in demand response markets. **By August 2025, Yunnan's installed green power capacity reached 150 GW, ranking first nationally. The share of installed green power capacity and generation exceeded 90% and non-fossil energy accounted for 46% of primary energy consumption, figures that place the province among the nation's front-runners.**

Whilst Yunnan leads the nation in energy transformation, it simultaneously faces increasingly stringent ecological constraints on hydropower and wind-solar resource development.

The inadequacy of power system regulation capabilities has become more pronounced, while the transformation of traditional industries and the development of emerging sectors have grown more urgent. In connection with the seasonal imbalance of green energy — abundant in summer yet scarce in winter — these issues pose a more severe challenge to ensuring energy and power security.

It is recommended to innovate energy transformation pathways further, deepen the integrated development of green energy and high-end manufacturing, whilst maintaining a focus on ecological conservation. This will not only establish a robust green energy foundation for Yunnan's comprehensive green economic and social transformation, but also provide practical insights and valuable experience for other regions seeking to leverage green energy for regional development. Firstly, advance new-type power systems and zero-carbon industrial park construction. In addition, support local consumption of green energy around industrial parks and continue promoting incremental distribution grids and integrated "source-grid-load-storage" projects. Moreover, Yunnan will accelerate exploration of innovative point-to-point green power supply models, for instance, by actively promoting the "green-powered green industry" development model and driving accelerated transformation and upgrading of the province's manufacturing sector. Secondly, turn ecological benefits into measurable economic value through green energy development and utilisation. This will ensure that the construction of new energy power stations proceeds in parallel with vegetation restoration and soil and water conservation, using clean energy development to foster ecological restoration. Moreover, actively explore the shared value model to link clean energy development with ecological compensation mechanisms, and encourage innovation in integrating clean energy with green agriculture and eco-tourism.

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