China Council for International Cooperation on Environment and Development

Collaborative Innovation in Energy and Environment for High-Quality Development

Scoping Study 2025

China Council for International Cooperation on Environment and Development (CCICED)

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Collaborative Innovation in Energy and Environment for High-Quality Development

Research on Key Issues and Strategies for Collaborative Innovation in Energy, Resources and Environment Under the "Dual Carbon Goals"

October, 2025

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** The co-leaders and members of this policy research project participate in the research in their personal capacities. The views and opinions expressed in this report do not represent those of their respective organizations nor CCICED.*

Executive Summary

Research Significance

Chinese modernization is characterized by harmonious coexistence between man and nature. During the energy transition marked by the replacement of traditional fossil fuels with new energy sources, strengthening collaborative innovation in energy and environment is an essential requirement for China to achieve its goals of carbon peaking by 2030 and carbon neutrality by 2060 (referred to as the "Dual Carbon Goals"), as well as to advance high-quality development to realize Chinese modernization.

Since the 18th National Congress of the Communist Party of China, the structure of energy production and consumption in China has been continuously optimized to be cleaner and more efficient, and the consumption of clean energy has been steadily increasing. Atmospheric pollutant emissions from thermal power plants have decreased by approximately 95% compared to their peak levels. Entering the "14th Five-Year Plan" period, and under the guidance of the "Dual Carbon Goals," building an eco-civilization in China has shifted its strategic focus to carbon reduction, injecting strong momentum into the development of new energy: China's installed capacity and power generation of new energy has held the top global position for many years, with leading technological capacity around the world. As the carbon peak goal will be achieved in the upcoming five years, the work of carbon reduction will transition into the carbon neutrality phase, and continue to vigorously develop new energy, and the gradual phase-out of coal is an inevitable trend.

During the process of replacing traditional energy sources with new energy, the energy transition faces dual challenges: On one hand, the role of coal power is gradually shifting from being the primary power source to guarantee fundamental power supply and provide flexible allocation, to gradually phasing out. Correspondingly, coal mines will also transition from consolidation to gradual exit, making it necessary to be vigilant about new environmental issues that may occur along this process. Given China's natural resource endowment and its needs for energy security, the modern coal chemical industries require moderate development; however, coal chemical projects face severe environmental protection and carbon reduction pressures. On the other hand, the vigorous development of new energy and the construction of new power systems may also trigger new environmental and ecological risks. Therefore, in order to advance high-quality development, it is essential to proactively identify and screen the environmental challenges and risks in the energy transition, conduct targeted research appropriately ahead of time, and provide scientific planning and policy guidance recommendations.

Collaborative development requires the overall construction of a multi-dimensional objective system using systematic thinking, achieving multiple benefits through comprehensive means, and promoting coordination and cooperation among different fields and departments during policy-making and implementation. The traditional linear governance logic of "sustaining economic growth by ensuring energy supply" or "protecting the environment with pollution control" is difficult to meet the requirements of high-quality development, and there is an urgent need for a transformation of a systematic governance concept of "collaborative innovation." Promoting the collaborative development of energy and the environment is the "key" to breaking the governance dilemma of "fragmentation" in the energy and environment fields, an important measure to address the three major challenges of climate change, environmental pollution, and resource constraints, and to achieve high-quality development and high-level protection. It is also the core support for practising Xi Jinping's thought on ecological civilization, building a beautiful China, and promoting the implementation of the “Dual Carbon Goals.”

Research Focus

This research consists of five parts, with the core content as follows:

1. **The significance of collaborative innovation in energy and environment:** This section elaborates on the strategic importance of energy-environment collaborative innovation in achieving the “Dual Carbon Goals” promoting high-quality development, and advancing high-level environmental protection.

2. **Current status and trends of energy-environment collaboration domestically and internationally:** This section reviews global energy transition trends and collaborative experiences, summarizes China’s achievements in energy transformation under the “Dual Carbon Goals,” and focuses on the top-level design and interdepartmental collaborative practices in energy-environment synergistic innovation in China.

3. **Collaborative issues and challenges during traditional energy transition:** Although China's energy transition has achieved remarkable results, difficulties also persist as the process continues. It is essential to maintain firm confidence while keeping a sense of vigilance and to proactively address new challenges. This section focuses on analyzing ecological and environmental issues during the gradual phase-out of coal, such as methane emissions, acid mine drainage, and heavy metal pollution from abandoned coal mines. It also discusses new environmental challenges during the development of modern coal chemical industries, including high carbon emission intensity, high costs of carbon emission control, and difficulties in the treatment of high-salinity wastewater and disposal/reuse of waste salts. Recommendations for collaborative innovation are proposed from both technological and policy perspectives.

4. **Potential resource and environmental issues during the sustained and vigorous development of new energy:** For instance, at the planning stage, land-use constraints have become a major limiting factor for the large-scale deployment of new energy. It is important to strengthen the coordination of energy and environmental policies from a full life-cycle perspective that encompasses "planning-construction-operation-decommissioning."

5. **Recommendations for collaborative innovation to promote high-quality development:** Based on the above research, this section proposes a national-level risk early-warning mechanism, a legal guarantee system, and key directions for further research. These recommendations aim to provide policy support for energy-environment collaborative innovation and facilitate high-quality development.

Main Policy Recommendations

1. **Establish a national-level comprehensive early-warning and coordination mechanism and conduct research on "prospective contingency plans."**

In order to deal with major environmental and resource issues that may arise from the gradual phase-out of coal mines, the scaled development of modern coal chemical industries, and the sustained large-scale expansion of new energy, it is recommended to establish a national-level comprehensive early-warning and coordination mechanism. Additionally, research on "prospective contingency plans" should be initiated in the upcoming 5 years to strengthen risk prevention

and ensure collaborative high-quality development of energy and the environment.

In real-world applications, indicators such as the improvement pace of environmental quality in China, the development speed and scale of new energy and its cost decreasing rate, as well as energy consumption growth, total coal consumption, and the scale of coal-fired power development have repeatedly exceeded the predictions of some experts or the expectations of official plans. This has led to insufficient synergy between policy and planning elements, posing significant risks to the healthy development of the energy industry. The upcoming 5 to 10 years represent critical stages for achieving two major strategic goals: carbon peaking and the building of a beautiful China. Ensuring high-level synergy between energy and the environment is therefore crucial.

First, create a national early-warning and coordination mechanism: Establish a comprehensive cross-departmental and cross-industrial (including national associations) research and coordination institution. This institution would integrate resources, perform comprehensive and interdisciplinary research through "early planning, deep analysis, and concrete preparation," develop scientific contingency plans and ensure proactive control of systemic risk management on a strategic level.

Second, develop a system of "proactive contingency plans": Scientifically evaluate the speed of new energy transition and the phase-out of fossil fuels. Conduct foresight studies on industrial evolution pathways and multi-faceted regulation concerning energy, environment, and resources. The aim is to develop more resilient policies for impacts from uncertainties and natural disasters, creating a contingency planning methodology and framework that has scientific assessment, precise response, and dynamic optimization, which would strategically reinforce risk prevention for high-quality development.

2. **Accelerate the development of a top-level legal framework against climate change**

Establishing this framework will provide a legal foundation for the overall management of energy transition, environmental protection, and climate governance. It will create a solid legal guarantee for high-quality development and the realization of “Dual Carbon Goals.”

Currently, China's climate actions mainly rely on top-level policy papers and departmental regulations. Although a comprehensive deployment with a “1+N” core policy system is already in place, it still faces challenges such as insufficient systemization, weak legal foundation, and poor coordination with existing energy and environmental laws. It is recommended to legislate a proven-effective national strategy, management system, “Dual Carbon Goals” responsibility mechanism and major regulations through national-level legislation. This legislation should clearly define the statutory responsibilities and obligations of governments, industries, and market entities in energy structure optimization, industrial low-carbon transition and climate governance. It would systematically regulate mitigation and adaptation activities related to climate change, enhance synergy and consistency of existing laws that address climate governance and energy, as well as environmental sectors, and improve the nation's climate governance capabilities to a more legalized, standardized, and institutionalized level.

3. In-depth research on collaborative innovation in energy and environment

The three pillars of energy development—security, green transition, and economic growth—are unified and inseparable, interdependent yet contradictory. They need to reach a dynamic balance under the guidance of sustainable development concepts. The core idea of energy-environment synergy and innovation is to identify "misalignments" during the transition from old to new, analyze their root causes and conditions, and explore solutions—all within the framework of high-quality development and the integrated goals of decarbonization, pollution reduction, ecological conservation, and economic growth. This preliminary study has screened and analyzed key issues and proposed initial recommendations. Future research should deep dive into two areas:

Firstly, design a collaborative development roadmap for the upcoming 5 years and beyond: Formulate near-, medium-, and long-term goals that are in line with the key milestones of “Dual Carbon Goals” and beautiful China development. The goals should define collaborative pathways between environmental resources and the phasing out of outdated coal mines, the planning of the modern coal chemicals industry, and the orderly expansion of new energy sources. Moreover, explore the pathways to minimize the environmental costs of coal mine closures, research on collaborative transition mechanisms for traditional energy bases transformation, ecological restoration and

compensation, and multi-agency monitoring; Explore modern coal chemical development roadmaps and their coupling with renewable industries to enable green upgrading; Innovate the orderly development for renewables, scientifically assess full life-cycle environmental impacts of new energy bases, and propose ecological protection policies and technical solutions, improve environmental impact monitoring systems in key regions (such as renewable bases).

Secondly, explore cross-department and cross-region decision-making and policy collaboration tools: Conduct research on the optimization of key policy tools across departments, the construction of green low-carbon standard systems, early-warning systems for energy-environment risks, and coordinated law enforcement mechanisms. Explore cross-regional energy development synergy pathways through models like "enclave economy" and improve inter-regional energy design mechanisms for ecological compensation, as well as cost-sharing for transition and collaborative governance.

Keywords: Energy Transition; Energy-Environment Synergy; High-Quality Development; Abandoned Coal Mines; Modern Coal Chemical Industry; New Energy

Contents

Chapter I. Research Background and Significance

Chinese modernization is characterized by harmonious coexistence between man and nature. Building a beautiful China is the key objective to building a modern socialist country in all respects. Achieving carbon peak by 2030 and carbon neutrality by 2060 is interdependent with Chinese modernization. The key tasks and fundamental drivers for achieving the "Dual Carbon Goals" are the energy transition that focuses on the large-scale replacement of fossil fuels with new energy sources and establishing new energy and power systems.

By 2035, China will have basically realized socialist modernization. It's also an important time period for the targets for achieving a beautiful China in all respects and promoting high-quality development supported by a better ecological environment. This milestone bridges the 2030 carbon peak and global SDG targets with the targets of Chinese modernization by 2050 and carbon neutrality before 2060. Therefore, despite the challenges and uncertainties, how to effectively align energy transition, high-quality development, and beautiful China construction with long-term carbon neutrality goals is crucial for collaborative innovation to advance high-quality development of energy and environment.

Energy transition acts as the core arena for advancing high-quality development, with electricity acting as both a mainstay and a lifeline for modern economic and industrial growth. Promoting high-quality development of new energy is essential to achieving high-quality socioeconomic progress. Over the past two decades, the share of renewable energy in global consumption has increased by about 5 percentage points, while fossil fuels decreased by nearly 3 percentage points. However, fossil fuels still dominate, accounting for approximately 80% (IEA) of the global energy system. During the same period, global greenhouse gas emissions rose from 26 billion tons to around 40 billion tons of CO_2 equivalent, with energy activities contributing to about three-quarters of total global emissions (IPCC).

As the world's largest energy producer and consumer, China's longstanding coal-dominated energy structure has supported economic growth but also brought various pressures, including climate change, environmental pollution, ecological degradation and resource constraints. Over the past decade, China accounted for nearly 80% of the global increase in CO_2 emissions, becoming the world's largest emitter (UNEP). Energy-related activities contribute about 76.9% of the country's total emissions (MEE, "The People's Republic of China Second Biennial Update Report on Climate Change"). Entering the phase of high-quality development, China will still face severe challenges such as complex regional compound pollution, high coal dependency, fragile ecosystems, and natural resource constraints.

Since the 18th National Congress of the Communist Party of China, China's energy production and consumption structures have been consistently optimized to be cleaner and more efficient, with the share of clean energy consumption steadily increasing, and air pollutant emissions from thermal power plants have dropped by about 95% compared to their peak. During the "14th Five-Year Plan" period, and guided by the "Dual Carbon Goals," ecological civilization construction has entered a strategic phase that is focusing on emission reduction, providing strong momentum for new energy development. China now leads the world in both installed capacity and generation of new energy, with global-leading overall technological prowess. As carbon peaking is expected to be achieved in the upcoming 5 years, efforts in emission reduction will transition toward carbon neutrality, making the continuous large-scale development of new energy and the gradual phase-out of coal an inevitable trend.

Throughout this process, the energy transition faces dual challenges: on one hand, coal power is shifting from a primary energy source to a supporting role to ensure a reliable baseline and backup energy supply supported by flexible allocation mechanisms, and is gradually phasing out. Correspondingly, coal mines will also be gradually consolidated and phased out, which requires careful management of potential environmental issues during the transition. On the other hand, the large-scale expansion of new energy and the construction of new power systems may also introduce new ecological risks. Therefore, advancing high-quality development requires proactively identifying environmental challenges and risks in the energy transition, conducting targeted research, and proposing scientific planning and policy guidance.

Collaborative development requires building a multi-dimensional objective system through systemic thinking and achieving multiple benefits with integrated approaches, and it should promote coordination and collective action across different domains and departments in policy design and implementation. The traditional linear governance logic, such as "sustaining economic growth by ensuring energy supply" or "protecting the environment with pollution control," no longer meets the demands of high-quality development. A shift toward systemic governance focusing on collaborative innovation is urgently needed. Advancing energy-environment synergy is crucial to overcoming fragmented governance in these sectors. It serves as a key measure for addressing the triple challenges of climate change, environmental pollution, and resource constraints, enabling high-quality development alongside high-level environmental protection. Furthermore, it forms a central pillar in the implementation of Xi Jinping's thought on ecological civilization, building a beautiful China and advancing "Dual Carbon Goals."

Chapter II. Status Quo and Trends of International and Domestic Synergy in Energy and Environment

1. International Trends of Energy and Environment Synergy

1.1 International Trends of Energy and Environment Synergy

Climate change is one of the greatest threats to global sustainable development. In order to achieve the Paris Agreement temperature goals, we are in a crucial phase of global action for climate mitigation, which is to realize an energy transition that phases out outdated capacities of traditional energy and advances the orderly development of new energy. The 28th Conference of the Parties (COP28) to the UNFCCC marked a historic consensus on transitioning away from fossil fuels, with a clear target to “triple global installed capacity of renewable energy and double energy efficiency by 2030.” Transforming the energy structure has thus become a global strategic priority for addressing climate change, promoting green growth, and enhancing energy security.

Although the energy transition and the scaling up of renewable energy have brought significant potential for climate mitigation, a growing body of international research and experiences suggests that poorly managed decarbonization efforts may cause unintended environmental harm (IPBES & IPCC, 2021)[1] and exacerbate biodiversity loss, undermining the ecosystems that human societies depend on (IUCN, 2021).[2] Land use and sea space occupation are among the most prominent impacts of energy development. Large-scale solar and wind power plants can directly degrade and fragment natural habitats, disrupt wildlife migration, add pressure on agricultural intensification, and even trigger indirect changes in land use (Shan Shui Conservation Center, 2024).[3] While shifting to renewable energy in transport is another essential climate response (IPCC, 2019), the extraction of critical minerals involved in this process may also pose serious environmental risks and biodiversity threats.

Therefore, there is an increasing international attention on how to align energy transition with ecological conservation, such as climate change and biodiversity protection, as well as advancing toward a nature-friendly energy transition while achieving high-quality development. The United Nations’ 17 Sustainable Development Goals also emphasize integrated, collaborative approaches,

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1 IPBES-IPCC CO SPONSORED WORKSHOP, BIODIVERSITY AND CLIMATE CHANGE, 2021

2 Mitigating Biodiversity Impacts of Solar and Wind Energy Development , 2021

3 Opportunities and Challenges of the Collaborative Development of Renewable Energy and Biodiversity in China， Shan Shui Conservation Center, 2024

promoting the need for a comprehensive perspective and collaborative mechanisms during policy-making to prevent conflicts and negative impacts across sustainability objectives.

1.2 International Practices on Energy and Environment Synergy

Many countries have adopted practices such as enacting laws and regulations, dynamically updating standards, promoting technological innovation, and enhancing enforcement and interdepartmental collaboration, providing valuable experiences in promoting energy-environment synergy. The following examples demonstrate Germany's experiences in traditional energy transition and the orderly development of renewable energy.

Pathway of Clean Coal Transition and Methane Capture

In Germany, emissions from coal-fired power plants have created some air pollution incidents, such as acid rain in the Hohenhonen region and NO_x pollution in the Ruhr area, which seriously impacted the air quality and residents' health in surrounding areas. By developing high-level policies and emission reduction pathways, Germany successfully achieved significant pollutant reductions and methane capture and utilization.

Policy and regulatory guidance. In 1974, Germany implemented an industrial emission permit system and enacted the "Federal Immission Control Act(BImSchG)." In 2000, the country launched a clean air program aimed at further reducing atmospheric pollutants and improving air quality. The program includes strengthening emission controls on industrial sources such as coal plants, promoting the development and adoption of clean energy, and encouraging technological innovation and R&D. At the same time, Germany passed the Renewable Energy Sources Act to incentivize and support the development and utilization of renewable energy, in order to substitute highly polluting energy sources like coal.

Implementation of emission reduction pathways. 1) Power Structure Adjustment: With the enactment of the "Technical Instructions on Air Quality Control" in 1974, Germany imposed stringent environmental requirements on newly built thermal power plants. This led to a sharp decline in the growth of coal-fired power units, and a significant increase in nuclear power generation. 2) Fuel Usage Strategy: The "Technical Instructions on Air Quality Control" mandated that new small-scale coal-fired and oil-fired installations use low-sulfur fuels, while larger facilities were required to install flue gas desulfurization (FGD) systems. As a result, most new industrial projects adopted low-sulfur fuels across various sectors, contributing to a substantial reduction in SO_2 emissions. 3) Flue Gas Desulfurization Measures: The Large Combustion Plant Ordinance (GFAVo) enacted in 1983 specifically targeted coal-fired power plants. Under this regulation, a vast majority of such plants installed FGD systems within 5 years. The use of low-sulfur fuels alone was insufficient to meet the legal requirements, prompting rapid advancement and deployment of FGD technology. 4) Methane Capture and Utilization: The Ruhr Industrial Zone pioneered innovative technology for “blending and upgrading high- and low-concentration gas,” which mixes gas sources to raise the utilization rate of low-concentration methane (15%–30%) to over 90%. This was complemented by the construction of 17 gas-fired power plants with a total capacity of 185 MW, generating 1 billion kWh annually. The captured gas was integrated into municipal heating networks, supplying communities with energy and achieving a methane capture rate of 99%.

By 1989, Germany’s SO_2 emissions had fallen to 960,000 tons, only 25.6% of the 1970 level, marking a 74.4% reduction and a 75.1% drop from the peak in 1973, with emissions stabilizing thereafter. The methane capture rate of 99% achieved through Ruhr Industrial Zone’s “blending and upgrading high- and low-concentration gas” grading technology ranks among the highest in the EU.

Collaborative Innovation in Biodiversity Conservation and Renewable Energy Development in the Wadden Sea

The Wadden Sea is the world’s first intertidal World Natural Heritage site, featuring the largest and most intact system of intertidal sandbars and mudflats globally. It is also one of the last remaining large-scale, fully functional intertidal ecosystems. As one of the leading countries in offshore wind power development, Germany has implemented comprehensive legal regulations and systematic project approval processes to ensure the protection of the Wadden Sea.

Robust legal and regulatory framework. The conservation and management of the Wadden Sea in Germany must comply with laws and regulations at the international, EU, and national levels. These regulations can be broadly categorized into procedural, source-oriented, and protection-object-oriented laws. Procedural regulations include various environmental assessment guidelines; source-oriented laws refer to regulations such as the Water Act, Maritime Act, and the International Convention for the Prevention of Pollution from Ships (MARPOL), which control pollution at its source to protect the ecological environment; and protection-object-oriented laws provide special legal protections for species such as migratory birds and seals. Additionally, German legislation also includes highly targeted standards with clear constraints and strong enforceability.

Systematically comprehensive approval process. Strategic environmental assessments are integrated throughout the planning process of offshore wind projects to ensure biodiversity protection. Offshore wind projects in Germany's Exclusive Economic Zone (EEZ) follow a multi-stage planning and approval procedure, with each stage requiring strategic environmental assessments. Project-specific environmental assessments are also mandatory. Each strategic environmental assessment requires thorough investigation and data sharing on environmental and biodiversity impacts (BSH, 2021b). The permitting and environmental assessment processes for offshore wind projects in Germany mandate full consideration of input from social organizations, expert reviews, and multi-stakeholder participation.

2. Main Trends of Energy Transition and Environmental Improvement in China

2.1 Continuous Improvement of Energy Consumption Structure

Driven by the two objectives of the "Dual Carbon Goals" and high-quality economic development, China's energy consumption structure continues to optimize, with the pace of low-carbon transformation significantly accelerating. From a long-term trend perspective, since the 18th National Congress of the Communist Party of China, the proportion of coal consumption has decreased from 68.5% to 53.2%, with a cumulative decline of 15.3 percentage points. Although coal consumption remains the dominant source, its share continues to decrease while shifting toward cleaner and more efficient utilization. The plateau phase of oil consumption has become apparent, while natural gas consumption shows a steady growth trend. The modernization of the industrial system, rising living standards, as well as factors such as electrification, computing power, and new energy vehicles, have driven the growth in electricity consumption across the whole society. The proportion of electricity in total energy consumption has further increased, with electricity consumption growth consistently outpacing economic growth. The share of non-fossil energy consumption has risen from 9.7% to 19.7%, achieving an increase of 10 percentage points. China's energy consumption is characterized by a stabilized total volume and continuous structure optimization(Fig 1).

The development of China's energy production structure is also in line with the needs of economic and social development, as well as energy transition. Between 2012 and 2024, the proportion of raw coal production in total energy production decreased from 76% to 69%. Since the "14th Five-Year Plan," the focus of coal production has accelerated its shift to central and western regions, with the steady advancement of five major coal supply and guarantee bases in Shanxi, Western Inner Mongolia, Eastern Inner Mongolia, Northern Shaanxi, and Xinjiang. The coal industry has accelerated its intelligent transformation and is significantly improving production efficiency and cleanliness. Limited by domestic resource endowments, oil production growth has been relatively slow, maintaining a stable share in total primary energy production. Natural gas production has maintained growth for consecutive years, gradually increasing its proportion in the primary energy production structure. Clean energy production, represented by hydropower, nuclear power, wind power, and solar power, has achieved a rapid leap forward. The proportion of non-fossil energy production has increased from 11% to 19%, realizing both energy security advancement and green development (Fig 2). The share of clean energy sources[4] such as natural gas, hydropower, nuclear power, wind power, and solar power has steadily increased, becoming a crucial supporting force in promoting energy structure adjustment, ensuring energy security, and fostering green development.

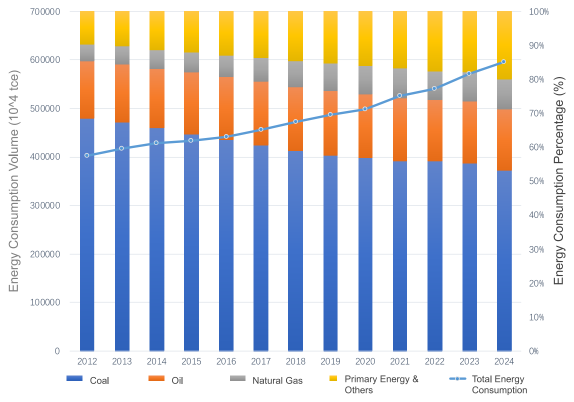

Fig 1. China Energy Consumption Structure 2012-2024

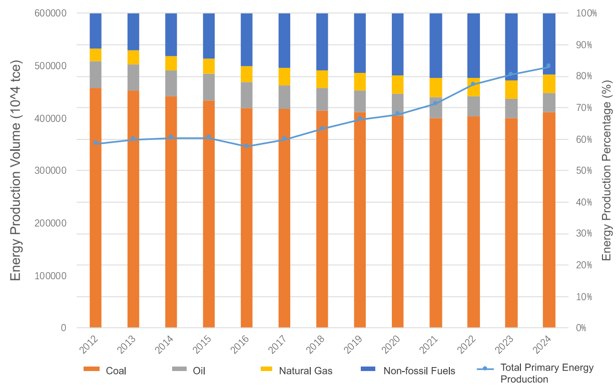

Fig 2. China Energy Production Structure 2012-2024

2.2 Robust Development of Renewable Energy

Driven by a combination of policy support, technological breakthroughs, and market demand, China's renewable energy sector is demonstrating unprecedented robust growth, becoming a core force in revolutionizing both energy production and consumption.

In terms of installed capacity, China has ranked first globally in renewable energy installations for consecutive years and continues to lead in growth rate. By the end of July 2025, the country's total installed power generation capacity reached 3.67 billion kilowatts, with renewable energy accounting for 2.126 billion kilowatts, representing 57.9% of the national total. Solar power capacity reached 1.11 billion kilowatts, with a year-on-year increase of 50.8%, and an average annual growth rate of over 40% during the "14th Five-Year Plan" period. Wind power capacity

[4] According to the definition of clean energy provided by the National Bureau of Statistics: Clean energy refers to energy sources that have minimal impact on the human environment during consumption, such as natural gas, hydropower, nuclear power, wind power, solar power, geothermal energy, ocean energy, biomass energy, and the electricity or thermal energy generated from these sources.

totalled 570 million kilowatts, up 22.1% year-on-year, maintaining an average annual growth rate of 16.6% in the same period. Hydropower, as a traditional renewable source, remains a critical baseload in the clean energy system, with a capacity stabilizing at 440 million kilowatts thanks to optimized distribution and the construction of new power stations. Other installed renewable sources, such as biomass and geothermal power, have also experienced steady growth, forming a diversified and collaborative development landscape.

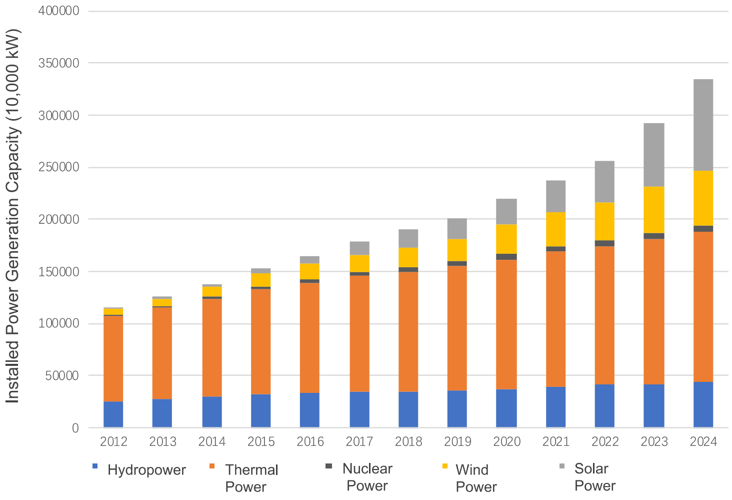

Fig 3. China Installed Power Generation Capacity by Type 2012-2024

In terms of electricity generation, renewable energy is playing an increasingly significant role in the power system and has become a crucial pillar in ensuring electricity supply. In 2024, China's renewable energy generation reached 3.26 trillion kilowatt-hours, accounting for 32.3% of the country's total electricity output. This has seen an increase of 13 percentage points compared to 19.3% in 2012. This includes the following: hydropower generated 1.43 trillion kWh, representing 14.1% of the total; wind power output reached 997 billion kWh, accounting for 9.9%. Due to factors like large-scale development of wind farms, widespread adoption of high-capacity turbines, and the application of smart operation and maintenance technologies, the average utilization hours of wind power steadily increased to 2,127 hours; solar power generation totalled 839 billion kWh, making up 8.3%. Driven by technological upgrades and shifts in supply-demand dynamics, prices of major photovoltaic equipment and materials in China decreased significantly. In 2024, the unit cost of centralized PV projects fell to approximately 3,141 yuan/kW, down 17.62% year-on-year, while distributed PV project costs dropped to around 3,200 yuan/kW, a decrease of 9.94%. Biomass power generation reached 208.3 billion kWh, providing a stable supply in areas such as waste-to-energy and agricultural and forestry waste power generation, thereby supporting resource recycling under the "Dual Carbon Goals."

From an application expansion perspective, renewables are penetrating beyond the power industry into various scenarios, forming an integrated “source-grid-load-storage” development landscape. In the domain of distributed applications, distributed PV now widely covers industrial plants, public buildings and residential rooftops, with new installations exceeding 110 GW in 2024, accounting for over 42% of total new PV capacity. The “self-consumption with grid feed-in” model supports cost reduction for companies and rural energy transition. Applications in transport, such as PV-integrated roads, shore power, and electric ships, are accelerating. In the domain of rural revitalization, integrated projects like “PV + agriculture,” “PV + livestock,” and “PV + desert control” are advancing, achieving both ecological and economic benefits.

In manufacturing, China dominates over 80% of global production capacity for solar PV modules, cells, wafers, and polysilicon, and accounts for more than 60% of wind turbine manufacturing. Breakthroughs in battery technology include a 70% share of global lithium battery production. By 2024, the installed capacity of new energy storage reached 73.76 GW, with total power and energy multiplying by 2.4 and 2.5 times, respectively, year-on-year. Large-scale projects (⩾100 MW) represent 62.3% of capacity, while medium (10-100 MW) and small (<10 MW) projects account for 32.8% and 4.9%, respectively. The average storage duration is 2.1 hours, with 15.4% of projects exceeding 4 hours and 71.2% between 2 and 4 hours. New storage systems increasingly support grid regulation and regional power supply.

Driven by hydrogen policy, its production and consumption continue growing. In 2024, national hydrogen production capacity exceeded 50 million tons/year, with a year-on-year growth of 1.6%, and its output exceeded 36.5 million tons, with 3.5% year-on-year growth. As for hydrogen production structure, fossil-based hydrogen that uses coal or gas, etc., dominates over 75% of total volume, while electrolytic hydrogen (including renewable and grid-powered) accounts for around 1%. By the end of 2024, over 600 renewable hydrogen projects have been planned, with 90 plus completed and 80 plus under construction. Completed renewable hydrogen capacity has reached around 125,000 tons/year. Demonstration of hydrogen projects is intensifying and forming a diversified landscape. China has formed an integrated clean energy supply chain covering PV, wind, advanced storage, and green hydrogen, and has strong competitiveness in expanding the green low-carbon industry.

2.3 Significant Outcomes of Energy Transition

Since the implementation of the “Dual Carbon” strategy, China's energy transition has increasingly yielded results. In 2024, the share of clean energy consumption (which comprises natural gas, hydropower, nuclear power, wind power, solar power) accounts for 28.6% of total energy consumption, an increase of 2.2 percentage points(in which the consumption share was 19.8% excluding natural gas, an increase of 1.9 percentage points), reflecting a clear trend toward a “greener energy” consumption and forming a positive pattern of coordinated transformation on both the production and consumption ends.

Ultra-low emission and flexibility upgrades of coal-fired power units have advanced steadily, leading to a significant reduction in pollutant emissions and improvement in operational flexibility. China has largely completed ultra-low emission transformation for conventional pollutants across its coal power sector, with total annual emissions now approximately 95% lower than the peak levels in 2011. During the “14th Five-Year Plan” period, more than 700 GW of coal power capacity underwent energy-saving, carbon-reduction, flexibility, and heating upgrades. The average coal consumption for power supply was 302.4 grams of standard coal per kWh, down by more than 7% from 2012. Carbon dioxide emissions per unit of thermal power generation fell to 823 g/kWh, 21.5% down from 2005, while CO_2 emissions per unit of electricity generation dropped to 528 g/kWh, 38.5% down from 2005. Meanwhile, key technologies, such as large-scale waste incineration and flue gas treatment, have reached internationally advanced levels, fully demonstrating China's continuous progress and competitive strength in clean technology.

2.4 Robust Development of Renewable Energy

The campaign to prevent and control air pollution has been intensified, leading to **steady improvements in air quality**. Between 2013 and 2023, China doubled its GDP while reducing the average concentrations of fine particulate matter (PM2.5) and sulfur dioxide by 54% and 81%, respectively. The number of heavily polluted days decreased by 83%, representing an unprecedented pace of improvement. In 2024, the average PM2.5 concentration in 339 cities at the prefecture level and above was 29.3 $\mu g/m^3$, with the days with good air quality reaching 87.2% and heavily polluted days accounting for only 0.9%. Compared to 2015, the proportion of cities meeting air quality standards surged from 29% to 66%, while the share of severely and highly polluted days dropped from 2.6% to 0.9%, a reduction of 67%. The annual average PM2.5 concentration fell from 46 $\mu g/m^3$ to 29.3 $\mu g/m^3$, a decline of 36.3%, bringing it below the World Health Organization’s first interim target of 35 $\mu g/m^3$. China is now the fastest-improving country in the world in terms of air quality, with its achievements in air pollution control praised by the United Nations Environment Programme as the "Beijing Miracle."

Efforts against climate change are vigorously advancing. The top-level design for “Dual Carbon” has been continuously refined. China has established the world’s most systematic and comprehensive top-level framework and policy system for carbon reduction, integrating the carbon peaking and neutrality goals into the broader context of ecological civilization and socioeconomic development. The world's largest carbon emissions trading market has been established and is operating smoothly. The national strategy on climate change adaptation has been implemented, and South-South cooperation on climate response has been consistently deepened, with a cumulative funding between 2011 to 2022 exceeding 1.2 billion RMB. Over the past decade, China's carbon dioxide intensity has decreased by approximately 35%, exceeding the targets committed to the international community.

Surface water quality continues to improve. The proportion of surface water sections with excellent water quality nationwide increased by 23.8 percentage points, approaching the standards of developed countries. The main stream of the Yangtze River achieved Grade II water quality for three consecutive years, and the main stream of the Yellow River reached Grade II water quality for the first time. The proportion of coastal waters with good quality increased by 17.6 percentage points. Black and odorous waterbodies in built-up areas of cities at the prefecture level and above have been essentially eliminated. The goal of "zero imports" of solid waste has been successfully achieved. Soil and groundwater environmental risks have been effectively controlled.

Ecosystem stability continues to strengthen. Integrated protection and systematic management of mountains, waters, forests, farmlands, lakes, grasslands, and deserts have been implemented, alongside improved ecological supervision mechanisms. The "Green Shield" initiative has been conducted for five consecutive years to enhance oversight of protected natural areas. Protected natural areas now cover 18% of China's land territory, and the terrestrial ecological conservation red-line area accounts for over 30% of the total land area. The wild populations of more than 300 rare and endangered wildlife species have remained stable or increased.

Eco-environmental governance capacity has been significantly enhanced. The Ministry of Ecology and Environment was established, integrating and forming comprehensive ecological and environmental enforcement teams. A vertical management system for monitoring, supervision, and enforcement has been implemented below the provincial level. Ecological and environmental supervision agencies have been set up for river basins and sea areas. National and provincial environmental quality monitoring responsibilities have been fully recentralized, and an ecological and environmental monitoring network has been largely completed. Two rounds of central ecological and environmental inspections were successfully concluded. More than 40 reform documents were drafted or issued, and systems, including pollutant discharge permits, ecological compensation, and environmental damage compensation, have been established and thoroughly implemented. Over 30 laws and administrative regulations related to ecological and environmental protection were enacted or revised, and specialized inner-Party regulations such as the “Regulations on Central Eco-Environmental Inspection” were implemented. The increasingly comprehensive institutional system provides reliable guarantees for ecological civilization construction.

3. Analysis on Energy and Climate Synergy in China

3.1 Synergy in Top-Level Strategy

China continues to promote institutional innovation, driving energy policy to shift from "total quantity expansion" to "structural optimization," and the environmental policy from "end-of-pipe control" to "source control." The coordination of energy and environmental policies is evolving toward "diversified overall planning," accelerating the construction of a new energy system with non-fossil energy as the main body, and the energy structure is constantly optimized.

In 2012, the 18th National Congress of the Communist Party of China incorporated ecological civilization construction into the national "five-in-one" overall layout, marking the first comprehensive integration of the green development concept into the national governance system. In the same year, the State Council released the "Plan for Energy Conservation and Emission Reduction during the 12th Five-Year Plan Period," determining the policy path for energy-saving targets and the development of clean energy. In June 2014, President Xi Jinping creatively put forward the new energy security strategy of "four revolutions and one cooperation," that is, promoting the energy consumption revolution, energy supply revolution, energy technology revolution, energy system revolution, and strengthening all-around international cooperation. This provides the fundamental compliance for promoting the high-quality development of energy in the new era. In the same year, the General Office of the State Council issued the "Energy Development Strategy Action Plan (2014-2020)," clearly stating that "green and low-carbon" is the core task of energy development, and establishing the expected goal of increasing the proportion of non-fossil energy consumption to about 15% and reducing the proportion of coal to less than 62% by 2020.

On September 22, 2020, Chinese President Xi Jinping solemnly declared at the general debate of the 75th session of the United Nations General Assembly that "China aims to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060." Since then, **China's ecological civilization construction has entered a strategic direction with carbon reduction as the focus**. During the "14th Five-Year Plan" period, there has been an endless stream of top-level design documents guiding the coordinated high-quality development of energy and the environment with systematic thinking. In 2021, the "Opinions of the Central Committee of the Communist Party of China and the State Council on Comprehensively and Accurately Implementing the New

Development Concept to Do a Good Job in Carbon Peaking and Carbon Neutrality" pointed out that to achieve the goals of carbon peaking and carbon neutrality, it is necessary to adhere to the principles of "national overall planning, giving priority to conservation, dual-wheel drive, unimpeded internal and external circulation, and risk prevention," and actively and steadily promote the "Dual Carbon" work to ensure a smooth and orderly transformation and controllable process risks, and significant progress has been made in the comprehensive green transformation of China's economic and social development. Top-level design documents such as the “Action Plan for Carbon Peaking before 2030” and supporting documents covering key areas such as energy, industry, transportation, and construction, as well as the carbon peaking action plans of provincial governments, have thus constructed a "1+N" policy system for promoting the "Dual Carbon" work. In 2022, the report of the 20th National Congress of the Communist Party of China put forward the requirements of jointly promoting carbon reduction, pollution reduction, green expansion, and growth, and the requirements of accelerating the construction of a new energy system. In 2024, the General Office of the State Council issued the "Work Plan for Accelerating the Establishment of a Dual Control System for Carbon Emissions," so that the top-level design principles of the "dual control of energy consumption" to the "dual control of carbon emissions" have been implemented at the institutional and planning levels. In summary, it can be seen that accelerating the integration of China's high-quality energy development and ecological environmental protection is the key. It is necessary to comprehensively plan energy development and ecological environmental protection in the process of building a clean, low-carbon, safe and efficient energy system, and jointly promote the high-quality development of energy and the high-level protection of the ecological environment, providing a solid guarantee for economic and social development and the building of a beautiful China.

3.2 Characteristics of Interdepartmental Synergy

A collaborative mechanism involving multiple departments to advance the strategic task of energy transition is taking shape. China’s energy transition policy formulation has initially established a coordination framework across various agencies, including the National Development and Reform Commission, National Energy Administration, Ministry of Ecology and Environment, Ministry of Industry and Information Technology, Ministry of Housing and Urban-Rural Development, Ministry of Agriculture and Rural Affairs, Ministry of Science and Technology, Ministry of Transport, and Ministry of Natural Resources. This mechanism features broad coverage, multiple tiers, and cross-sectoral engagement, effectively enhancing policy coherence and synergy. Gradually, an energy transition coordination model characterized by “multi-department collaboration and multi-dimensional policy integration” has been formed (Fig 4).

The coordination of policies across departments has promoted collaborative progress in energy transition and ecological environmental protection. First, energy policies increasingly reflect multi-objective coordination that emphasizes cleanliness, low-carbon, safety, and efficiency, with greater integration of ecological and environmental considerations. China has placed high importance on building a robust energy policy system, continuously strengthening guidance in key areas such as structural optimization of energy supply, demand-side management, environmental protection in the energy sector, and institutional reforms. Nearly a thousand policy documents have been introduced, encompassing laws and regulations, medium- to long-term development plans, specialized policies, market mechanism design, and standards. This has gradually established a clean, low-carbon, safe, and efficient-oriented energy policy system that ensures horizontal coordination and vertical integration. As ecological civilization construction advances, terms such as "green," "ecological," and "high-quality" appear more frequently in energy policy papers, reflecting that green development is increasingly becoming a core value in energy policy. The number of policies integrating energy and environmental goals has risen year by year. As of May 2025, approximately 44% of energy transition-related policies include content that coordinates energy and environmental objectives. A growing number of energy transition policies incorporate ecological and environmental protection as well as efficient resource use into their design, strengthening co-governance of ecosystems, resource and environmental carrying capacity, and pollution control while advancing energy structure optimization and efficiency improvements (Fig 5). For example, the "14th Five-Year Plan for Renewable Energy Development" and the "14th Five-Year Plan for a Modern Energy System" require that renewable energy expansion be aligned with land-use and ecological conservation policies, promoting coordinated siting of wind and solar projects with ecological red lines and forest protection. Policy papers on coal industry restructuring, such as the "Guidelines on Strengthening the Clean and Efficient Use of Coal," emphasize simultaneous advancement of clean substitution and ecological restoration, facilitating land reclamation and green transition in mining areas. **Second, ecological and environmental policies increasingly reflect the trend toward high-quality energy development, positioning low-carbon energy as a key element in building ecological civilization institutions.** These policies require that high-quality energy development significantly reduce environmental pressure and promote harmonious ecological development, thereby supporting the construction of a beautiful China with a sustainable energy foundation. For instance, the "Three-Year Action Plan for Winning the Blue Sky Defense Battle" called for integrated energy structure adjustment and air pollution prevention and control, with comprehensive source control and industrial transformation. The "Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste during the 14th Five-Year Plan" and the "Master Plan on Major Projects for the Conservation and Restoration of National Key Ecosystems (2021-2035)" explore standardized recycling and high-value regenerative pathways for solid waste from emerging industries, such as decommissioned PV modules and wind turbine blades, guiding the integration of environmental protection and new energy industry development.

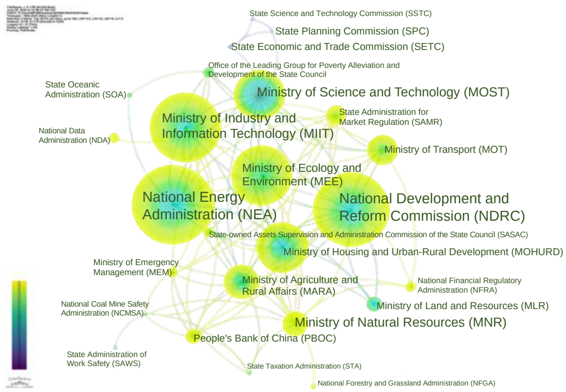

Fig 4. Collaborative Network of Energy Transition Policy-Making Bodies in China

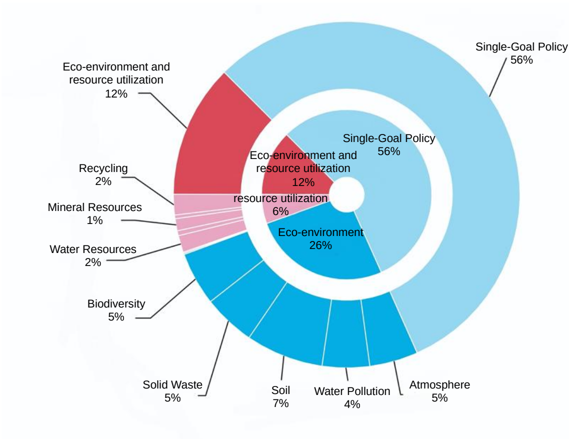

Fig 5. Collaborative Areas of Energy Transition and Environment in China

3.3 Practices of Interdepartmental Synergy

In recent years, leveraging inter-ministerial coordination mechanisms, the state has guided local governments to explore distinctive collaborative models by leveraging pilot demonstrations, institutional guidance, and financial support. Currently, practical experiences have been accumulated across multiple regions in effectively linking green energy development, clean and efficient utilization, and ecological environmental governance. These efforts provide valuable references for achieving synergistic transformation of energy structure optimization and ecological environmental quality improvement on a broader scale.

Significant achievements have been made in air pollution prevention and control in energy-related sectors. Since 2013, China has implemented the "Air Pollution Prevention and Control Action Plan," the "Three-Year Action Plan for Winning the Blue Sky Defense Battle," and the "Action Plan for Continuous Improvement of Air Quality." From 2013 to 2022, coal consumption in key regions decreased by approximately 200 million tons. The structure of coal usage has shifted from primarily coal transport to a balanced approach of both coal transport and power transmission. Ultra-low emission retrofits were completed for 1.06 billion kilowatts of coal-fired power units, accounting for 96% of the country's total coal power capacity, establishing the world's largest clean coal power generation base. The number of coal-fired boilers nationwide dropped from 520,000 in 2013 to less than 100,000 in 2022, reducing coal consumption by over 400 million tons. Efforts to replace scattered coal consumption in northern China have resulted in more than 39 million rural households transitioning from coal to electricity or gas by the end of 2023.

Pilot initiatives for collaborative innovation in pollution reduction and carbon mitigation. Synergizing pollution and carbon reduction is a critical measure for advancing carbon peak and carbon neutrality goals and represents a concentrated embodiment of energy-environment coordination. The Ministry of Ecology and Environment, together with the National Development and Reform Commission, the Ministry of Industry and Information Technology, and the National Energy Administration, issued the "Implementation Plan for Pollution Reduction and Carbon Mitigation" to promote innovation in this area. A list of pilot zones, including 21 cities and 43 industrial parks, was released, encouraging regions to explore context-specific pathways and innovate management systems based on local characteristics. With a focus on enhancing synergies between pollution and carbon reduction, current practices have established a framework characterized by interdepartmental collaboration, coordinated governance, pilot exploration, and collaborative innovation.

Efficacy of Energy-Environment Synergy Pathways Becomes Evident as Pollution-Carbon Reduction Synergy Advances through Exploration

Ordos is the only city in the Inner Mongolia Autonomous Region selected for the innovative pilot on pollution reduction and carbon mitigation. It has carved out a distinctive path of energy-environment synergy amid its transformation as a national energy base. Its approach "riding the wind, chasing the sunlight, lifting with zero carbon, and arming up hydrogen" offers practical pilot experiences for green transition in resource-based regions.

The city is comprehensively advancing the integrated development of "new energy + desert control," implementing the Kubuqi Desert "PV Great Wall" project, and accelerating the construction of large-scale wind and solar bases. The 2 GW pilot project of the Kubuqi Desert Ordos North-Central New Energy Base, among China's first batch of 10 GW-level renewable bases, has been fully grid-connected.

It is also implementing "coal chemical + green hydrogen/green oxygen" coupling projects, demonstrating integrated "renewable power generation – electrolytic hydrogen production – carbon capture" pathways to produce methanol and aviation fuel. The world's largest green hydrogen-coal-to-olefins industrial base has been established here.

The promotion of "rail entering mining and industrial zones" has shifted bulk cargo such as coal and coke from road to rail and containerized transport. The demonstration and application of "digital dry port" new energy heavy-duty trucks have positioned Ordos as a national demonstration base for hydrogen-dominated new energy heavy truck adoption.

Since the launch of the 14th Five-Year Plan, Ordos has maintained excellent air quality rates above 90%, while reducing energy consumption per unit of GDP by 25.8% and carbon intensity by 13.6%. In 2024, the city's GDP reached 636.3 billion yuan, marking its third trillion-yuan leap since the start of the 14th Five-Year Plan period. This signifies a historic shift toward collaborative development between pollution-carbon reduction and economic growth. The degree of pollution-carbon synergy increased by over 29% year-on-year, reaching 86.5%[5].

Pilot Projects for Clean Heating in Northern China During Winter. The winter clean heating program in northern China is a vital livelihood project that coordinates the optimization of the energy supply structure and the enhancement of regional ecological and environmental carrying capacity. It also serves as a key practice in the coordinated governance of energy and the environment. The Ministry of Finance, in conjunction with the Ministry of Housing and Urban-Rural Development, the former Ministry of Environmental Protection, and the National Energy Administration, issued the "Notice on Launching Pilot Work for Winter Clean Heating in Northern China Supported by Central Financial Funds." This notice promotes renovation measures focused on replacing scattered coal with clean energy, and several batches of pilot city lists have been determined successively. By the end of 2023, the area covered by clean heating in northern China had increased by 1.07 billion square metres compared with the end of 2016, with the clean heating rate rising by 46 percentage points. In the Beijing-Tianjin-Hebei region and its surrounding areas, as well as the Fenwei Plain, the PM2.5 concentration had decreased by 41.1% and 30.6% respectively, compared with 2016, while the number of heavily polluted days had dropped by 61.2% and 41.8% respectively. The replacement of scattered coal with clean heating contributed over 30% to the improvement of regional ambient air quality, significantly enhancing people's quality of life.

Collaborative Progress in Energy Structure Optimization and Environmental Quality Improvement: Significant Results from Clean Heating Pilot

Shijiazhuang, a key city for clean heating in the Beijing-Tianjin-Hebei region and surrounding areas, was among the first batch of cities included in the central government's financial support program for clean winter heating pilots in northern China. Leveraging its regional energy strategy, the city has progressively established a multi-energy complementary clean heating

[5] Data Source: Press Briefing on the Collaborative Innovation Pilot for Pollution Reduction and Carbon Sequestration in Ordos, August 19, 2025

system incorporating approaches like “solar+,” “coal-to-electricity,” “coal-to-gas,” and “geothermal+,” providing a demonstration model for achieving clean heating transition in northern China.

The city comprehensively promoted the application of renewable energy in heating, developing regional solar-assisted heat pump central heating projects and implementing demonstration zones for the cascaded development and use of geothermal resources. It accelerated the large-scale integration of industrial waste heat into urban heating systems. By coordinating natural gas central heating, ultra-low-emission retrofits in urban centralized heating systems, and the use of clean electricity and waste heat, Shijiazhuang prioritized ultra-low-emission retrofits for coal-fired heating units and extended central heating networks, enhancing both the cleanliness and reliability of regional heating.

Through the “Rural Distributed Household Retrofit and Energy Efficiency Improvement” initiative, the city promoted tailored technical pathways such as “coal-to-gas,” “coal-to-electricity,” and “biomass/distributed PV + electric heating,” supported by operational subsidies and after-sales service guarantees. These measures balanced affordability for residents with long-term operational costs, effectively reducing the risk of coal recurrence and improving energy efficiency. The effort to manage scattered coal use in agricultural production has been fully completed.

To strengthen the capacity for clean energy supply, the city developed and improved infrastructure, including natural gas, heating, and power transmission and distribution networks, providing solid support for clean heating. It enhanced the backbone natural gas transmission lines and urban distribution networks, expanding the coverage of pipeline gas and LNG to towns and villages. Power grid upgrades in both urban and rural areas were accelerated to improve power supply reliability. In line with urban heat source optimization, the city explored expanding the heating radius of thermal networks to maximize the capacity of heat sources and extend centralized heating to surrounding towns and villages. Furthermore, the production and distribution system for clean briquettes was refined, with widespread adoption among users for whom clean energy alternatives are not feasible.

In 2022, Shijiazhuang’s average PM2.5 concentration had decreased by 53.5% compared to 2016, and its comprehensive air quality index ranking improved from the bottom position it had held for years. Simultaneously, a new heating structure has taken shape, primarily based on combined heat and power and industrial waste heat, supplemented by clean energy sources such as natural gas, electricity, sewage source heat pumps, and air source heat pumps—

achieving 100% clean energy heating. While ensuring residential heating needs, the city has effectively advanced the synergy between energy supply structure optimization and ecological environment improvement. Its annual performance evaluation scores for clean heating have consistently ranked among the highest nationally.

Despite the remarkable achievements in China's energy and environmental synergy, with policy mechanisms fostering positive trends and laying a solid foundation for rational energy use and ecological protection, **the ongoing energy transition continues to present complex challenges**. Legacy issues from long-term energy development remain partially unresolved, including systemic ecological debts such as post-mining land rehabilitation, groundwater remediation, and industrial renewal, as well as structural contradictions resulting from delayed environmental governance during past rapid expansion. At the same time, the new energy revolution introduces additional complexities: evaluation and management systems for the life-cycle environmental impacts of large-scale wind and solar facilities are still incomplete, and conflicts between intensive renewable energy development and the conservation of ecologically sensitive areas are becoming increasingly apparent. These challenges involve both the environmental and social costs of phasing out conventional energy and the ecological constraints and institutional safeguards required for sustainable renewable energy expansion. To achieve the deep integration of the "Beautiful China" vision and the "Dual Carbon Goals," it is essential to not only consolidate existing synergy mechanisms and maintain confidence, but also to proactively identify and address both historical governance gaps and emerging risks in the energy transition with a forward-looking and precautionary approach. Therefore, Chapters III and IV will focus on the collaborative issues and challenges, actual and potential, arising from the phase-out of conventional energy capacity and the rapid expansion of new energy development.

Chapter III. Problems and Challenges of Energy-Environment Synergy in Traditional Energy Transition

1. Problems and Challenges Arising from the Phasing-out of Coal Mines

1.1 Basic Situation: The increasing phase-out of coal is an inevitable trend

With the progress toward carbon neutrality, the increasing phase-out of coal mines due to obsolescence and structural adjustments has become inevitable. In 2014, the number of coal mines nationwide stood at 11,000. By 2016, due to declining raw coal production and mine restructuring, the number of mine closures increased significantly, reducing the total to fewer than 8,000. By 2020, the number had further decreased to 4,700, with the output share of small mines (under 300,000 tons annual production) falling below 10%. Although large-scale mines (1.2 million tons and above) may cause stronger regional ecological disturbances due to intensive extraction, their standardized and scaled operations significantly reduce the difficulty of pollution supervision. The output share of large mines rose to around 80%. By 2023, the number of coal mines had declined to 4,300. According to statistics from the National Energy Administration, by the end of 2024, more than 6,500 coal mines had been closed nationwide, eliminating approximately 1.2 billion tons of backward coal production capacity.

1.2 Current Policy

Since 2009, China has progressively established a comprehensive legal, regulatory, and policy framework for mine ecological governance, driving its evolution from the establishment of responsibility mechanisms and legal improvements to market-oriented innovations and technical standardization.

For coal mines still in operation but slated for future closure, relevant laws and regulations emphasize a responsibility mechanism of **"prevention first, process control, and post-closure restoration."** These rules stress the primary responsibility of enterprises, requiring them to set aside funds in advance, formulate restoration plans, and pass closure acceptance inspections to achieve integrated "mining-restoration" practices. According to regulations such as the "Guiding Opinions on Coal Mine Backfill Mining" (NEA Coal [2013] No. 19), "Regulations on Mine Geological Environmental Protection" (2019 Revision) (MLR Order No. 5), "Opinions on Comprehensively Implementing Competitive Granting of Mining Rights" (NRR [2019] No. 7), "Mineral Resources Law of the People's Republic of China" (2019 Amendment), "Notice on Further Strengthening Environmental Impact Assessment Management for Coal Resource Development" (EIA [2020] No. 63), and technical standards like "Technical Code for Coal Mine

Land Reclamation and Ecological Restoration" (GB/T 43934-2024) and "Technical Specification for Monitoring and Evaluation of Mine Land Reclamation and Ecological Restoration" (GB/T 43935-2024), operating coal enterprises are required to establish an environmental management and restoration fund during the mining phase, prepare ecological restoration plans, complete ecological restoration before mine closure, and pass official acceptance inspections by relevant authorities before formal exit. The principle of **"whoever develops, restores"** is strictly enforced. Mining rights-granting contracts must specify ecological restoration requirements, with strengthened mid-process and post-event supervision to achieve closed-loop responsibility throughout the entire mining life cycle.

For historically abandoned coal mines, where operations have ceased, and responsible entities are often absent or unidentifiable, relevant laws and regulations emphasize a restoration mechanism based on **"government leadership, societal participation, and market-oriented operation."** This approach clarifies methods for investigation and assessment, funding mobilization, and responsibility determination, leveraging policy incentives, financial support, and technical standards to address the issues of "no one in charge, no funds for restoration."

According to provisions including the "Regulations on Land Reclamation" (State Council Decree No. 592), "Opinions on Exploring Market-Oriented Approaches to Promote Mine Ecological Restoration" (NRR [2019] No. 6), "State Council General Office Opinions on Encouraging and Supporting Social Capital Participation in Ecological Conservation and Restoration" (G.B.F. [2021] No. 40), "Technical Plan for Investigation and Assessment of Ecological Damage and Pollution in Historical Mines in the Yellow River Basin" (MEE Office Science Fund Function [2022] No. 185), "Technical Specification for Verification of Historical Mines" (TD/T 1071-2022), and the "Master Plan for the Protection and Restoration of Major National Ecosystems (2021–2035)," the remediation of historically abandoned coal mines is advanced through diversified investment combining "fiscal funds + social capital," and a pathway centred on assessment → classification → market-driven incentives. The principle of "**whoever restores, benefits"** is promoted, encouraging social capital to participate and obtain rights or benefits such as land use or resource development. By adopting a strategy of verification and assessment first, followed by differentiated restoration, the longstanding challenges of "unmanaged sites and funding shortages" are systematically addressed.

1.3 Existing Problems

(1) Ecological and environmental issues arising from coal mine closures

Acidic wastewater and heavy metal pollution from abandoned mines. Water accumulated in abandoned coal mines is often acidic (with pH as low as 2.92) and contains high concentrations of heavy metals (such as cadmium, arsenic, zinc, etc.). If discharged directly without treatment, such wastewater can contaminate surrounding soil and water sources through surface runoff and seepage, threatening biodiversity and human health. Although some abandoned mines have implemented basic mitigation measures (e.g., injecting lime slurry to neutralize acidic water), sediments remain deposited at the bottom, failing to resolve the pollution fundamentally.

Methane Emissions. Methane (CH_4) is a potent greenhouse gas with a global warming potential (GWP) over 80 times that of carbon dioxide over a 20-year period and about 25–30 times over a 100-year horizon. Abandoned coal mines contribute approximately 40% of global energy-related methane emissions. The International Energy Agency (IEA)'s 2023 Global Methane Tracker also noted that coal mines are among the fastest-growing sources of methane emissions in the fossil fuel sector. Due to longstanding technical and economic challenges, methane emissions from abandoned mines have been largely unregulated and remain unresolved. Although the 2024 revised "Emission Standard for Coalbed Methane (Coal Mine Gas)" lowered the prohibited methane concentration threshold from 30% to 8%, monitoring and utilizing low-concentration gas (such as ventilation air methane with concentrations below 1%) remain difficult.

As the world's largest coal producer and consumer, China also has a vast number of abandoned coal mines. Preliminary estimates indicate there are approximately 10,000 such mines, a significant proportion of which continue to emit methane. Annual emissions may reach several million or even tens of millions of tons of methane, equivalent to hundreds of millions of tons of carbon dioxide, posing a serious challenge to China's "Dual Carbon Goals."

(2) Technical and Policy Challenges

Technical Complexity and Lack of Standards. Treating mine water requires tailored technical approaches based on geological conditions, yet the absence of unified standards hinders widespread implementation. Methane reduction technologies, such as direct combustion of low-concentration gas for heating, face bottlenecks in explosion-proof equipment and precise monitoring. Current safety regulations lag behind technological innovation needs.

Unclear Ownership and Lack of Benefit-Sharing Mechanisms. Contradictions between mining rights and land ownership often lead to disputes over rehabilitated mine sites. After the closure of numerous small, scattered mines, there is a lack of integrated planning and funding for steps such as mine backfilling and methane extraction and utilization, resulting in direct methane leakage. Mining enterprises fail to fulfill restoration obligations, and local governments do not establish long-term supervision mechanisms, causing remediation efforts to stall. Some abandoned mines lack clear responsible entities, and even restored mine resources are reclaimed by the state and redistributed, preventing companies that bore restoration costs from benefiting from subsequent development (e.g., tourism, land reclamation), leading to government-enterprise conflicts. Although some local governments have proposed "preemptive remediation," requiring coal mines to complete village relocation and ecological restoration plans before operation, effective benefit coordination mechanisms are still lacking in implementation.

2. Environmental Issues Faced by Modern Coal Chemistry Development

China's energy resource endowment characteristics and the needs of its energy security strategy have spurred the development of the modern coal chemical industry in China. Compared with the traditional coal chemical industry, the modern coal chemical industry demonstrates significant technological advancement. Currently, China ranks among the world's most advanced in both output and technology of the modern coal chemical industry, making it an important supplement to the petrochemical and chemical industries. However, challenges such as high energy and resource consumption, substantial carbon emissions, and water resource constraints in the modern coal chemical industry are becoming increasingly prominent.

2.1 Basic Situation: The scale of the modern coal chemical industry has been increasing year by year

The modern coal chemical industry, centred on coal gasification technology, focuses on four major sectors: coal-to-olefins, coal-to-liquids, coal-to-natural gas, and coal-to-ethylene glycol. In 2017, the National Development and Reform Commission and the Ministry of Industry and Information Technology issued the “Modern Coal Chemical Industry Innovation and Development Layout Plan,” designating four modern coal chemical industry demonstration zones: Ordos in Inner Mongolia, Yulin in Shaanxi, Ningdong in Ningxia, and Zhundong in Xinjiang. Since then, the scale of the modern coal chemical industry has gradually expanded. According to the “2025 China Coal Industry Development Research,” the scale of the modern coal chemical industry remained stable with growth in 2024, with the total output of the four major products reaching approximately 31.73 million tons, a year-on-year increase of 8.3%. Data from the China Petroleum and Chemical Industry Federation show that in 2024, the coal conversion capacity of China's modern coal chemical industry for the four major sectors was 138 million tons of standard coal per year, with actual coal conversion amounting to about 120 million tons of standard coal, replacing approximately 38.1 million tons of oil and gas equivalent.

2.2 Current Policy

While actively promoting the development of its modern coal chemical industry, China also places strong emphasis on the collaborative advancement of energy and the environment. It requires that the industry, in the process of scaling up, must balance energy security, ecological and environmental protection, and water resource carrying capacity. The goal is to build a green and collaborative development system along with a safe and environmentally friendly production system, thereby driving the industry toward greener, low-carbon, and high-efficiency development.

In 2017, the National Development and Reform Commission and the Ministry of Industry and Information Technology issued the "Modern Coal Chemical Industry Innovation and Development Layout Plan," proposing that the industry's development requires scientific planning. This includes "selecting regions with relatively abundant coal and water resources and favourable environmental capacity to plan and build demonstration zones for the modern coal chemical industry." It also emphasizes comprehensive management to promote green development, such as "demonstrating the application of technologies like carbon dioxide emission reduction, shifting from end-of-pipe treatment to integrated management, and enhancing the industry's clean and low-carbon development level."

In 2023, the National Development and Reform Commission, together with the Ministry of Ecology and Environment and other departments, issued the "Notice on Promoting the Healthy Development of the Modern Coal Chemical Industry," guiding the industry in planning layout, technological innovation, low-carbon development, and safety and environmental protection. For example, in the planning process, attention must be paid to "requirements for territorial spatial planning and regional ecological environment zoning control, with strict prohibitions on new coal chemical production capacity in key air pollution control regions." In terms of technological innovation, it encourages "integrated and innovative development coupling modern coal chemicals with renewable energy, green hydrogen, and carbon capture, utilization, and storage (CCUS)." To advance the green and low-carbon development of the industry, it calls to "guide existing modern coal chemical enterprises to implement energy-saving, carbon-reducing, water-saving, and pollution-reducing upgrades, accelerate comprehensive volatile organic compounds treatment, stepwise recycling of high-salt wastewater, advanced resource-based treatment, and resource utilization of solid wastes such as ash and slag." Additionally, project siting must meet environmental requirements, such as environmental impact assessments and the "Three Simultaneities" system.

Furthermore, the "Opinions on Strengthening the Clean and Efficient Utilization of Coal", jointly issued by the NDRC and other departments in 2024, identifies the modern coal chemical industry as a “typical” technological pathway for the clean and efficient use of coal. It emphasizes the need to “promote the integrated development of modern coal chemicals with green electricity, green hydrogen, energy storage, and carbon capture, utilization, and storage, fostering the industry’s advancement toward high-end, diversified, and low-carbon development.”

Innovative Practices of Modern Coal Chemical Enterprises in Ordos

Ordos in Inner Mongolia is one of the four modern coal chemical industry demonstration zones approved in 2017 by the National Development and Reform Commission and the Ministry of Industry and Information Technology. In April 2025, the research team visited Ordos and conducted field studies at three modern coal chemical enterprises engaged in coal-to-liquids and coal-to-olefins production, gaining insights into their innovative applications in green and low-carbon technologies and comprehensive water resource utilization.

Advanced Environmental Facilities Enable Clean and Efficient Coal Utilization. At China’s largest coal-to-olefins facility and a national demonstration project for deep coal processing, the enterprises have constructed over 20 environmental protection units, including wastewater treatment, water reuse, high-salt water crystallization, and flue gas desulfurization and denitrification systems. These achieve "zero wastewater discharge," compliant exhaust gas emissions, and proper solid waste disposal. The overall clean energy conversion efficiency exceeds 44%, and fresh water consumption remains below 3 tons per ton of standard coal.

Innovative Project Management Enhances Industrial Competitiveness. By adopting an integrated, park-based, intensive, and industrially collaborative model, the enterprises have established an industrial symbiosis within the park—enabling resource sharing and by-product exchange among interconnected and mutually supportive companies. This approach transforms traditional industrial systems, significantly improving resource and energy efficiency, reducing intermediate product transportation costs, substantially lowering final product costs, and enhancing market competitiveness.

Major Demonstration Project for Carbon Capture, Utilization, and Storage (CCUS). Ordos is home to the world’s first full-chain demonstration project for 100,000 tons/year CO_2 capture and deep saline aquifer storage, which has successfully addressed the global challenge of large-scale storage in continental low-permeability reservoirs of the Ordos Basin. By 2024, the project had safely and stably injected 302,600 tons of CO_2, achieving internationally leading technological standards.

Promoting Integrated Development of Coal Chemicals with Green Hydrogen and Renewable Energy. Through a green model integrating coal chemical production with hydrogen energy, enterprises have built a full industrial chain, from methanol carbonylation to acetic acid and further to chemical products like EVA and VAE, extending, complementing, and strengthening the existing polyolefin industrial chain. The project will consume 30,000 tons of green hydrogen, expand annual production capacity by 240,000 tons of MTO-grade methanol, and construct new facilities for acetic acid, vinyl acetate, EVA, VAE, and LNG, enabling low-carbon development via coal-green hydrogen coupling. Upon completion, the project is expected to achieve an internal rate of return of 20.35% and an average annual net profit of 831 million yuan.

Additionally, one enterprise is planning a 500,000 tons/year off-grid wind-solar hydrogen-to-green ammonia demonstration project, comprising three core components: wind-solar power generation, hydrogen production/storage via water electrolysis, and green ammonia synthesis. The project will use dedicated renewable power stations to directly supply electricity to the hydrogen and ammonia production plants. Air separation and ammonia synthesis units will prioritize using co-generated wind and solar power while maintaining grid connection to ensure stable chemical production during insufficient renewable generation, thereby advancing low-carbon development.

2.3 Existing Problems

(1) Challenges in carbon reduction for the modern coal chemical industry are becoming prominent

The modern coal chemical industry uses coal as its primary feedstock. The inherently high carbon-to-hydrogen (C/H) ratio of coal leads to high carbon dioxide emissions during its conversion into chemical products. In 2023, China's total carbon emissions reached 12.6 billion tons of CO_2 equivalent, with the modern coal chemical industry (including coal-to-methanol) emitting approximately 408 million tons, accounting for about 3.39% of the national total.

First, the high energy intensity of the process results in significant carbon emission intensity. The production process of modern coal chemicals is complex. Most products require coal to first be gasified into syngas, which then undergoes a series of chemical reactions to form final compounds. In contrast, petrochemicals use liquid crude oil or natural gas, already mixtures of hydrocarbons, as feedstocks, requiring shorter processes to produce basic downstream chemicals. The solid nature and low hydrogen content of coal mean that producing hydrocarbons via coal chemistry involves more reaction steps, and gasifying solid material demands more energy. Thus, producing initial downstream chemicals through petrochemical routes involves less phase change energy and relatively lower carbon emissions. For example, producing one ton of olefins via coal emits 5.8 tons of CO_2, whereas ethane cracking and naphtha-based olefin production emit only 0.78 tons and 0.93 tons of CO_2, respectively. During field visits, the research team learned that coal chemical tail gas contains high concentrations of CO_2. Although CCUS technology can reduce emissions, its large-scale application is limited by high storage costs and strict geological requirements.

Second, the industry faces substantial policy-driven carbon control pressures and rising costs. Policies and regulations such as China's "Dual Carbon Goals" and the launch of the national carbon emissions trading market are increasing compliance burdens. While the power, steel, cement, and aluminum smelting industries are currently included in the carbon market, sectors like petrochemicals and chemicals are expected to be incorporated in the future. This will subject modern coal chemical companies to carbon quotas and trading costs, increasing operational expenses. Dual control policies over energy consumption also restrict project approvals and impose energy-saving retrofit requirements, potentially diminishing the competitiveness of some products. Growing public concern about environmental quality has further heightened social scrutiny of modern coal chemical projects. In international trade, "carbon Customs tax" policies such as the EU's Carbon Border Adjustment Mechanism (CBAM) are being gradually implemented. Products with high carbon footprints, like those from modern coal chemical processes, face increased costs and reduced competitiveness in global markets and may even be excluded from certain markets. On the technological front, upstream and downstream industries and consumers are increasingly demanding green, low-carbon products. High carbon footprints in modern coal chemical products expose them to "decarbonization" pressures. However, transitioning to low-carbon operations requires enormous investments. Although CCUS is critical, it remains costly. While companies like Yanchang Petroleum and Sinopec Qilu Petrochemical have launched demonstration projects, investment and operational expenses are substantial. Currently, carbon capture in modern coal chemical projects involves further refining, purifying, and pressurizing existing high-concentration CO_2 tail gases, complex procedures that lead to higher capture costs. For example, in a coal-to-liquids plant, the variable cost of capturing CO_2 to meet storage conditions (purity $\geqslant$99%) can reach 100 - 150 yuan/ton, with a full cost of about 189 yuan/ton. Taking a typical coal-to-olefins project as an example, where CO_2 emissions per ton of olefins are approximately 10.5 tons (with about 5.8 tons emitted from the low-temperature methanol washing section), the capture cost for CO_2 from this section is estimated at 120 RMB/ton. Thus, the CO_2 capture cost per ton of olefins is about 696 RMB. Based on typical olefin market prices at the end of 2024, this capture cost accounts for roughly 10% of the product value. Therefore, although CCUS can partially mitigate carbon emissions, it significantly increases the costs of modern coal chemical projects, further reducing profitability.

(2) High costs in brine wastewater treatment and challenges in disposal and utilization of waste salt

The modern coal chemical industry generates large volumes of high-concentration, complex wastewater during production, with brine being the most challenging component due to its intricate composition and difficulty in treatment. For example, in coal-to-liquids production, every ton of oil produced via direct coal liquefaction generates 4.8 tons of wastewater, with typical pollutant concentrations including: COD 2,000–5,000 mg/L, ammonia nitrogen: 200–600 mg/L, cyanide 10–30 mg/L. These levels far exceed the limits set by China's "Integrated wastewater discharge standard (GB 8978-1996)" for second-category discharges: COD ⩽500 mg/L, ammonia nitrogen ≤25 mg/L, cyanide: ≤1.0 mg/L. This significant disparity makes treatment extremely difficult. Although the mainstream brine treatment process "ultrafiltration reverse osmosis + evaporation crystallization" can achieve "zero liquid discharge," it faces growing challenges due to high costs, high energy consumption, and difficulties in handling by-products.

First, high energy consumption and costs are major concerns. The requirement for zero wastewater discharge has led to environmental protection investments accounting for up to about 15% of total project costs in modern coal chemical projects. For instance, in the Ordos region, large coal chemical projects can generate millions of tons of brine annually. Treating each ton of brine using Mechanical Vapor Recompression (MVR) or multi-effect evaporation technology typically consumes 40–80 kWh of electricity, depending on salinity, and this does not include energy used in pretreatment or reverse osmosis. For a project producing millions of tons of brine per year, annual electricity costs for brine treatment alone can reach hundreds of millions of RMB, significantly increasing operational expenses and indirectly contributing to carbon emissions. The high cost of wastewater treatment conflicts sharply with corporate profitability goals, making sustained and normalized zero-discharge operation difficult to maintain.

Second, disposal and utilization of brine by-products remain challenging. If the crystallized salt from brine evaporation cannot be effectively utilized for higher-value applications, it must be disposed of as hazardous waste in landfills, occupying land and posing risks of soil and groundwater contamination through rainwater leaching. While technologies such as nanofiltration membranes and cooling crystallization can separate mixed salts, they are still in the demonstration phase and face limitations. For example, nanofiltration requires frequent membrane replacement, and cooling crystallization is prone to corrosion, leaks, and clogging. These issues currently render the overall economics of such processes unfavourable. Even after separation, a certain amount of residual mixed salt remains, which must be treated as hazardous waste, imposing a substantial financial burden on enterprises and yielding poor environmental benefits. Furthermore, current industrial salt standards lack clear parameters distinguishing harmful substances, such as ammonia nitrogen and heavy metals, that are characteristic of salts derived from coal chemical wastewater. This ambiguity could impact downstream industries that use such salt products, potentially leading to secondary pollution.

(3) Air pollutant emissions constrain air quality improvement

Firstly, modern coal chemical projects are accompanied by significant emissions of air pollutants, which have become a prominent factor restricting continuous regional air quality improvement. In typical processes, stages such as combustion, gasification, and synthesis release large quantities of pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM10 and PM2.5), and volatile organic compounds (VOCs). Given the availability of actual monitoring data and the need for unified statistical standards, the analysis will focus specifically on SO_2 and NOx, two types of pollutants with substantial emissions, clearly defined control standards, and relatively complete data.

Based on the strictest emission limit requirements outlined in key standards such as the "Integrated emission standard of air pollutants," the "Emission standard of air pollutants for industrial kiln and furnace," and the "Technical Guide for Performance Grading of Key Industries During Heavy Pollution Weather (Coal Chemical Industry)," and considering the process characteristics and waste gas volume ranges of typical projects (e.g., 3,000–4,000 m^3/ton for coal-to-methanol and 4,500–6,000 m^3/ton for coal-to-olefins), the emission factors for modern coal chemical products are set as follows:

Table 1 SO2 and NOx Emission Factors of Modern Coal Chemical Products

Product	SO2 Emission Factor (kg/t）	NOX Emission Factor (kg/t)
Coal-to-Methanol (CTM)	0.15	0.3
Coal-to-Liquids (CTL)	0.38	0.6
Coal-to-Natural Gas (CNG)[6]	0.22	0.4
Coal-to-Olefins (CTO)	0.56	0.35

6 Note: The emission factor unit for coal-to-natural gas is kg/km^3

Coal-to-Ethylene (CTEG)	Glycol	0.15	0.35

Taking the Ordos region as an example, and based on the aforementioned emission factors along with estimated production volumes of key modern coal chemical products in recent years, the total emissions of SO_2 and NOx from the modern coal chemical industry have shown a significant upward trend since 2020. Against the backdrop of a generally stable or slightly declining total industrial pollutant emissions, the modern coal chemical sector has conversely grown, becoming a major source of new pollutant emissions. In 2020, the modern coal chemical industry in Ordos emitted approximately 24,000 tons of SO_2 and 38,000 tons of NOx. By 2023, these figures had risen to about 37,000 tons of SO_2 and 57,000 tons of NOx, representing increases of 54.2% and 50%, respectively.

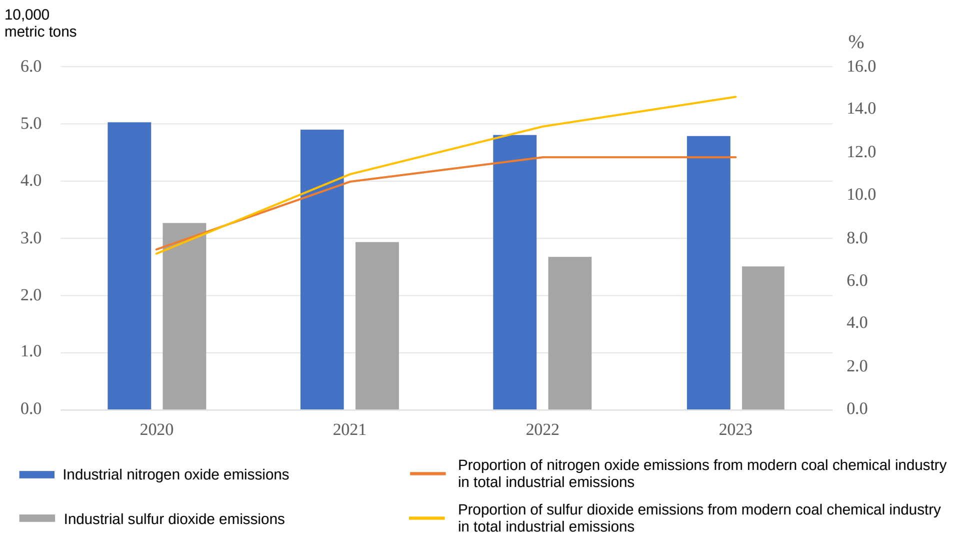

Fig 6 Industrial Nitrogen Oxide and Sulfur Dioxide Emissions in Ordos (2020-2023) and the Proportion Accounted for by the Modern Coal Chemical Industry

While emission reduction efforts in traditional industries have gradually shown results, the emission issues from the modern coal chemical sector are partially offsetting these gains, becoming one of the major constraints to regional air quality improvement. The high-pollution, high-emission nature of modern coal chemical operations poses a practical challenge to environmental control objectives and must be adequately addressed. There is an urgent need to strengthen total emission control and enforce cleaner technology standards in this industry to prevent a situation where “new pollution counteracts past reductions.”

Secondly, the treatment technologies for gaseous emissions from modern coal chemical processes require improvement. The emissions often consist of complex multi-component mixtures that are difficult to control. The VOCs generated during production, including alkanes, alkenes, aromatic hydrocarbons, and sulfur/nitrogen-containing compounds, are highly diverse. Many of these VOCs are toxic and volatile, and existing treatment technologies struggle with low efficiency and instability when handling high-concentration, multi-component, and trace-level VOCs, in addition to involving high operating costs. Unorganized VOC emissions readily occur from complex piping, storage tanks, and loading/unloading operations in modern coal chemical plants. Effectively capturing and treating these emissions requires highly sensitive Leak Detection and Repair (LDAR) technologies as well as efficient and low-cost end-of-pipe treatment solutions. Furthermore, challenges remain in managing low-concentration, trace-level toxic and hazardous gases. Coal gasification and combustion processes may generate trace-level amounts of highly toxic substances such as dioxins, arsenic, and mercury. Existing detection technologies often lack sufficient sensitivity and accuracy, while the development of highly efficient adsorbents, catalysts, and other targeted treatment methods for these trace substances remains relatively lagging behind.

Thirdly, management of air pollutant emissions in the modern coal chemical industry remains inadequate. The current regulatory system tends to focus on single pollutants, with insufficient coordination in the joint control of multiple pollutants such as SO_2, NOx, VOCs, PM, and NH_3. Some enterprises, constrained by costs, continue to use outdated equipment for VOC treatment or fail to operate air pollution control devices consistently, leading to suboptimal treatment outcomes. Additionally, the absence of a unified platform for monitoring data and a lack of cross-regional joint prevention and control mechanisms further weaken overall regulatory effectiveness.

Chapter IV. Resource and Environmental Challenges Potentially Faced by the Large-Scale Development of New Energy

1. Basic Situation: Rapid development of new energy with breakthroughs in wind and solar power

China's renewable energy sector has developed rapidly, achieving leapfrog growth over the past decade. The country has built the world's largest and fastest-growing renewable energy system, with the share of renewable power capacity increasing from 40% to around 60%. In 2024, China's renewable energy capacity grew by over 23% year-on-year, accounting for approximately 56% of total installed capacity and becoming a new force in ensuring power supply. In 2025, renewables continued to dominate new capacity additions, approaching 60% of the nation's total installed capacity.

Renewable power generation also achieved new breakthroughs. In the first half of 2025, national renewable electricity generation reached 1,799.3 TWh, a 15.6% increase year-on-year. Renewable energy accounted for nearly 40% of China's total electricity generation, exceeding the combined electricity consumption of the tertiary industry and residential sectors during the same period. The incremental electricity generated from wind and solar power exceeded the total growth in national electricity consumption.

However, the rapid and large-scale expansion of new energy has also brought challenges to ecological environmental and resource protection. The demand for land and other resources for wind and solar development, their operational impacts on ecosystems and the environment, and the recycling and disposal of decommissioned facilities have become increasingly prominent due to this accelerated growth.

2. Existing Policies

Existing laws and regulations, energy development plans, and supporting policies have already begun to address the ecological and environmental impacts associated with new energy development, introducing varying degrees of policy requirements. The "Energy Law of the People's Republic of China," effective from January 1, 2025, explicitly states that "energy development and utilization activities shall comply with laws and regulations related to ecological and environmental protection, reduce pollutant and greenhouse gas emissions, and prevent damage to the ecological environment." The "14th Five-Year Plan for a Modern Energy System" released in 2022 emphasizes "strengthening the policy guidance for energy ecological and environmental protection, conducting environmental impact assessments for energy base development plans and key projects in accordance with the law, improving land and sea use policies, and strictly implementing regional 'Three Lines and One List' ecological zoning control requirements." Simultaneously, the "14th Five-Year Plan for Renewable Energy Development" underscores the need to "practice the development philosophy that lucid waters and lush mountains are invaluable assets, place greater emphasis on ecological and environmental protection, and integrate it throughout the entire process of renewable energy planning and construction."

With the rapid large-scale expansion of new energy, relevant authorities have promptly introduced technical and management measures to address characteristic issues such as equipment decommissioning, recycling, and land-use management. For example, regarding the recycling of decommissioned new energy equipment, the National Development and Reform Commission issued the "Guidelines on Promoting the Recycling of Decommissioned Wind-Power and Photovoltaic Equipment" in 2023, proposing to "actively build a recycling system for wind and photovoltaic equipment covering green design, standardized recycling, high-value utilization, and harmless disposal, completing the final link in the green, low-carbon, and circular development of the wind and photovoltaic industry chains." The "Guiding Opinions on Accelerating the Green Development of the Manufacturing Industry" jointly released by the Ministry of Industry and Information Technology and six other departments in 2024 call to "accelerate the R&D and industrial application of comprehensive utilization technologies for new solid wastes such as decommissioned photovoltaic modules and wind turbine blades." The Ministry of Ecology and Environment also released the "Technical Specifications of Pollution Control in the Recycling and Treatment of Waste Photovoltaic Equipment (Draft for Comments)" in 2024, which "specifies technical requirements for pollution control throughout the entire process of dismantling, collection, transportation, storage, disassembly, comprehensive utilization, and disposal of waste photovoltaic modules, brackets, and other equipment." Regarding land-use management during new energy development, the Ministry of Natural Resources issued the "Notice on Supporting the Development of the Photovoltaic Power Generation Industry and Regulating Land Use Management" in 2023 to "guide rational layout, implement categorized land management, expedite the processing of project land procedures, strengthen land supervision, and prudently address historical issues." F**urthermore, influenced by international trade policies and market access rules, there is growing global attention on the ecological and environmental impacts of new energy development from a full life-cycle perspective. The gradual improvement of China's carbon footprint management system will help trace pollution emissions and resource consumption in the upstream stages of the new energy equipment industry chain, such as resource extraction and manufacturing, providing a foundation for assessing ecological and environmental impacts throughout the**

life cycle. In its "Progress Report on the Construction of the Product Carbon Footprint Management System (2025)," the MEE pointed out that the "two cornerstones" of China's carbon footprint management system, product carbon footprint accounting standards and carbon footprint factor databases, and the "three institutional mechanisms," product carbon labelling certification, product carbon footprint grading management, and carbon footprint information disclosure, have been initially established. Meanwhile, the MEE, in collaboration with the National Bureau of Statistics and other relevant departments, has released national 2023 carbon footprint factors for coal power, gas power, hydropower, nuclear power, wind power, photovoltaic power, solar thermal power, biomass power, electricity transmission and distribution, and the national electricity mix, and has improved the routine release mechanism. Notably, the product carbon footprint management system for the photovoltaic industry is being accelerated, all of which will contribute to promoting the green and low-carbon development of the new energy industry chain and supply chain.

3. Existing Problems

3.1 Inadequate system for preventing and controlling ecological and environmental impacts

With the rapid expansion of wind and solar power, current environmental management requirements are no longer sufficient to meet new ecological protection demands. On one hand, as emerging industries, wind and solar power are mostly subject to traditional environmental impact assessment (EIA) regulations for construction projects, lacking specific and detailed evaluation guidelines tailored to their characteristics. On the other hand, while recent policies have focused on the recycling of decommissioned wind and photovoltaic (PV) equipment, there is a lack of detailed guidance on how to integrate industry development with strategic environmental assessments, ecological zoning controls, and environmental access requirements at the early planning stage to achieve pollution prevention at the source. Additionally, although the state has encouraged new energy development in areas with low land-use value, such as deserts, Gobi areas, barren lands, and coal mining subsidence areas, policies for constructing new energy projects on contaminated sites or abandoned mining lands remain underdeveloped.

3.2 Impending large-scale decommissioning of wind and solar equipment

In 2023, China recycled over 50,000 tons of metal and other resources from decommissioned wind power equipment and approximately 10,000 PV modules, recovering more than 6,000 tons of resources. While relevant authorities have issued policies to promote the recycling and disposal of decommissioned equipment, issues such as incomplete industry standards and insufficient market quality supervision have led to resource waste and environmental pollution due to unscientific and incomplete recycling practices. For example, the recycling process for PV modules is complex, yet there is a lack of pollution control plans for the collection, storage, transportation, and dismantling stages, as well as insufficient regulatory constraints and technical guidance for recycling enterprises, especially small workshops and factories. Moreover, the recycling of wind turbine components faces practical challenges, such as high transportation costs, immature technologies, and unclear responsibility attribution. The absence of supporting standards, regulations, and fiscal incentives has resulted in low enthusiasm for recycling within the industry.

3.3 Resource constraints, particularly for land use, pose significant challenges

Studies predict that to achieve carbon neutrality goals, under a scenario combining centralized and distributed wind and solar power development, installing 6 billion kW of new energy capacity will require the permanent acquisition of 37,400 to 77,500 square kilometres of land. Large-scale wind and solar bases in "desert-Gobi-barren" areas and the utilization of coal mining subsidence zones have become the main fronts for new energy development. However, the planning for local consumption and transmission corridors for these "desert-Gobi-barren" bases is inadequate. Meanwhile, land-use requirements in these areas and subsidence zones also constrain new energy development. **Firstly, land functionality in "desert-Gobi-barren" regions is fragmented.** These areas are primarily used for centralized PV and wind projects, which do not occupy agricultural or forest land and do not change land-use purposes. However, as many are located in ecological functional zones, some regions include large stretches of protected desertification control land. In some areas, previously unused land has been reclassified as basic farmland, forest, or grassland, which are restricted development zones. This fragmented land allocation hinders concentrated and intensive project layout. **Secondly, there is a lack of institutional arrangements for the reuse of coal mining subsidence areas.** One important approach for resource-based cities to develop new energy is to implement PV projects in subsidence areas through innovative models like ecological restoration, aiming to expand new energy land use and improve comprehensive land utilization efficiency. However, in practice, some project sites, though actually idle areas like barren hills or sandy land in subsidence zones, are still designated as residential, commercial, or even cultivated or forest land in territorial spatial plans. The lag in adjusting land-use classifications has become a major obstacle to the implementation of PV projects.

Chapter V. Problems and Challenges of Energy-Environment Synergy in Traditional Energy Transition

1. Establish a national-level comprehensive early-warning and coordination mechanism and conduct research on "prospective contingency plans."

In order to deal with major environmental and resource issues that may arise from the gradual phase-out of coal mines, the scaled development of modern coal chemical industries, and the sustained large-scale expansion of new energy, it is recommended to establish a national-level comprehensive early-warning and coordination mechanism. Additionally, research on "prospective contingency plans" should be initiated in the upcoming 5 years to strengthen risk prevention and ensure collaborative, high-quality development of energy and the environment.

In real-world applications, indicators such as the improvement pace of environmental quality in China, the development speed and scale of new energy and its cost decreasing rate, as well as energy consumption growth, total coal consumption, and the scale of coal-fired power development have repeatedly exceeded the predictions of some experts or the expectations of official plans. This has led to insufficient synergy between policy and planning elements, posing significant risks to the healthy development of the energy industry. The upcoming 5 to 10 years represent critical stages for achieving two major strategic goals: carbon peaking and the building of a beautiful China. Ensuring high-level synergy between energy and the environment is therefore crucial.

First, create a national early-warning and coordination mechanism: Establish a comprehensive research and coordination institution that comprises cross-departmental and cross-industrial (including national associations). This institution would integrate resources, perform comprehensive and interdisciplinary research through "early planning, deep analysis, and concrete preparation," develop scientific contingency plans, and ensure proactive control of systemic risk management on a strategic level.

Second, develop a system of "proactive contingency plans": Scientifically evaluate the speed of new energy transition and the phase-out of fossil fuels. Conduct foresight studies on industrial evolution pathways and multi-faceted regulation concerning energy, environment, and resources. The aim is to develop more resilient policies for impacts from uncertainties and natural disasters, creating a contingency planning methodology and framework that has scientific assessment, precise response, and dynamic optimization, which would strategically reinforce risk prevention for high-quality development.

2. Accelerate the development of a top-level legal framework against climate change.

Establishing this framework will provide a legal foundation for the overall management of energy transition, environmental protection, and climate governance. It will create a solid legal guarantee for high-quality development and the realization of "Dual Carbon Goals."

Currently, China's climate actions mainly rely on top-level policy papers and departmental regulations. Although a comprehensive deployment with a "1+N" core policy system is already in place, it still faces challenges such as insufficient systemization, a weak legal foundation, and poor coordination with existing energy and environmental laws. It is recommended to legislate a proven-effective national strategy, management system, "Dual Carbon Goals" responsibility mechanism and major regulations through national-level legislation. This legislation should clearly define the statutory responsibilities and obligations of governments, industries, and market entities in energy structure optimization, industrial low-carbon transition and climate governance. It would systematically regulate mitigation and adaptation activities related to climate change, enhance synergy and consistency of existing laws that address climate governance and energy, as well as environmental sectors, and improve the nation's climate governance capabilities to a more legalized, standardized, and institutionalized level.

3. In-depth research on collaborative innovation in energy and environment

The three pillars of energy development—security, green transition, and economic growth—are unified and inseparable, interdependent yet contradictory. They need to reach a dynamic balance under the guidance of sustainable development concepts. The core idea of energy-environment synergy and innovation is to identify "misalignments" during the transition from old to new, analyze their root causes and conditions, and explore solutions—all within the framework of high-quality development and the integrated goals of decarbonization, pollution reduction, ecological conservation, and economic growth. This preliminary study has screened and analyzed key issues and proposed initial recommendations. Future research should deep dive in two areas.

Firstly, design a collaborative development roadmap for the upcoming 5 years and beyond: Formulate near-, medium-, and long-term goals that are in line with the key milestones of "Dual Carbon Goals" and beautiful China development. The goals should define collaborative pathways between environmental resources and the phasing out of outdated coal mines, the planning of the modern coal chemicals industry, and the orderly expansion of new energy sources. Moreover, explore the pathway to minimize the environmental costs of coal mine closures, research on collaborative transition mechanisms for traditional energy bases transformation, ecological restoration and compensation, and multi-agency monitoring; Explore modern coal chemical development roadmaps and their coupling with renewable industries to enable green upgrading; Innovate the orderly development for renewables, scientifically assess full life-cycle environmental impacts of new energy bases, and propose ecological protection policies and technical solutions, improve environmental impact monitoring systems in key regions (such as renewable bases).

Secondly, explore cross-department and cross-region decision-making and policy collaboration tools: Conduct research on the optimization of key policy tools across departments, the construction of green low-carbon standard systems, early-warning systems for energy-environment risks, and coordinated law enforcement mechanisms. Explore cross-regional energy development synergy pathways through models like the "enclave economy,"[7] and improve inter-regional energy design mechanisms for ecological compensation, cost-sharing for transition, and collaborative governance.

[7] "Enclave economy" is a regional economic cooperation model that breaks administrative boundaries. It specifically refers to two or more regions that are administratively independent of each other, which transcend administrative divisions and, based on equal consultation and voluntary cooperation, aim directly to complement and efficiently utilize production factors. Through the collaborative development of various industrial parks in designated areas and mechanisms such as planning, construction, management, and profit distribution, it achieves a mutually beneficial regional economic development model.

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