China's Energy Structure Transition Toward Carbon Neutrality: Carbon Emission Characteristics, Bottleneck Constraints and Prospects

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Abstract. Against the backdrop of escalating global climate change and energy security pressures, promoting a low-carbon transformation of the energy structure has become a crucial pathway to achieving sustainable development. China is currently at a critical stage of synergistically advancing economic development, energy security, and carbon emission reduction targets. This paper reviews the evolution of China's energy supply and demand structure in recent years and further explores the main constraints of energy structure, technological innovation, and grid absorption capacity on the low-carbon energy transition. Research shows that China's energy structure is gradually shifting towards a low-carbon direction, with the proportion of fossil fuel supply and consumption continuing to decline, carbon emissions from some key industrial sectors stabilizing or decreasing, and positive progress being made in energy electrification and new energy development. However, resource constraints, key technological bottlenecks, and insufficient grid absorption capacity for high proportions of new energy remain significant factors hindering the energy transition. In the future, China's energy system will further develop towards zero-carbon supply, electrified consumption, distributed energy storage, and intelligent dispatch. Accelerating breakthroughs in key technologies such as hydrogen energy, advanced energy storage, and carbon capture, utilization, and storage (CCUS) is essential to support the achievement of carbon neutrality goals.

Keywords: Energy transition, low-carbon transformation, carbon neutrality.

1. Introduction

Driven by rapid economic growth, China's demand for energy keeps expanding. The country is now at a critical juncture balancing economic development, low-carbon transition and energy security. The primary driving force for energy transition stems from the existential threat posed by climate change to humanity. Since the Industrial Revolution, massive combustion of fossil fuels has released large volumes of greenhouse gases such as carbon dioxide into the atmosphere, triggering global warming and air pollution.

The second driving force arises from national energy and resource security. Constrained by the resource endowment of "rich coal, lean oil, scant gas", China still faces severe structural pressure to guarantee energy and mineral-resource security. Essentially, low-carbon energy transition represents humanity's necessary self-rescue for survival. Reducing over-reliance on imported fossil fuels will mitigate exposure to geopolitical or political-risk shocks, lower external-energy dependence, and strengthen the independence and resilience of energy supply.

Over recent decades, the share of fossil-fuel supply and consumption has gradually declined, and encouraging progress has been made in the green low-carbon shift. Industry remains a major carbon-emitter: key sectors such as iron-steel and cement have seen stable or falling emissions since 2020. Carbon emissions from the building sector have slowed their growth, yet total emissions keep rising owing to improved living standards and sustained economic expansion. China's low-carbon energy transition is still subject to multiple constraints: resource endowment, technological innovation bottlenecks, and power-grid capacity limits.

This paper aims to sort out the evolutionary trends of China's energy supply-demand structure in recent years, and examines energy-use and carbon-emission profiles across industry, building, transport and other sectors. It identifies major obstacles including energy-structure limitations,

technological hurdles and insufficient grid accommodation. On this basis, it sketches the outlook for carbon-neutral-targeted energy-system transformation. Historical experience demonstrates that an energy transition driven by clean sources is not only necessary but also feasible. It will reshape industrial layouts through technological progress and industrial-upgrading, and inform forward-looking planning for smart power grids and energy-storage infrastructure.

2. Current status of energy transition

In terms of total primary-energy supply, total primary-energy output has increased year by year alongside economic growth. It rose from 3.62 billion tonnes of standard coal equivalent in 2015 to 4.98 billion tonnes of standard coal equivalent in 2024, with an overall fluctuating upward growth rate [1]. From the perspective of primary-energy supply mix, between 2015 and 2024, the share of fossil-energy supply dropped from 85.5% in 2015 to 76.2%, while the proportion of non-fossil-energy supply increased from 14.5% to 23.8% [1] (Figure 1).

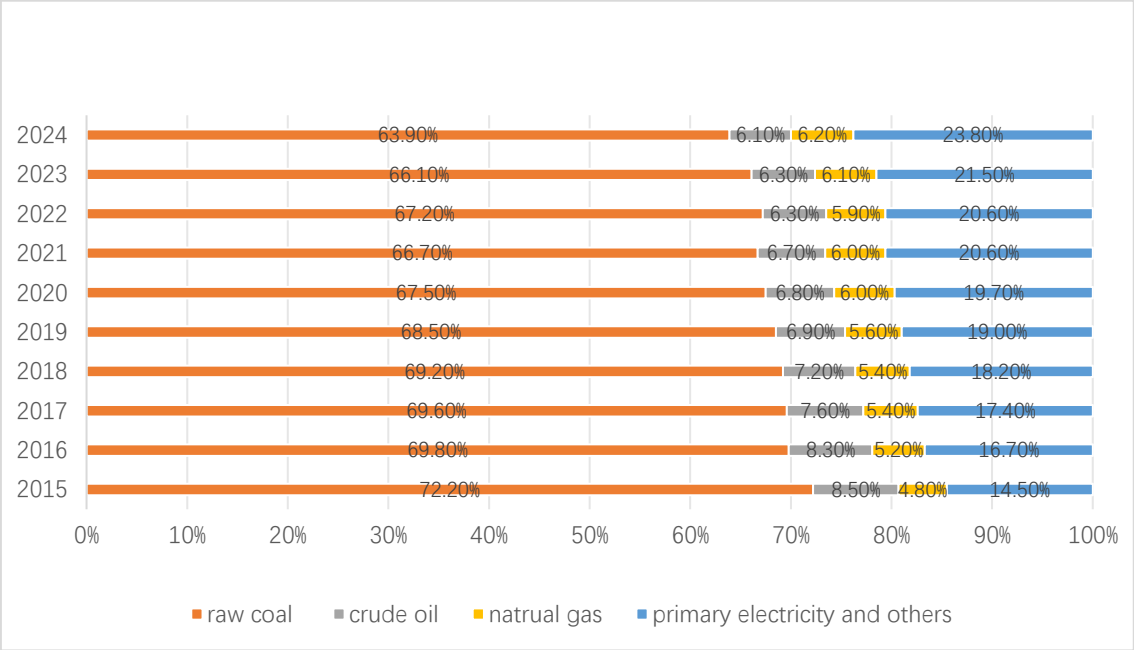


Figure 1. Percentage distribution of primary energy supply [1]

In terms of installed power capacity, the power sector has achieved remarkable results in green and low-carbon transformation over the past decade. By the end of 2025, China's total installed capacity of renewable energy reached 2.34 billion kW (including 450 million kW for hydropower, 640 million kW for wind power, 1.2 billion kW for solar power and 47 million kW for biomass power), representing a year-on-year increase of 24%, and accounting for approximately 60% of China's total installed power capacity (3.89 billion kW). The combined installed capacity of wind and solar power stood at 1.84 billion kW, making up 47% of the total, surpassing coal-fired power capacity (1.539 billion kW) for the first time.

From the perspective of total primary-energy consumption, total primary-energy consumption has grown year by year with economic development. It increased from 4.34 billion tonnes of standard coal equivalent in 2015 to 5.96 billion tonnes of standard coal equivalent in 2024, with a fluctuating upward growth rate [1]. In terms of the primary-energy consumption mix, from 2015 to 2024, the share of fossil-energy consumption fell from 88% in 2015 to 80.2%, while the proportion of non-fossil-energy consumption rose from 12% to 19.8% (Figure 2).

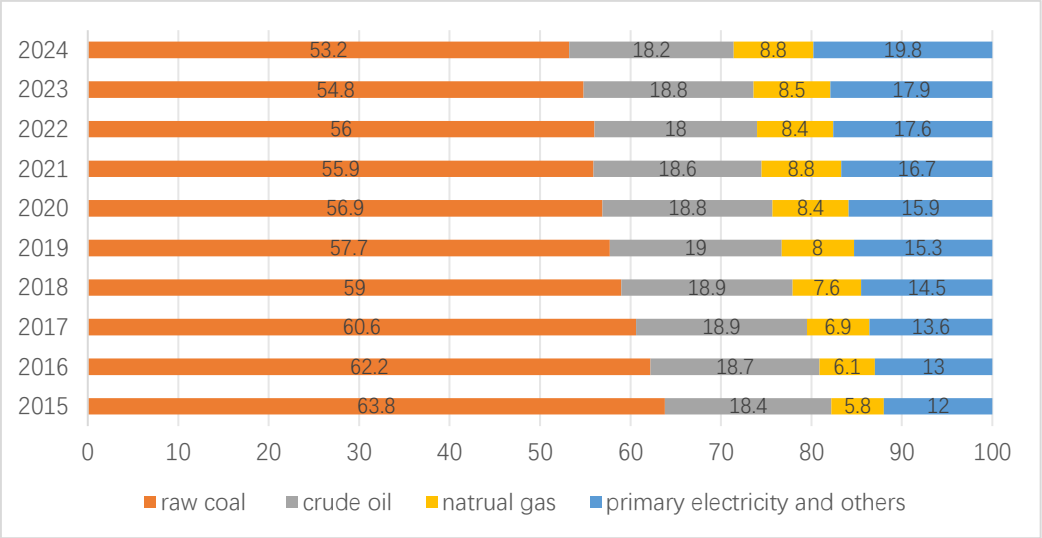


Figure 2. Percentage distribution of primary energy consumption [1]

By the end of 2025, the share of non-fossil energy in total energy consumption rose by approximately 2 percentage points year-on-year. It surpassed petroleum to become the second-largest energy source and the main contributor to energy growth. By the end of 2025, the share of power generation from non-fossil energy exceeded 43%.

3. Carbon emission analysis of key sectors

3.1. Industrial sector

The achievement of China's "Dual-Carbon" goals is highly dependent on the low-carbon transformation of the industrial sector. In 2022, total CO_2 emissions from China's industrial sector reached 7.98 billion tonnes, including 4.97 billion tonnes of direct emissions from energy activities and industrial processes, and 3.01 billion tonnes of indirect emissions stemming from electricity and heat consumed in industrial production. Industrial emissions accounted for 68.5% of China's total emissions, highlighting the critical role of industrial emission reduction in delivering China's "Dual-Carbon" goals [2]. Carbon emissions of major industries are shown in Figure 3.

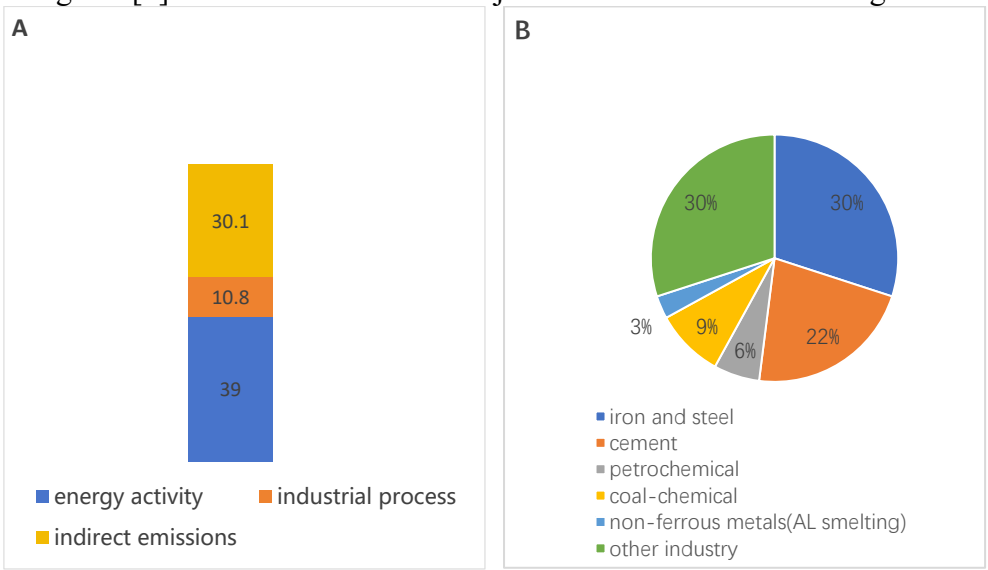


Figure 3. Carbon emissions from China's industrial sector (A), and Proportion of direct carbon emissions from major industrial sectors (B) [2].

Among them, the iron and steel industry is China's largest industrial greenhouse-gas-emitting sector. China produced 1.018 billion tonnes of crude steel and 1.34 billion tonnes of steel products in

2022. Its crude-steel output reached 1.005 billion tonnes in 2024, accounting for 55% of the global total. From 2010 to 2022, CO_2 emissions from China's iron and steel industry stayed between 1.49 billion and 1.82 billion tonnes, hitting 1.82 billion tonnes in 2022. Carbon emissions remained stable alongside steady steel output from 2020 to 2022. Heavily reliant on fossil fuels, steel production represents a heavy-industrial sector with considerable difficulties in emission reduction [2].

As an industry with rigid carbon-emission characteristics, China has ranked first globally in cement output for 40 consecutive years. Cement demand is mainly driven by building and infrastructure construction. After 2020, as urbanisation and housing demand gradually became saturated, domestic market demand for cement contracted markedly. In 2022, national cement output fell to its lowest level in nearly a decade at 2.12 billion tonnes, down by 11 % compared with 2020. The overall evolution of carbon emissions in China's cement industry from 2010 to 2022 can be summarised in three phases: rapid growth, moderate rise at a high level, and peak-and-decline. Driven by rising cement clinker output and sustained cement demand from infrastructure such as railways and highways as well as real-estate construction, CO_2 emissions of China's cement industry surged from 1.05 billion tonnes to 1.38 billion tonnes between 2010 and 2020 [2]. Following the proposal of the "Dual-Carbon" goals, the cement industry was listed among the first batch of key emission-controlled sectors. Affected by weak market demand, stringent policy constraints and advances in carbon-reduction technologies, its CO_2 emissions showed an obvious downward trend after 2020, dropping to 1.19 billion tonnes in 2022 [2].

3.2. Building operation

Carbon emissions from building operation cannot be neglected, more than half of which stem from electricity consumption. Maintaining comfortable indoor temperature and humidity, operating lighting and household appliances all consume large amounts of energy. Space heating in winter and space cooling in summer. Carbon emissions from building operation cannot be neglected, more than half of which stem from electricity consumption. Maintaining comfortable indoor temperature and humidity, operating lighting and household appliances all consume large amounts of energy. Space heating in winter and space cooling in summer represent two major sources of building-related energy use.

From 2000 to 2024, the operational energy consumption of civil buildings across China increased by 1.02 billion tonnes of standard coal (tce), representing an average annual growth rate of 6.5%, with the growth rate falling to 3.2% in 2024. The operational carbon emissions of national civil buildings rose by 1.81 billion tonnes of CO_2, at an average annual growth rate of 5.7%. With the further advancement of energy conservation and carbon reduction in the building sector, the growth rate dropped to 2.5% in 2024, equivalent to only 44% of the average growth rate, showing a notable slowdown.

4. Main challenges facing energy-structure transformation

4.1. Constraints of energy structure

China's resource endowment of "rich coal, lean oil and scant gas" has meant that coal has acted as the cornerstone of national energy security over the past decades. Coal is not only a fuel for power generation, but also widely used as raw material and heat source in high-energy-consuming industries such as iron-and-steel, coal-chemical and cement sectors. Part of coal is consumed as industrial feedstock rather than simply burnt as fuel. This portion cannot be directly substituted by straightforward electrification, which further increases the difficulty of carbon reduction. In terms of consumption composition, China's coal consumption is concentrated in two major segments: thermal power and heavy industry. Thermal power undertakes peak-shaving and supply-security tasks for power grids. While new-energy energy-storage technologies are not yet fully mature, coal-fired power still plays a back-up supporting role. A large number of high-energy-consuming industrial chains are built upon coal, featuring extensive upstream-and-downstream links with multiple practical

constraints concerning equipment assets, employment and local economy. For this reason, coal production capacity cannot be phased out rapidly in the short term. Aggressively cutting coal capacity may trigger energy-security risks such as insufficient power supply and drastic fluctuations in industrial-chain costs.

Meanwhile, structural divergence exists within the coal-related industrial chain. Some outdated, low-efficiency coal-consuming facilities are still in operation, characterised by high coal consumption per-unit product and intense carbon-emission intensity. Although advanced coal-fired power and coal-chemical facilities achieve higher efficiency, retrofitting the existing stock requires enormous investment. On the new-energy side, installed wind and solar capacity has grown rapidly. Nevertheless, restricted by insufficient energy-storage capacity, wind and solar curtailment occur, and new energy cannot fully fill the energy gap left by coal phase-out. Accordingly, China's energy transition does not simply mean "phasing-out coal". Instead, it aims to transform coal from a dominant energy source into a back-up and regulating energy source, and achieve the orderly succession between fossil energy and new energy.

4.2. Requirements for technological innovation

For industries hard to electrify such as iron-and-steel and cement, CCUS (Carbon Capture, Utilisation and Storage) serves as a critical back-stop technology for deep decarbonisation. Though technical feasibility has been verified in several demonstration projects, large-scale promotion still faces multiple barriers. Improving carbon-capture technologies is the first step for CCUS and has become a key research field for industrial emission reduction [3,4]. Post-combustion capture is well-suited to numerous existing thermal-power and building-material industrial facilities in China. Among relevant technologies, chemical amine scrubbing represents the mainstream for current commercial demonstration, yet it suffers from drawbacks including high regeneration-energy consumption and solvent loss [5]. Future technical evolution for capture focuses on developing novel solvents, adsorption and membrane-separation materials to cut capture-related energy consumption [6]. Meanwhile, modular and miniaturised equipment should be developed to adapt to complex flue-gas conditions in iron-and-steel, cement and other industries.

Carbon-dioxide transport infrastructure remains inadequate. The lack of complete dedicated CO_2 transmission pipelines causes spatial mismatch between industrial emission sources and geological storage sites, hindering large-scale deployment of the whole industrial chain [5]. Most CO_2 utilisation pathways remain at the demonstration stage. Apart from CO_2-enhanced oil recovery, routes such as synthetic-fuel production and mineral carbon sequestration are constrained by catalyst efficiency and limited product-market capacity, and cannot absorb large-volume industrial CO_2[5]. In terms of geological storage, major obstacles include CO_2-leakage risks, long-term monitoring techniques, site-evaluation systems, laws and regulations, as well as public acceptance [7]. Similarly, practical constraints such as long-term monitoring and site-assessment systems impede CCUS advancement. At present, CCUS has not achieved large-scale popularisation in China; it is generally in the transition phase from industrial demonstration to early-stage commercialisation.

For sectors accessible to electrification such as transportation, raising electrification levels constitutes an important measure for carbon reduction, whereas breakthroughs are still needed in energy-conversion and energy-storage technologies.

Green-hydrogen energy storage is vital for long-cycle peak shaving of power grids with high shares of renewable energy, yet practical application is subject to multiple bottlenecks. As an emerging technology, AEM features low cost and fast response, and permits non-noble-metal catalysts. Theoretically, it fits distributed hydrogen-production scenarios coupled with building-mounted photovoltaic systems. Despite promising prospects for AEM, limited by poor membrane-material stability, PEM electrolysis remains the dominant option for scenarios combining distributed photovoltaic power and green-hydrogen energy storage to cope with fluctuating new-energy conditions. Such technical trade-offs indicate that future large-scale hydrogen application will most probably rely on combinations of multiple technologies rather than one single dominant

electrolyser design. Different electrolysis technologies will serve distinct operational segments within renewable-energy systems [8].

4.3. Improvement of supporting power grid systems

The large-scale connection of distributed photovoltaics, energy storage facilities, electric vehicles and other entities to the power grid places brand-new requirements on grid dispatch and operation.

First, the inherent volatility and intermittency of wind and solar power lead to temporal mismatches between power generation and load. Photovoltaic power output peaks in daytime and does not fully align with actual building electricity loads. Surplus daytime power needs to be fed into the grid, while electricity has to be drawn from the main grid at night. Such bidirectional power flow increases dispatch difficulty, and power fluctuations cannot be completely offset relying merely on regulation from conventional thermal power units [8].

Second, large-scale grid integration of distributed power sources creates challenges for power forecasting and balance. Building-side distributed photovoltaic installations are scattered, and their output shows strong randomness subject to meteorological conditions. It is difficult to accurately predict power generation and user loads. Without effective forecasting tools, local energy imbalance may occur and jeopardise the safe and stable operation of power grids [9].

Third, the potential of flexible load resources remains underexplored. Regulatable resources such as electric vehicles and user-side energy storage have not been fully incorporated into dispatch frameworks. Load-side aggregation and response mechanisms are imperfect and fail to adjust loads in response to variations in new-energy output, which hinders the practical implementation of the "load follows generation" model [10].

Fourth, existing power-grid infrastructure shows insufficient adaptability. Reverse power delivery from massive distributed photovoltaic units creates shocks to distribution-network voltage and power-flow control. The lack of a complete dispatch framework to mobilise demand-side flexible resources limits the full accommodation of new-energy generation.

5. Prospects for energy transition

5.1. Advancing the deployment of zero-carbon energy

The core of energy transition lies in zero-carbon energy supply and electrified consumption. The pursuit of carbon neutrality is essentially a re-electrification process built upon zero-carbon energy [11].

On the energy supply side, On the one hand, existing coal-fired units shall be retrofitted for energy conservation and carbon reduction, and high-energy-consuming backward processes shall be phased out. On the other hand, the installed capacity of onshore and offshore wind power and distributed photovoltaics should be expanded. Efforts shall be made to develop electrochemical energy storage and long-duration green-hydrogen storage technologies, and optimise cross-regional power allocation.

On the energy consumption side, electrification should be adopted wherever feasible, substituting coal, oil and gas with electricity, with technological innovation as the core driving force. In industrial sectors, fossil-fuel-powered equipment will be replaced by electric alternatives. For example, coal-fired boilers and kilns can be substituted by electric ones. In steel production, electric-arc-furnace steelmaking will replace the traditional blast-furnace ironmaking and converter steelmaking processes. In the transport sector, electric vehicles will be widely promoted. In the building sector, electric heating and electric water heaters will replace coal-or gas-driven heating and hot-water supply systems, so as to deliver decarbonisation and zero-carbon development across all sectors.

5.2. Promoting technological innovation

Wind and solar generation features intermittency and volatility. Therefore, CCUS-equipped thermal power plants and nuclear power will deliver zero-carbon power while serving as guaranteed

and regulatable power sources, playing an irreplaceable role. Meanwhile, CCUS is also indispensable for sectors that are hard to fully electrify, such as steel and cement industries. For the next-generation energy system, future CCUS research priorities include developing new low-energy-consumption capture-related materials and optimising system processes, and advancing the in-depth integration of CCUS with renewable energy including wind and solar power [5].

To absorb surplus green electricity generated by solar and wind facilities, excess power can be converted into green fuels including hydrogen-ammonia, alcohol-ether and synthetic fuels. In future practice, green-hydrogen energy storage should give full play to its strengths in large-capacity and long-period energy transfer, so as to address the shortage of long-cycle peak-shaving capacity for power systems with high new-energy penetration [8].

5.3. Optimising power-grid adaptability

The new-type power system dominated by new energy must be flexible. Leveraging big data, cloud computing and artificial intelligence, more flexible operation modes and powerful regulatory tools should be established, building a safe operation system adapted to the dominant role of new energy. It is neither reasonable nor feasible to force new energy to imitate the operation patterns of conventional energy sources.

Intelligent digital power grids will emerge, alongside new industrial formats and business models such as multi-energy complementation, virtual power plants, industrial and commercial energy storage, Vehicle-to-Grid (V2G), and load aggregation. This brings disruptive requirements for system planning, operational control and market mechanisms. It helps secure energy supply under high-share new-energy integration and reduces safety costs for power systems.

6. Conclusion

This paper reviews the achievements of China's energy transition over the past decade and analyses existing challenges including technical bottlenecks and grid accommodation capacity in the ongoing energy-structure transformation. The main conclusions and prospects are presented as follows.

China's energy transition is trending toward zero-carbon energy supply, electrified consumption, networked energy storage and precise dispatching. Energy generation will become ubiquitous: rooftop photovoltaic panels, wind turbines in farmlands and other facilities will continuously produce energy. Energy storage will likewise be widely distributed. Batteries of electric vehicles, household energy-storage devices and industrial-scale energy-storage power stations will jointly form a distributed energy-storage network. Energy consumption will grow smarter, with artificial intelligence and Internet-of-Things technologies enabling precise matching between energy supply and demand. In the future, further breakthroughs should be made in cutting-edge technologies such as hydrogen energy, advanced energy storage, and CCUS. A new-type energy system shall be built, shifting from "resource dependence" to "technology-driven support". Moreover, a safe operation system adapted to the dominant role of new energy needs to be established, so as to guarantee energy-supply security with high-penetration new-energy integration and reduce the safety-related costs of the power system.

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