Research on Pathways to Carbon Peaking and Carbon Neutrality in the Yangtze River Delta Region

Research Group on Regional Coordination Pathway Optimization for Carbon Peaking and Carbon Neutrality

2025

联系方式
guojing@caep.org.cn

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Abstract

The Yangtze River Delta region (hereinafter referred to as the Yangtze Delta region), as one of China's most dynamic and innovative economic zones, bears a crucial mission in the national carbon peaking and carbon neutrality strategy. Covering only 4% of the country's land area, this region accounts for 25% of industrial output while emitting approximately 20% of the nation's carbon dioxide. Its low-carbon transition holds significant exemplary value for achieving China's national carbon neutrality goals.

From 2005 to 2024, carbon dioxide emissions in the Yangtze River Delta region surged from 1.17 billion tons to 2.4 billion tons, exhibiting a trend of "sustained growth, structural adjustment, and indirect increase." The power and industrial sectors collectively accounted for 67% of total emissions, making them key areas for regional carbon reduction efforts. Spatially, emission intensity exhibited a pattern of "higher along rivers and coasts, lower in mountainous areas," with Jiangsu, Shanghai, and northern Zhejiang being the most prominent.

The Yangtze River Delta region faces three major challenges in its low-carbon transition: First, its industrial system is heavily industrialized, with over 19,000 industrial parks distributed across the region, and high-energy-consuming industrial clusters accounting for as much as 62% of carbon emissions. Second, the energy structure exhibits significant "high-carbon lock-in" effects, with coal consumption exceeding 50% of total energy use and 80% of energy relying on external imports. Third, administrative barriers and imperfect market mechanisms persist, with disparities among the three provinces and one municipality in carbon quota allocation and emission reduction standards, and a unified carbon market yet to be established.

This study systematically investigates the low-carbon development pathways for the Yangtze River Delta region from 2020 to 2060, based on the China Regional Coordination Pathway Optimization Integrated Assessment Model for Carbon Peaking and Carbon Neutrality (CAEP-CP 3.0). Results indicate that the region's optimized carbon emission trajectory will unfold in four distinct phases: gradual peak (2020–2027), moderate decline (2027–2035), rapid reduction (2036–2050), and stabilization near zero (2051–2060). Regional carbon emissions are projected to peak at 2.43 billion tons in 2027, decline by 10% from the peak by 2035, achieve rapid reduction between 2035 and 2050, and approach net-zero emissions by 2060. Energy structure transformation is pivotal to achieving these targets, with non-fossil energy share rising to 55% by 2035 and reaching 91% by 2060.

The low-carbon transition in the Yangtze River Delta region relies on the coordinated

development of key industrial chains. The photovoltaic industry chain has formed the world's most comprehensive system, with Jiangsu alone accounting for over 40% of the nation's photovoltaic module production capacity. The lithium battery industry has established a closed-loop system encompassing "upstream materials—midstream manufacturing—downstream applications—end-of-life recycling." The integrated circuit industry has established a regionally coordinated pattern where "design is centered in Shanghai, packaging and testing in Jiangsu, materials in Zhejiang, and storage in Anhui." The hydrogen energy sector will build GW-scale electrolytic hydrogen production plants and regional hydrogen networks. These four major industrial chains will play a crucial role in the low-carbon transition.

The low-carbon transition of the Yangtze River Delta region hinges on the implementation and leadership of major climate initiatives. This study systematically outlines ten key projects with an estimated total investment of 1 to 2 trillion yuan, including: a regional integrated green hydrogen network demonstration project, a large-scale offshore CCUS demonstration project, a zero-carbon industrial park and collaborative industrial decarbonization retrofitting project, and a multi-gigawatt deep-sea offshore wind power base cluster project.

Achieving carbon neutrality goals requires substantial funding. According to this study's calculations, the total funding requirement from 2025 to 2030 will reach 7.05 trillion yuan, with the energy sector accounting for 3.67 trillion yuan—over 50% of the total. From 2031 to 2060, funding needs are projected to surge to 63 trillion yuan.

Based on this, the study proposes three core policy recommendations. First, establish a new regional system for total emissions control and market-based allocation through a three-tiered coordination mechanism: "regional carbon budget—metropolitan carbon credits—enterprise carbon quotas," creating a pilot zone for deepening national carbon market reforms in the Yangtze River Delta. Set aggregate targets of net-zero carbon growth during the 15th Five-Year Plan period and comprehensive reduction during the 16th Five-Year Plan period, forming a three-tiered management model linking "enterprise carbon compliance—metropolitan area carbon pool—regional carbon clearing." Second, innovate a "chain-leader-driven industrial chain carbon governance system," where leading enterprises serve as "carbon chain leaders" and assume primary responsibility for coordinated emissions reduction across the entire industrial chain. Third, establish the Yangtze River Delta as a "dual-cycle originator" for global climate technologies and an international "carbon standard export hub," propelling Chinese standards into international norms.

I

Current Status of Carbon Dioxide Emissions in the Yangtze River Delta Region

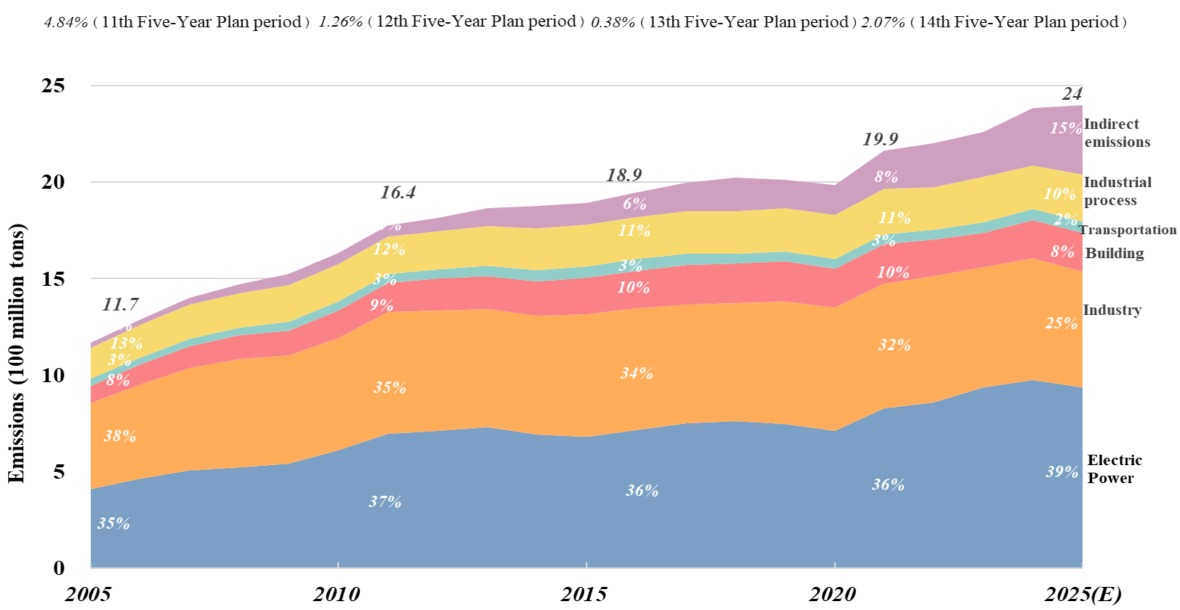
01

OVERVIEW OF CARBON DIOXIDE EMISSIONS IN THE YANGTZE RIVER DELTA REGION

From 2005 to 2025, the total carbon emissions in the Yangtze River Delta region increased from 1.17 billion tons to 2.4 billion tons, exhibiting an overall trend of "continuous growth, structural adjustment, and indirect increase." During the 11th Five-Year Plan period (2006–2010), emissions rose from 1.29 billion tons to 1.64 billion tons, with an average annual growth rate of 4.8%. Power generation and industry were the primary sources of emission growth, collectively accounting for over 70% of the increase. During the Twelfth Five-Year Plan period (2011–2015), the growth rate slowed to an average annual increase of 1.3%. Industrial emissions stabilized (34% share), while the power sector continued to grow (36% share), reflecting the initial effectiveness of energy conservation policies. During the 13th Five-Year Plan period (2016–2020), emissions rose gradually before slightly declining by 2020, with an average annual growth rate of 0.4%. Emissions from power andindustry saw a slight decrease, while the building sector showed steady growth, reflecting increased energy consumption driven by the end-user demand. During the 14th Five-Year Plan period (2021–2025), carbon emissions are projected to rise rapidly, reaching an estimated total of 2.4 billion tons by 2025 with an average annual growth rate of 2.1%. The power and industrial sectors will be the primary sources of emissions, with projected 2025 emissions of 940 million tons and 600 million tons respectively, accounting for 39% and 25% of the total. Indirect emissions follow, projected to reach 360 million tons with an annual growth rate exceeding 10%. Overall, the carbon emission structure in the Yangtze River Delta region is shifting from industrial dominance to being driven by electricity and end-use consumption. This necessitates strengthening coordinated emission reductions through clean power supply and end-use energy efficiency.

Figure 1: Sectoral Carbon Emissions Changes in the Yangtze River Delta Region, 2005–2024

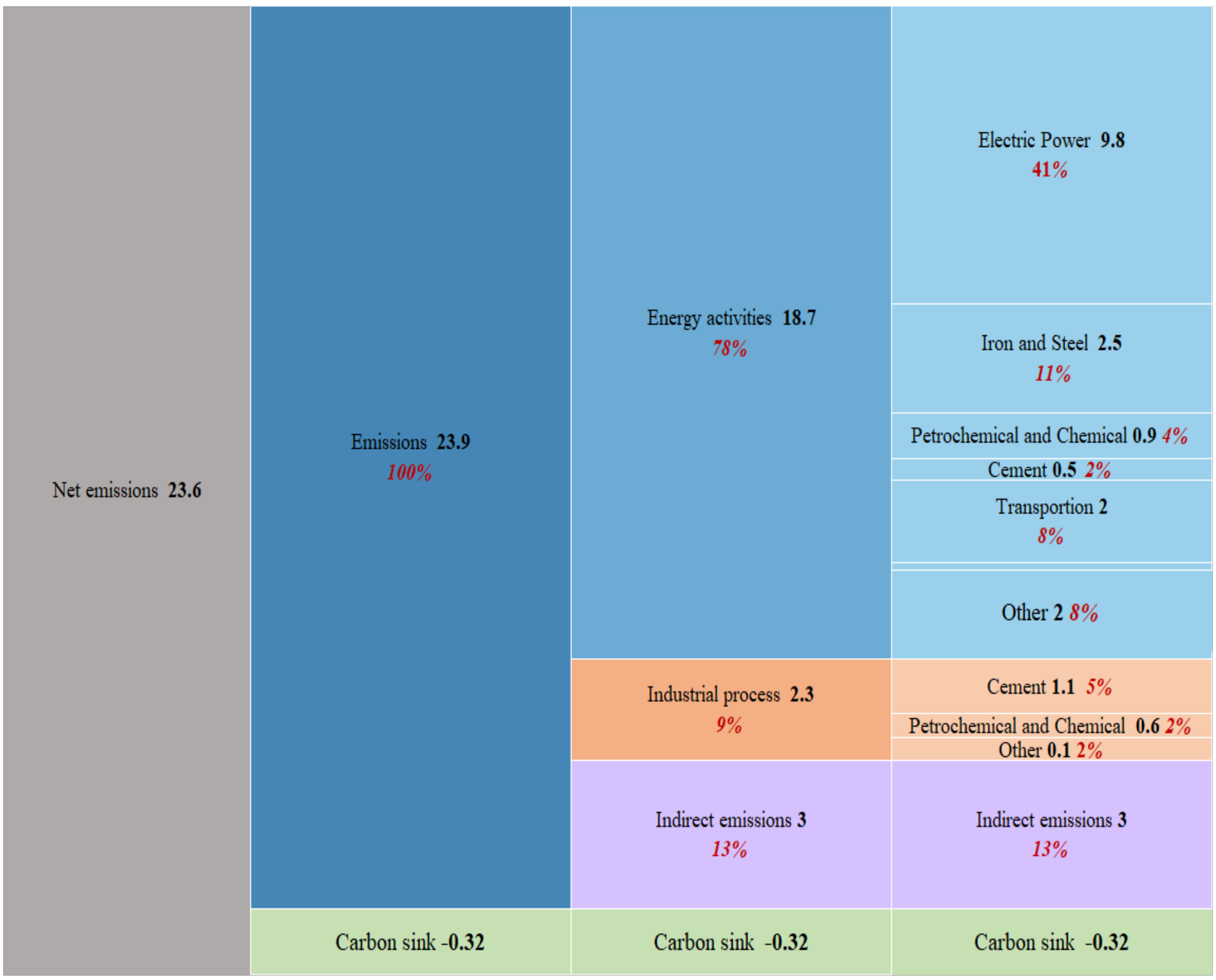
Note: 2025 emissions are based on China Carbon Bulletin data from the Environmental Planning Institute of the Ministry of Ecology and Environment.



In 2024, the Yangtze River Delta region recorded total carbon emissions of 2.39 billion tons, with the power and industrial sectors collectively accounting for 67% of emissions—making them key areas for regional carbon reduction. From an emissions structure perspective, energy activities constituted the primary source, contributing 78% of total emissions. The power sector led with emissions reaching 980 million tons, followed by steel, transportation, and petrochemical industries. Process emissions and indirect emissions accounted for 9% and 13% of total emissions, respectively. The cement industry alone represented 48% of process emissions, making it a critical focus for industrial process reduction efforts. By sector, emissions from power, steel, cement, petrochemicals, and transportation stood at 980 million, 250 million, 160 million, 150 million, and 200 million tons, respectively. Carbon sinks absorbed 30 million tons, resulting in net emissions of 2.36 billion tons. The power and industrial sectors collectively accounted for 67% of emissions, making them the primary targets for future carbon reduction efforts in the Yangtze River Delta.

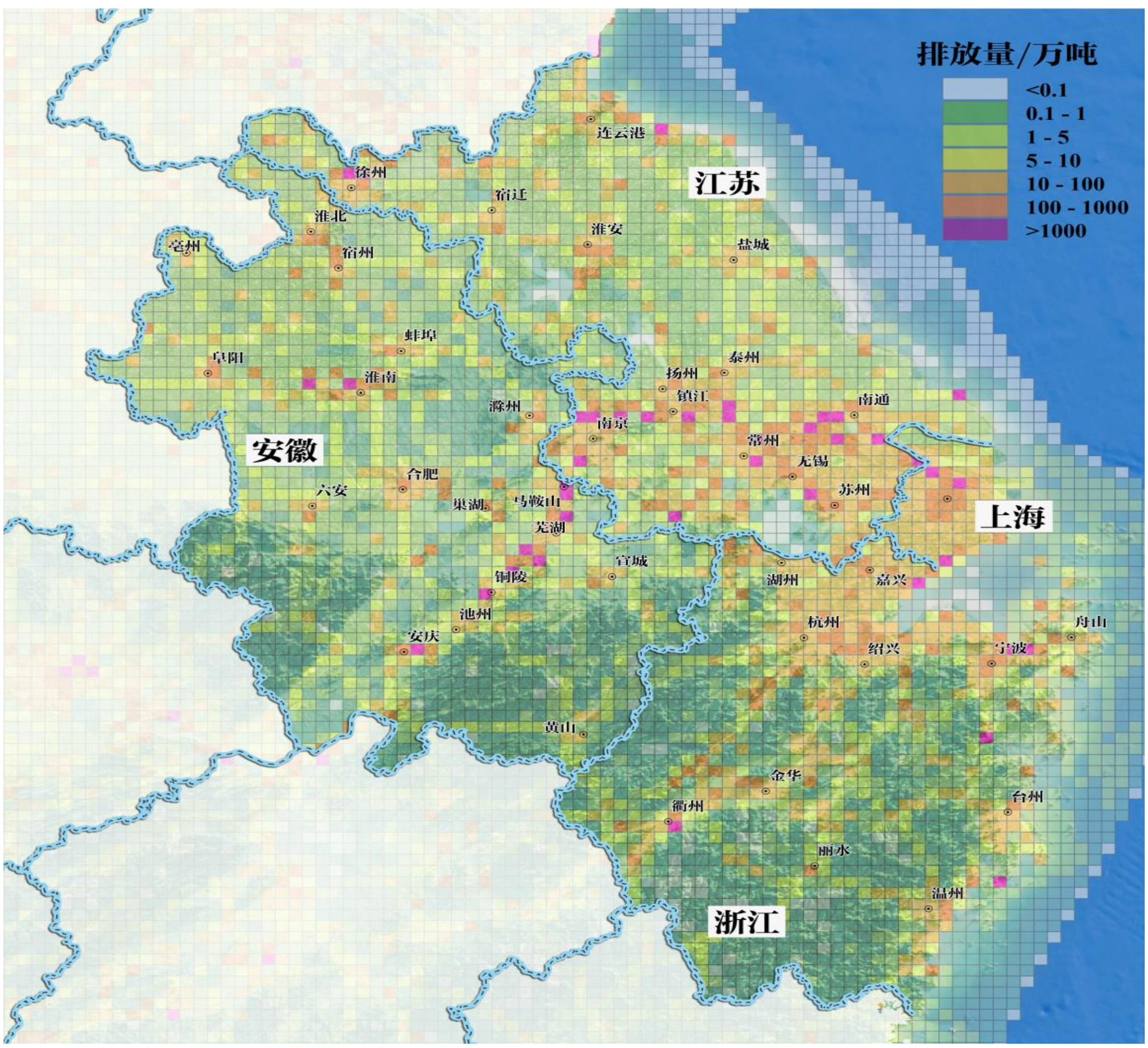
Figure 2: Carbon Emissions Structure in the Yangtze River Delta Region in 2024 (Unit: 100 million tons)

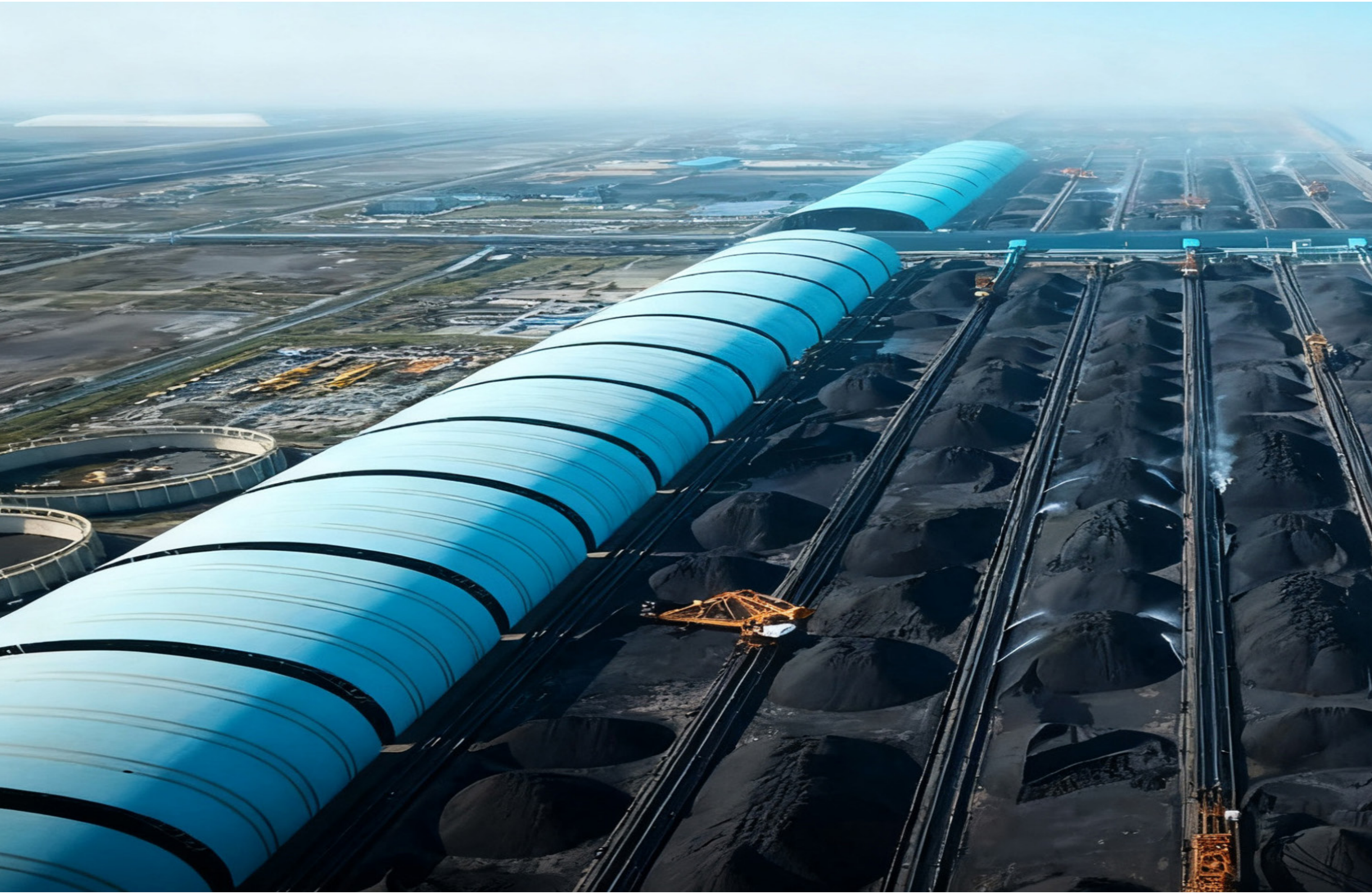
Note: Carbon sinks include geological sequestration and forest carbon sinks.



The spatial distribution of carbon emissions in the Yangtze River Delta region in 2024 exhibits a pronounced pattern of higher emissions along rivers and coastlines and lower emissions in mountainous areas. Jiangsu, Shanghai, and northern Zhejiang exhibited the highest emission intensities, with hotspots concentrated in major cities and industrial clusters such as Nanjing, Suzhou, Wuxi, Changzhou, Nantong, Ningbo, and Shanghai. Multiple grid cells recorded emissions exceeding 100,000 to 1,000,000 tons, highlighting the region's characteristics of dense industrial activity, high energy consumption intensity, and concentrated population distribution. In contrast, central-southern Anhui and southwestern Zhejiang exhibit low emission patterns, with most grid cells emitting less than 10,000 tons. This is primarily linked to their industrial structures dominated by ecological conservation, agriculture, and low-emission industries. The spatial distribution of carbon emissions in the Yangtze River Delta region is highly coupled with industrial distribution, population density, and energy utilization patterns, with areas of higher industrialization and urbanization forming distinct emission hotspots.

Figure 3: Spatial Pattern of Carbon Emissions in the Yangtze River Delta Region in 2024 (10km)





II

Opportunities and Challenges Facing Low-Carbon Transformation and Development

02

OPPORTUNITIES AND CHALLENGES OF LOW-CARBON TRANSITION

The Yangtze River Delta region possesses a comprehensive industrial system and abundant innovation resources, endowing it with the industrial foundation and technological potential for low-carbon transformation. However, the region suffers from scarce energy resources, with 80% of its energy supply dependent on external transfers. Coal consumption has long accounted for over 50% of its energy mix, while the concentration of high-energy-consuming industries and the spatial transfer of carbon emissions have become increasingly prominent issues.

The heavy industrialization of the Yangtze River Delta region poses significant challenges to its low-carbon transition. The region hosts over 19,000 industrial parks, accounting for 29% of the national total. High-energy-consuming industries such as steel, chemicals, power and heat production, and building materials form the industrial backbone, with industrial heating contributing approximately 50% of the nation's total carbon emissions. Take Jiangsu Province as an example: coal consumption accounts for a staggering 67% of its energy mix. Energy-intensive industries have long contributed significantly to regional economic growth, yet they have also entrenched a development path characterized by "high input, high emissions, and high output." These industries commonly suffer from aging equipment and slow technological iteration. Achieving deep decarbonization requires massive investments in technological upgrades. Direct emissions from the industrial sector alone constitute 62% of the region's total carbon emissions, with indirect emissions accounting for 38%, presenting an arduous task for reduction. Meanwhile, while industrial clustering enhances economic efficiency, it also concentrates carbon emissions spatially. Transformation in a single region or sector could trigger supply chain disruptions. Balancing emission reduction targets with industrial competitiveness thus presents an urgent challenge.

The "high-carbon lock-in" effect in the Yangtze River Delta region's energy structure significantly constrains the low-carbon transition process. During the 14th Five-Year Plan period, coal will still account for over 50% of primary energy consumption in the region, while petroleum will maintain a share of 12–16%. Fossil fuels collectively represent more than 85% of the energy mix, with non-fossil energy sources not becoming the dominant energy form until

after 2040. This structure stems from the region's scarce energy resources. Shanghai produces virtually no primary energy locally, while Zhejiang relies on other provinces for 80% of its energy supply, resulting in persistently high external dependence. Although Anhui's renewable energy capacity accounts for 49% of its total installed capacity, Jiangsu, Zhejiang, and Shanghai remain heavily reliant on coal-fired power and imported thermal electricity, creating a regional imbalance characterized by "green in the west, carbon in the east." More critically, the region's total primary energy demand continues to grow. This high external dependency exposes the area to dual risks of both volume and price volatility during its low-carbon transition. It faces potential gas shortages triggered by international geopolitical tensions and soaring energy costs that could erode the economic benefits of renewables like solar and wind power.

Administrative barriers and imperfect market mechanisms hinder the integrated advancement of low-carbon transformation in the Yangtze River Delta. Regional integration in the Yangtze River Delta has a positive effect on carbon emission transfers, with intra-subregional coordination proving more effective than cross-regional collaboration. Administrative divisions have led to fragmented carbon reduction efforts. Although the Yangtze River Delta Ecological Green Integrated Development Demonstration Zone has launched pilot carbon sink trading programs and explored establishing regional carbon credit mechanisms, disparities remain among the three provinces and one municipality in carbon quota allocation, emission reduction standards, and accounting methods, preventing the formation of a unified carbon market. For instance, while Shanghai's carbon market operates maturely, its linkage mechanisms with Jiangsu, Zhejiang, and Anhui remain incomplete, creating obstacles for cross-regional project certification and mutual recognition of emission reductions. Simultaneously, the absence of ecological compensation mechanisms prevents the internalization of environmental costs associated with carbon leakage. Some regions circumvent emission reduction responsibilities through industrial relocation, posing risks of carbon leakage. This lack of coordination hinders the optimal allocation of low-carbon resources across the region, constraining the overall effectiveness of the transition.

III

Optimal Pathways for Carbon Peaking and Carbon Neutrality in the Yangtze River Delta Region

Based on the China Assessment Platform for Energy and Climate (CAEP) 3.0 model for regional coordination pathways toward carbon peaking and carbon neutrality, this study constructs a regional implementation pathway tailored to the Yangtze River Delta (YRD) region. Leveraging the YRD's unique attributes as China's economic core, energy consumption hub, and frontier of technological innovation, the pathway anchors to four critical milestones: 2030, 2035, 2050, and 2060. It comprehensively addresses core domains including energy structure transformation, interregional carbon emission interaction regulation, coordinated development of key low-carbon industrial chains, deployment of major climate engineering projects, and investment demand assessment. 2050, and 2060. It systematically covers core domains including energy structure transformation, regulation of interregional carbon emission interactions, coordinated development of key low-carbon industrial chains, deployment of major climate engineering projects, and investment demand calculations. This framework drives the region's systemic transition from high-carbon to low-carbon development, from traditional manufacturing to green intelligent manufacturing, and from resource dependency to innovation-driven and green-led growth. It provides a replicable demonstration model and valuable experience for China's national carbon neutrality process.

03

OPTIMIZING PATHWAYS TOWARDS CARBON PEAK AND CARBON NEUTRALITY IN THE YANGTZE RIVER DELTA REGION

3.1 Carbon Emission Pathway for 2020–2060

This study systematically evaluates low-carbon development emission pathways for the Yangtze River Delta region from 2020 to 2060, exploring the timing of carbon peak and carbon neutrality milestones. It focuses on analyzing emission changes under the enhanced carbon neutrality pathway (IMP-Trans), aiming to provide scientific pathway references and methodological support for the region's phased and orderly achievement of carbon peak and carbon neutrality.

Under the enhanced carbon neutrality scenario, the carbon emission trajectory of the Yangtze River Delta region from 2020 to 2060 exhibits phased emission characteristics: "gradual peak—moderate decline—rapid reduction—stabilization near zero." According to the CAEP-CP 3.0 large-scale scenario simulation, during the "gradual peak" phase, carbon emissions will rise from 1.99 billion tons in 2020, peaking at 2.43 billion tons in 2027. The region's carbon performance (GDP per unit of CO_2 emissions) is projected to increase from 1.2 yuan/ton in 2020 to 1.5 yuan/ton in 2027, significantly exceeding the national average (rising from 0.8 yuan/ton to 0.9 yuan/ton). The timing of this peak aligns with the national carbon peak target. Although carbon emissions continue to grow, their growth rate has slowed compared to the historical average during 2010–2020. This deceleration is primarily attributed to factors including the region's sustained economic expansion and rigid growth in energy demand, the power sector's high external dependence on coal-fired electricity, as well as advancing urbanization and increasing transportation needs.

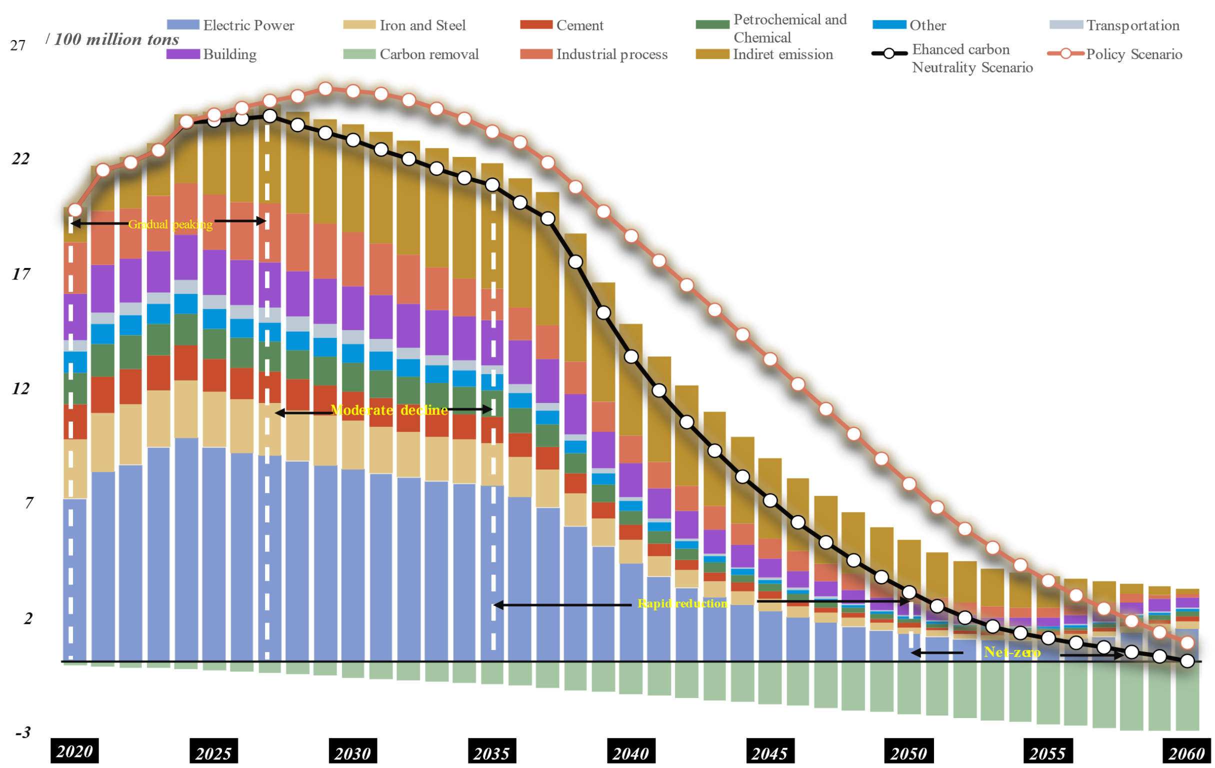
During the "Moderate Decline" phase (2027–2035), carbon emissions begin a gradual decrease with a compound annual reduction rate of 1.4%, resulting in a total reduction of 10%. This phase sees further optimization of the industrial structure, with the Yangtze River Delta integration policy driving the transformation of manufacturing toward high-end and green development (e.g., the growth of Zhejiang's digital economy and Jiangsu's advanced manufacturing clusters). Concurrently, high-energy-consuming industries advance capacity reduction (e.g., the steel industry's carbon peak action requires achieving peak emissions before 2025). The energy mix continues to shift toward cleaner sources, with outdated coal-fired power units gradually phased out and the share of renewable energy steadily increasing. New buildings fully implement ultra-low energy consumption standards (with Shanghai and Hangzhou leading the way), while electrification rates in the transportation sector continue to rise. During this phase, the carbon performance of the Yangtze River Delta region is projected to grow steadily from 1.5 yuan/ton to 2.5 yuan/ton.

During the "Rapid Emissions Reduction" phase (2036–2050), carbon emissions exhibit a steep downward trajectory with a compound annual reduction rate of 9.4%. This period sees the large-scale deployment of deep decarbonization technologies. The power sector largely phases out coal-fired generation, retaining only a limited number of peak-shaving units coupled with Carbon Capture, Utilization, and Storage (CCUS). Renewable energy sources account for over 70% of the electricity mix. Hydrogen and energy storage technologies see widespread adoption in industrial and transportation sectors, with industries like steel and cement achieving commercialization of hydrogen-based steelmaking and CCUS technologies. Road transportation undergoes full electrification, while regional rail networks expand to reduce reliance on road freight. Buildings extensively incorporate building-integrated photovoltaics (BIPV) and intelligent energy-saving systems.

During the "approaching near-zero" phase (2051–2060), carbon emissions decrease at a compound annual rate of 4.4%, gradually approaching near-zero levels. By this stage, the regional energy system will be highly decarbonized, with renewable energy expected to exceed 90% of the mix. For hard-to-abate sectors—such as certain industrial processes, long-haul aviation, and shipping—CCUS, carbon sinks (forests), and negative emissions technologies will be required to offset these residual emissions.

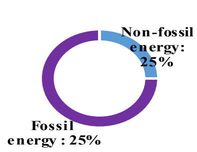
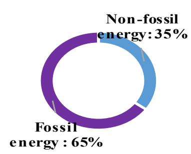
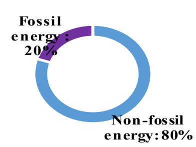
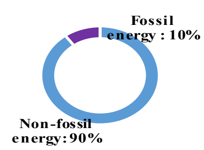
Figure 4: Emission Pathways for the Yangtze River Delta Region from 2020 to 2060 under Policy Scenario and Enhanced Carbon Neutrality Scenario

Note: Carbon removal includes forest carbon sinks and geological sequestration.



The future path toward low-carbon development will focus on key directions such as clean energy production, multi-energy complementary coordination, regional market integration, and enhanced power system flexibility. First, accelerate the reduction and clean utilization of "black energy," prudently leverage the peak-shaving support role of "blue energy" during the transition period, and comprehensively elevate the development level of "green energy." Promote large-scale construction of wind, solar, and nuclear power, actively explore the integrated development of distributed solar and offshore wind power, and gradually foster emerging industries such as hydrogen energy. Building on this foundation, leveraging the Yangtze River Delta's complete industrial chains, energy-intensive industries, and technological innovation strengths, we will promote multi-energy complementarity among electricity, gas, and hydrogen. This includes establishing a coordinated mechanism for generation, grid, load, and storage to enhance energy system operational efficiency and support the electrification of transportation, buildings, and industrial end-uses. Subsequently, deepen regional power market integration by refining spot, capacity, and ancillary service markets, expanding cross-provincial green power and mutual assistance transactions, and optimizing clean power allocation across broader regions to reinforce the Yangtze River Delta's pivotal role in China's energy landscape. Ultimately, accelerate the large-scale application of virtual power plants, energy storage, and demand response. Promote the implementation of low-carbon technologies such as CCUS and carbon sinks. Forge a new development paradigm featuring the coordinated advancement of "high-proportion clean energy + flexible resources." Consolidate the Yangtze River Delta's leading position in achieving peak carbon emissions first and advancing toward carbon neutrality.

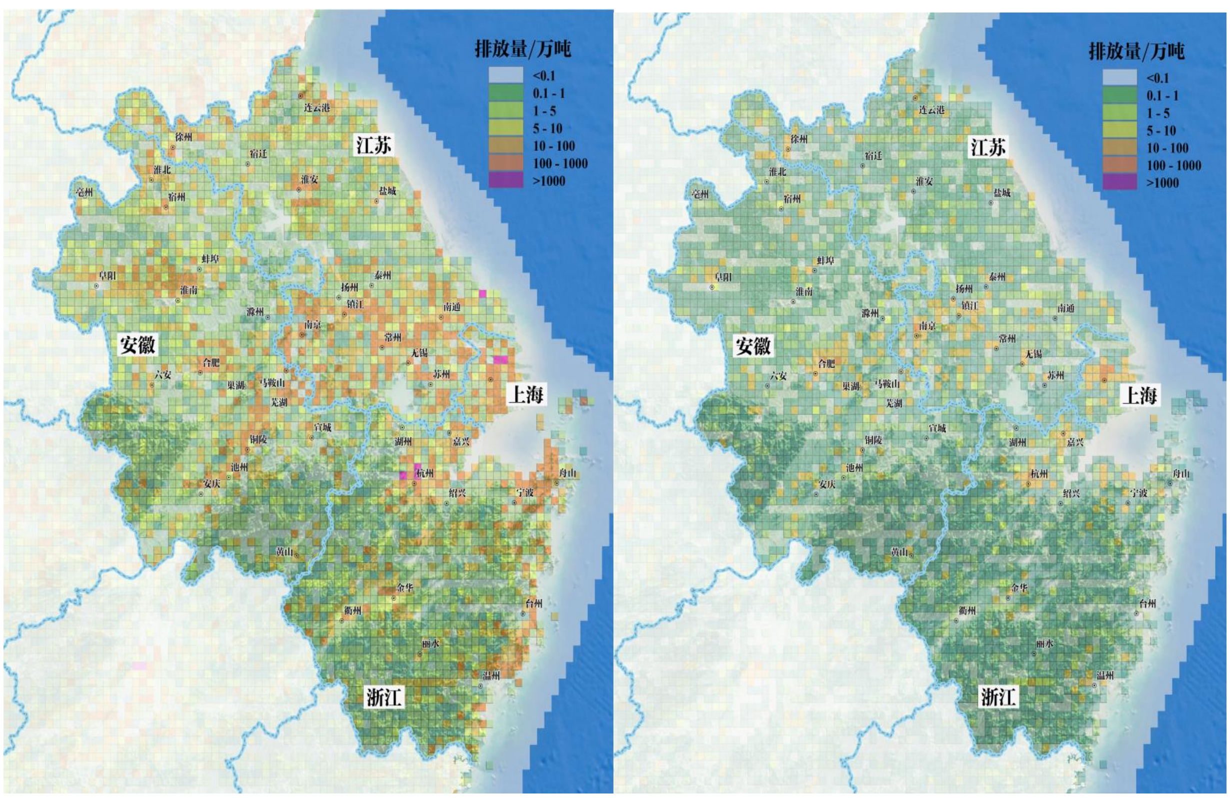
Table 1: Low-Carbon Development Pathway Targets for the Yangtze River Delta Region

Development Goals		2030 Grey energy	2035 Blue energy	2050 Green energy	2060 (Net) Zero CO2
Energy mix	Proportion				
	Terminal electrification	45%	55%	70%	90%
Multi-energy complementation		An initial coordinated system of electricity, gas, renewables, and nuclear has been established, with integrated source, grid, load, and storage demonstration projects widely deployed.	A integrated system of wind, solar, load, storage, and hydrogen has been established, supporting large-scale deployment of electrified transportation and hydrogen utilization.	The construction of energy corridors has significantly expanded, cross-regional transmission of electricity and hydrogen has been strengthened, and a low-carbon energy system has been established.	A comprehensive net-zero carbon energy system has been established, centered on wind and solar, complemented by nuclear power and hydrogen, and supported by energy storage and demand response.
Virtual Power Plant		Pilot virtual power plants have been launched in cities such as Shanghai and Nanjing, integrating distributed photovoltaics and energy storage.	Virtual power plants are being fully promoted in Hangzhou and Ningbo, establishing regional dispatch platforms, actively participating in electricity market transactions, and enhancing system flexibility and operational control.	Virtual power plants extensively cover industrial, commercial, and residential sectors, coordinating wind, solar, nuclear, and storage resources, enabling cross-regional optimized dispatch, and supporting high renewable energy penetration.	A comprehensive smart virtual power plant system has been established, centered on Shanghai for region-wide real-time regulation, making virtual power plants a key pillar of the carbon-neutral energy system.

By 2035, high-emission zones will primarily cluster in key economic hubs, encompassing Suzhou, Wuxi, and Changzhou in southern Jiangsu; Hangzhou and Jiaxing in Zhejiang; and Shanghai. These areas will become concentrated emission zones due to their high industrial density and population concentration. By 2060, the spatial pattern of emissions undergoes significant reshaping. First, the concentration of existing emission hotspots intensifies: the high-emission zone in southern Jiangsu (centered on Suzhou and Wuxi) continues to expand. Second, Anhui Province will experience particularly pronounced emission growth: the region radiating outward from Hefei as its core will see emission intensity increase from low to high (with color intensity deepening), directly linked to Anhui's role in undertaking more industrial development tasks within the Yangtze River Delta integration, making it an emerging high-emission area. Third, emissions from coastal cities in Zhejiang such as Ningbo, Taizhou, and Wenzhou will be significant, a change likely closely related to the rise of the marine economy and the expansion of coastal industries.

By 2035 and 2060, the spatial structure of emissions in the Yangtze River Delta exhibits two core characteristics: First, the concentration of emission hotspots increases; second, the scope of emissions expands both inland toward Anhui and toward coastal cities, reflecting adjustments in industrial layout and shifts in economic centers during the region's integration process.

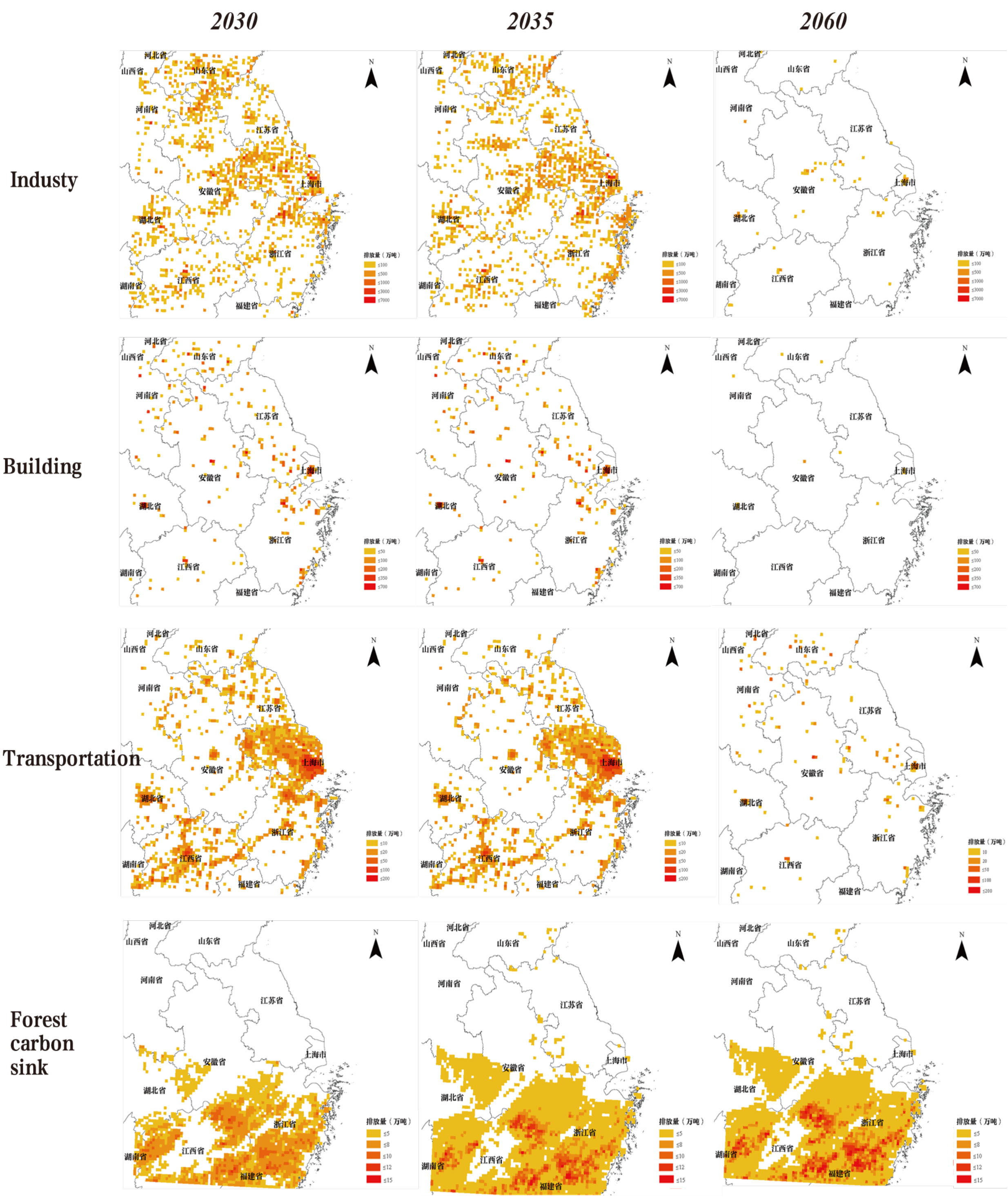
Figure 5: Spatial Structure of Carbon Emissions in the Yangtze River Delta Region (10 km) in 2035 (Left) and 2060 (Righ)



From 2030 to 2060, emission hotspots in the industrial, transportation, and construction sectors will gradually shrink and relocate due to industrial restructuring and urbanization. Forest carbon sinks and geological sequestration potential will rapidly increase, becoming the "ballast" for achieving carbon neutrality by 2060. By 2030, industrial emission hotspots will concentrate in economically developed regions like Shanghai and northern Zhejiang. As industrial restructuring reduces high-emission zones, only central Shanghai, central Anhui, and some northern Zhejiang cities will maintain emissions of 1–5 million tons by 2060. Emissions from the building sector align with urbanization trends, concentrating in the core areas of large and medium-sized cities in Zhejiang and southern Anhui between 2030 and 2060. As urbanization deepens, these hotspots will expand toward the peripheries of urban agglomerations. Emissions hotspots in the transportation sector are highly concentrated along major transport corridors such as the Beijing-Shanghai High-Speed Railway, Shanghai-Nanjing Intercity Railway, Shanghai-Hangzhou High-Speed Railway, and Shanghai-Kunming High-Speed Railway, exhibiting strong correlation with core population and economic clusters. By 2060, this emissions pattern is projected to undergo a fundamental transformation: emission hotspots will significantly diminish as the transportation sector achieves near-complete electrification, with hydrogen energy also seeing widespread adoption. In forest carbon sink areas, the core carbon sink regions in 2030 will exhibit a multi-point distribution pattern, primarily concentrated in areas with high vegetation coverage such as the entire province of Zhejiang and southern Anhui. These regions will play a crucial carbon sequestration role due to their robust ecological foundations. By 2060, with the sustained advancement of ecological projects such as large-scale afforestation, the scope of forest carbon sinks in Zhejiang will significantly expand, establishing the region as one of the nation's core focal points for forest carbon sequestration.

Regarding the assessment of biomass energy carbon capture and storage (BECCS) potential, the Yangtze River Delta region is projected to achieve cumulative CO_2 sequestration of 10.7 billion tons between 2020 and 2060. Jiangsu Province will lead the region in CO_2 capture and storage, with a cumulative storage volume reaching 7.42 billion tons. Due to the lack of suitable storage basins, Zhejiang Province and Shanghai will have extremely low CO_2 storage volumes under all scenarios.

Figure 6: Emission Distribution by Sector at 10km Grid Resolution for 2030, 2035, and 2060 under the Enhanced Carbon Neutrality Scenario

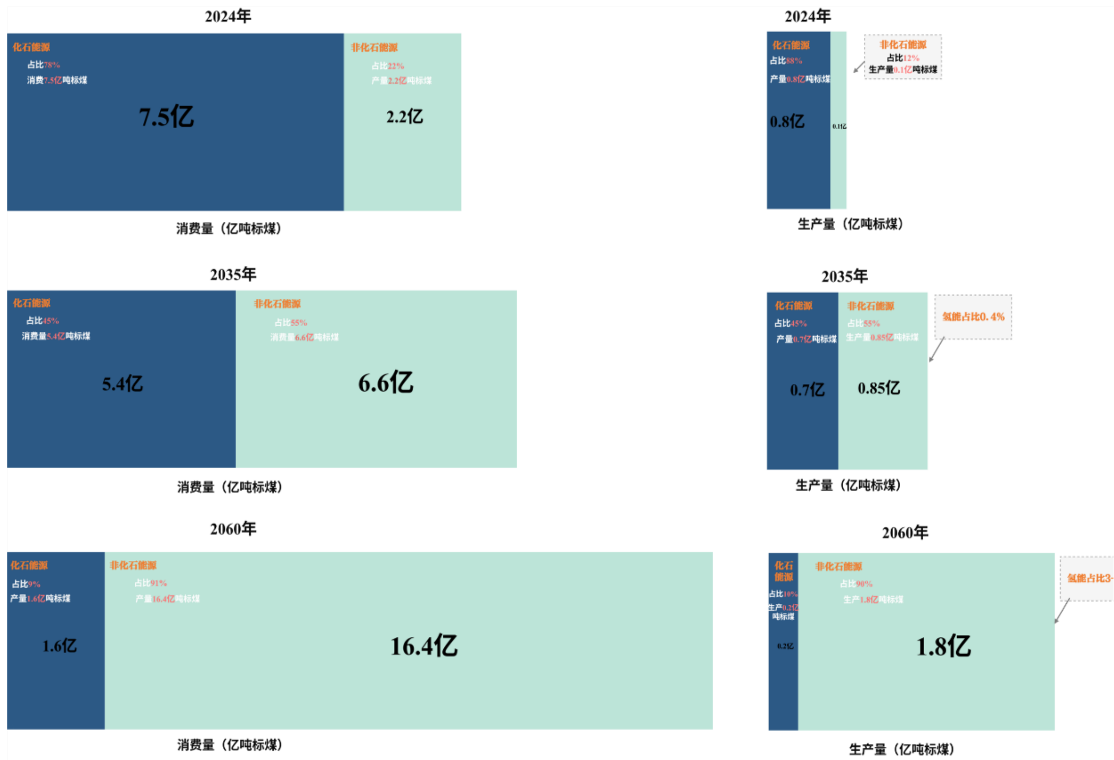


3.2 Energy Structure Transformation

Building upon a clear understanding of carbon emission trendsand composition within theYangtze River Deltaregion under the dual carbon goals, further analysis of energy structure transformation pathways tailored toregional realities is crucial for achieving carbon peak and carbon neutrality, By accelerating the transition towardcleaner and lower-carbon energy, leveraging the advantages of distributed clean energy, offshore wind power, andnyclear power. and promoting the coordinated development of electrification and multi-energy complementarity, we cansupport the green industrial upgrading and high-quality development of the Yangtze River Delta region, therebyachieving coordinated progress in economic growth, energy security, and environmental sustainability.

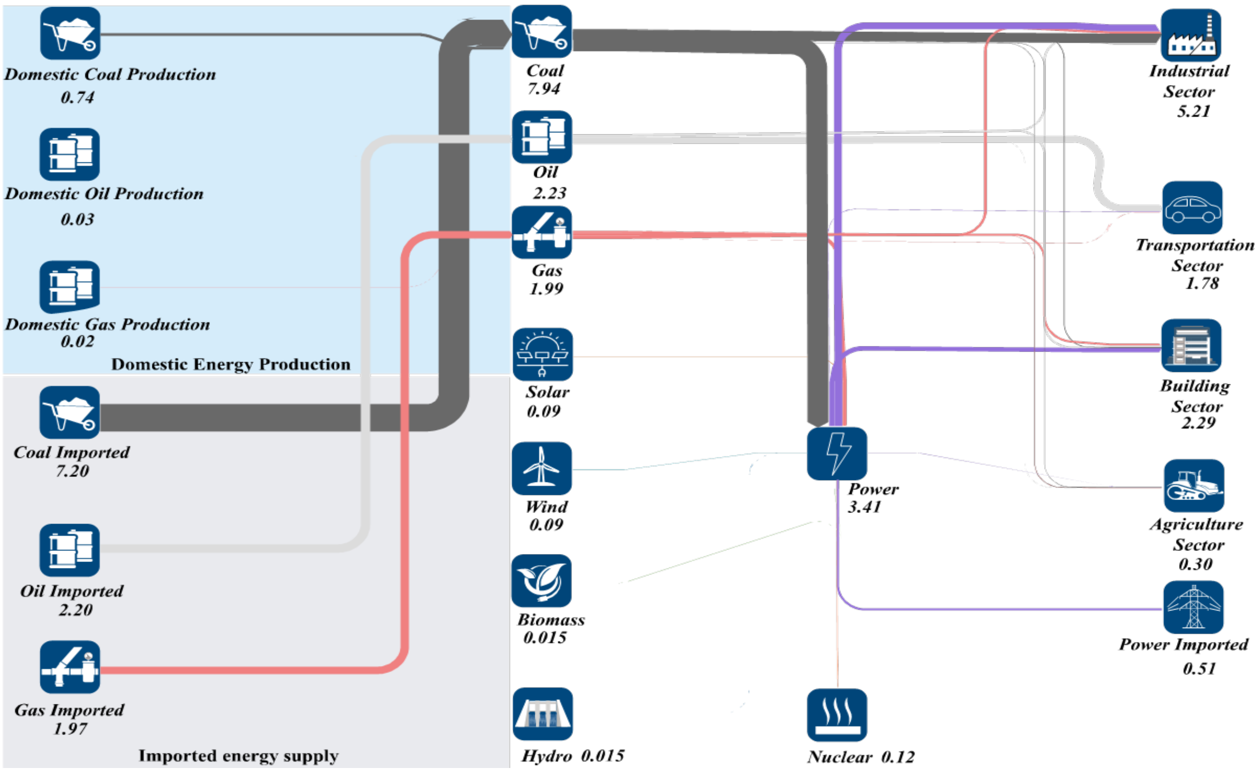
The green energy transition in the Yangtze River Delta region will be advanced in phases, gradually establishing a clean, low-carbon, safe, and efficient energy system to pioneer a national model for energy transformation. In 2024, the region's primary energy consumption reached approximately 970 million tons of standard coal equivalent, with fossil fuels accounting for a high 78% and non-fossil energy sources only 22%. Total energy production stood at just 90 million tons of standard coal equivalent, primarily from coal production in Anhui Province, with fossil fuels dominating at 88% of the total. This highlights the region's current fundamental pattern of "high consumption, low output, and fossil fuel dependence." Under strengthened carbon neutrality policies, by 2035, total energy consumption will rise to approximately 1.2 billion tons of standard coal—a 24% increase from 2024—while non-fossil energy's share will climb to 55%, becoming the dominant component in the consumption structure. Fossil energy's share will decrease to 45%. The energy production side will undergo a simultaneous structural transformation. Although the total production volume will remain low at 155 million tons of standard coal, the share of non-fossil energy will rise to 55%, significantly weakening coal's dominant position. By 2060, total consumption will further increase to approximately 1.8 billion tons of standard coal equivalent, with non-fossil energy sources accounting for a high 91% and fossil fuels reduced to just 9%, essentially achieving a decarbonized energy system. Production will rise to 200 million tons of standard coal equivalent, with non-fossil energy contributing nearly 90%, marking the deep greening of the regional energy supply system.

Figure 7: Energy Production and Consumption in the Yangtze River Delta Region for 2024, 2035, and 2060 Under an Enhanced Carbon Neutrality Pathway



In 2024, the energy landscape of the Yangtze River Delta region exhibited distinct characteristics of "high consumption, low production, and strong dependence." The region's total primary energy consumption reached 970 million tons of standard coal, while local production amounted to only 90 million tons of standard coal. This implies that a staggering 93% of energy must be imported from external sources, with coal, oil, and natural gas imports totaling approximately 720 million, 220 million, and 200 million tons of standard coal, respectively. Total electricity generation from wind, solar, hydropower, biomass, and nuclear sources amounted to 33 million tons of standard coal. In the sectoral terminal energy consumption structure, the industrial sector dominated as the primary energy consumer, accounting for 55%. Terminal energy consumption in the transportation, construction, and agriculture sectors stood at approximately 18 million, 23 million, and 3 million tons of standard coal, respectively. To achieve deep emission reductions and energy efficiency improvements, the Yangtze River Delta region urgently needs to implement multiple measures. These include increasing the share of non-fossil power generation, reducing power generation losses, accelerating the electrification of end-use sectors, and further increasing the proportion of clean power imported from other regions.

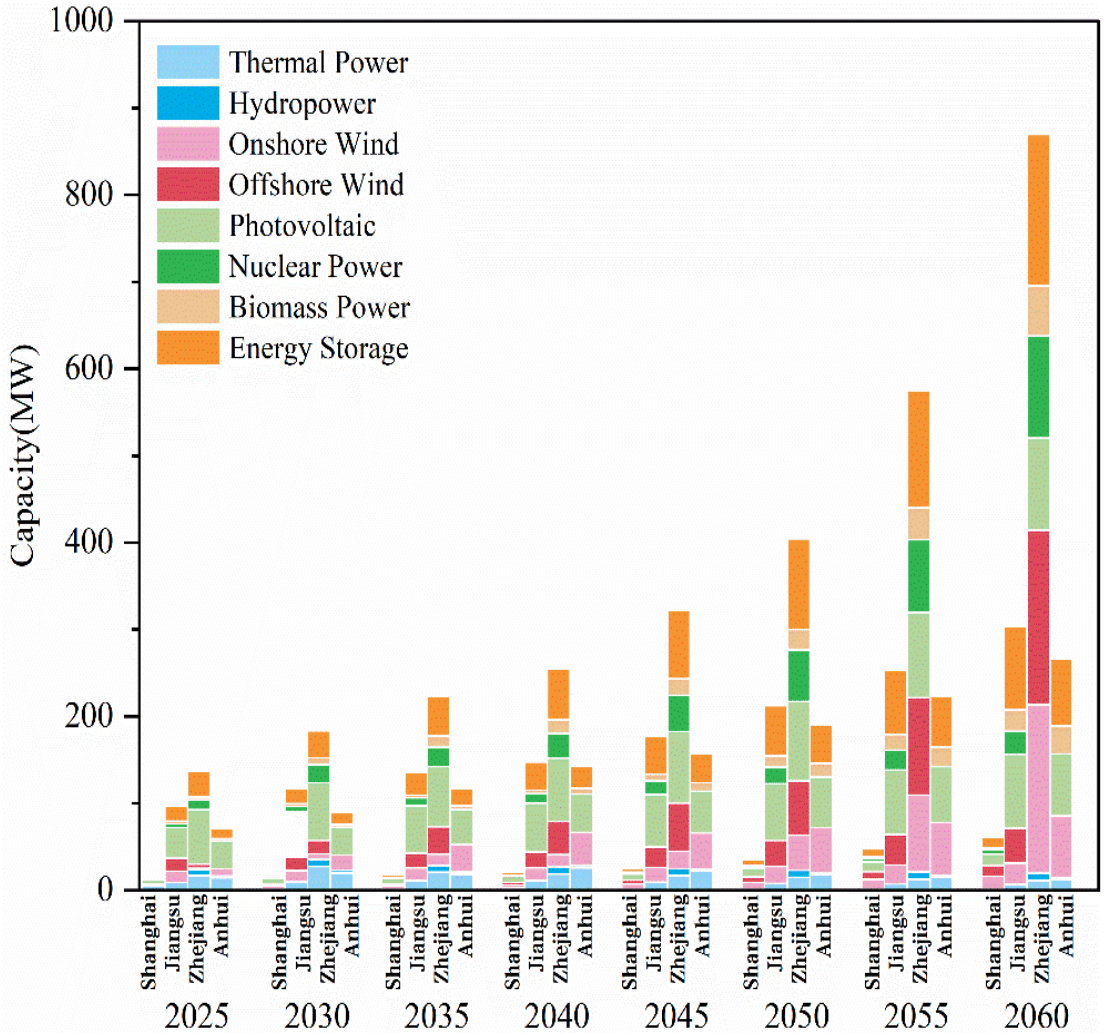
Figure 8: Energy Flow in the Yangtze River Delta Region in 2024 Under an Enhanced Carbon Neutrality Pathway



From a regional power generation perspective, Shanghai will still rely primarily on thermal power in 2025 (approximately 15.3 GWh, accounting for over 30%), supplemented by solar and wind power. By 2060, thermal power will decrease to less than 3 GWh (less than 2% of the total), while solar and wind power combined will exceed 59 GWh (over 80% of the total), making clean energy the absolute dominant source. Leveraging its coastal advantages, Jiangsu Province will see offshore wind power generation reach 42 GWh by 2025 and surge to nearly 410 GWh by 2060, becoming the regional power pillar. Nuclear power will grow steadily in parallel, rising from 36.9 GWh in 2025 to 217 GWh in 2060, maintaining a share of approximately 15%. Zhejiang Province will see faster nuclear power development, increasing from 91.7 GWh in 2025 to 767.9 GWh in 2060 (nearly 40% share). This will form a diversified clean energy mix alongside 403.9 GWh of photovoltaic power and 116.4 GWh of offshore wind power by 2060. Anhui Province, lacking suitable conditions for nuclear and offshore wind power, will primarily rely on photovoltaic (PV) power (growing from 31.6 GWh in 2025 to 337 GWh in 2060, accounting for nearly 60% of the total) and onshore wind power (accounting for 5–6%). Biomass power generation will remain steady at around 16–17 GWh (accounting for 3–4%).

Figure 9: Electricity Generation in the Yangtze River Delta Region Under Different Scenarios, 2025–2060

Note: Data sourced from the research findings of Xie et al., (2024)



3.3 Interregional Carbon Emission Interactions

Carbon emissions in the Yangtze River Delta exhibit a distinct "core consumption-peripheral production" pattern, with Shanghai serving as the primary net carbon import hub. Multi-regional input-output accounting reveals that 49% of Shanghai's carbon dioxide emissions from end-use consumption (construction, transportation, services, and residential living) originate from other provinces. This implies that nearly half of Shanghai's consumption-related emissions are generated through out-of-region production, highlighting the significant role of local consumption demand in driving production and carbon emissions in surrounding provinces. In contrast, Zhejiang, Jiangsu, and Anhui exhibit markedly lower external dependence for their consumption emissions, with out-of-region production-induced emissions accounting for less than 30% each. This disparity reveals the economic division of labor within the Yangtze River Delta: Shanghai's consumption-oriented core drives substantial production-end emissions across the regional industrial chain. In terms of emission pull effects, every ton of direct emissions generated locally in Shanghai further induces 1.3 tons in Zhejiang, 0.4 tons in Anhui, 0.4 tons in Jiangsu, and a combined 0.9 tons in other provinces/regions—totaling approximately 3 tons. This outcome reflects the highly vertical division of labor within the Yangtze River Delta's industrial chains and its tight economic ties, further confirming Shanghai's status as a quintessential "consumption-driven, externally emitted" region. Notably, Shanghai's central position within the Yangtze River Delta's carbon emissions landscape means that its emission reductions or peaking efforts hold decisive significance not only locally but also have the potential to drive emission reduction progress in surrounding provinces through industrial chain linkage effects.

Figure 10: Analysis of Carbon Emission Drivers Across Provinces and Municipalities in the Yangtze River Delta Region

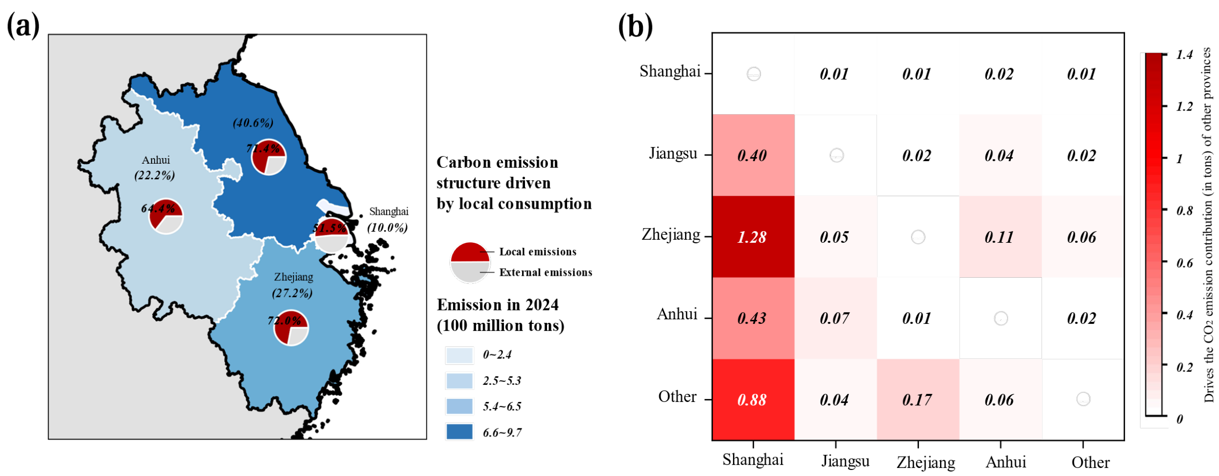
(a) Total carbon emissions in the Yangtze River Delta region and the structure of locally consumed carbon emissions in 2024; (b) Interactions among carbon emissions in the Yangtze River Delta region

Note 1: The pie chart in Figure (a) illustrates the carbon emission structure driven by consumption across provinces. The red portion represents local emissions corresponding to local consumption, while the gray portion indicates external emissions associated with local consumption.

Note 2: The percentages in parentheses in Figure (a) represent the proportion of the province's 2024 carbon emissions relative to the total carbon emissions of the Yangtze River Delta region.

Note 3: The color intensity in Figure (b) represents the unit area emission pull coefficient of the horizontal axis province on the vertical axis province. Specifically, it indicates the relative emissions increase in the vertical axis province for every 1-ton increase in CO_2 emissions from the horizontal axis province. Darker colors signify a stronger pull effect.

Note 4: "Other provinces and regions" in Figure (b) refers to the aggregate of all provinces and regions nationwide excluding the Yangtze River Delta region.

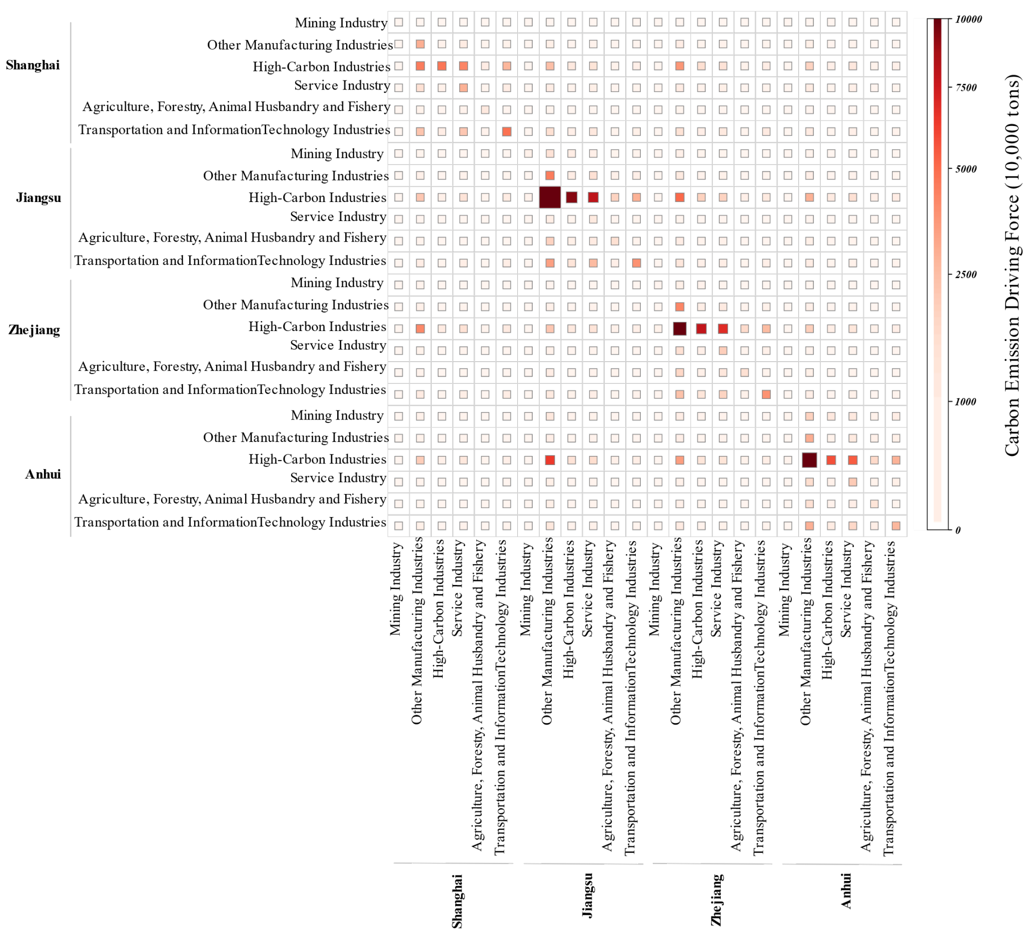


An Empirical Analysis of Interactions in Carbon Emissions Across Major Industries Among Provinces in the Yangtze River Delta Region (covering mining, high-carbon industries, other manufacturing, services, agriculture, forestry, animal husbandry, and fisheries, as well as transportation, warehousing, and information technology industries) reveals that other manufacturing and service activities within Jiangsu, Zhejiang, and Anhui provinces exert a significant pull effect on carbon emissions from high-carbon industries within their respective provinces. This phenomenon reveals the inherent logic whereby downstream consumer demand transmits through supply chain networks to upstream high-carbon production segments. Specifically, the scale expansion and demand growth of downstream industries directly stimulate capacity expansion in upstream high-carbon industries, thereby accelerating the accumulation of regional carbon emissions. Based on a systematic analysis of interprovincial linkages and carbon emission transmission mechanisms within the Yangtze River Delta region, future regional emission reduction policies must transcend the fragmented governance framework of individual provinces and shift toward a regional collaborative governance model. Specifically, leveraging upstream-downstream industrial chain coordination mechanisms, demand-side management tools should be strengthened: On one hand, cross-regional collaborative measures such as industrial structure optimization and unified technical standards should constrain emission intensity in upstream high-carbon industries. On the other hand, downstream service sectors and other manufacturing industries should be guided toward low-carbon consumption and green procurement practices, compelling upstream production processes to transition toward low-carbon operations from the demand side. Ultimately, this will provide systematic policy support for the Yangtze River Delta region to achieve its carbon peak and carbon neutrality goals on schedule.

Figure 11: Analysis of Carbon Emission Interactions Among Industries Across Provinces and Municipalities in the Yangtze River Delta Region

Note 1: The color intensity in the figure represents the magnitude of emission pull effects across provinces and industries on the vertical axis. Specifically, the horizontal axis shows how production activities in different provinces and industries drive direct carbon emissions across provinces and industries on the vertical axis. Darker colors indicate stronger pull effects.

Note 2: The high-carbon industries in the chart include heavy industries such as steel, cement, and chemicals. The transportation and information technology sectors encompass all transportation and information technology services, including warehousing, postal services, information transmission, and software.



3.4 Low-Carbon Collaborative Development of Key Industrial Chains

As the convergence point of national strategies and the economic anchor of the Yangtze River Delta region, its path to low-carbon transformation is not solely dependent on the rise of several emerging industries. Rather, it represents a systemic transformation involving the comprehensive integration of energy, manufacturing, consumption, and digital technologies.

(1) Global Hub for Integrated Energy Technology Innovation and System Solutions in "Green Energy—Smart Grid—Energy Storage Technology"

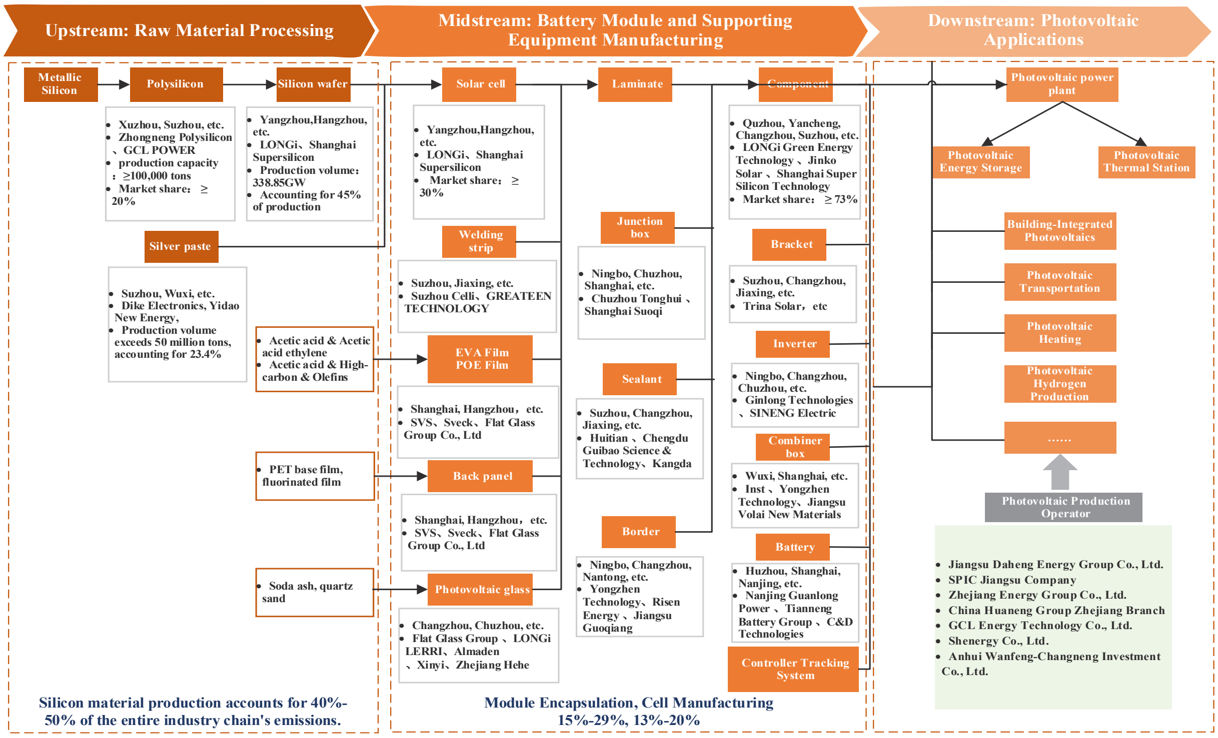
Positioned to become a globally leading hub for exporting green energy system solutions, the Yangtze River Delta region has transcended traditional manufacturing boundaries. It is driving the industrial chain's evolution from single-product manufacturing toward a closed-loop, full-value-chain ecosystem encompassing technical standard setting, core equipment R&D, system integration design, smart operation services, and green financial support. The region's robust photovoltaic and offshore wind power equipment manufacturing capabilities form the foundational support for this strategy. Its core strategic value lies in leveraging Shanghai's R&D innovation strengths, Jiangsu's smart manufacturing base, Zhejiang's digital economy momentum, and Anhui's application scenario support to integrate these dispersed "nodes" into a synergistic "network." This process requires prioritizing the development of integrated dispatch capabilities for distributed PV, deep-sea offshore wind power, next-generation nuclear energy, and diversified energy storage (including electrochemical storage and hydrogen storage). Building this capability relies on high-computing-power chips supplied by the integrated circuit industry, combined with advanced IoT technology and AI algorithms. This will create a regional "energy brain" and virtual power plant (VPP) network system enabling efficient coordination among generation, grid, load, and storage. Drive the industrial value chain to achieve a leap in capability from "product sales" to "service provision and standardization."

The Yangtze River Delta region has established the world's most comprehensive photovoltaic industry chain. Jiangsu Province accounts for over 40% of China's photovoltaic module production capacity, while its core segments—including silicon wafers and cells—have maintained the nation's top production volume for a decade. The Yancheng Photovoltaic Industrial Park has secured 68.5 GW of cell production capacity and 87 GW of module capacity, ranking among the country's leaders. Chuzhou, Anhui, holds a 20% share of China's photovoltaic glass market, while Yiwu, Zhejiang, has cultivated three leading enterprises with annual output values exceeding 10 billion yuan each, aiming to achieve a 100-billion-yuan output value scale by 2025. This industrial advantage stems from the precise division of labor: "R&D in Shanghai and Jiangsu, manufacturing in Anhui and Zhejiang." Shanghai focuses on technological innovation, Jiangsu specializes in module manufacturing, Jiaxing and Jinhua develop high-efficiency cells, while Chuzhou supplies key materials. Together, they form a complete chain covering polysilicon, wafers, cells, modules, and equipment. By 2024, the regional photovoltaic industry's revenue had already exceeded one trillion yuan.

Polysilicon production represents the primary carbon emission source within the photovoltaic manufacturing supply chain. Analyzing carbon emissions across photovoltaic production stages reveals that polysilicon manufacturing accounts for approximately 40% to 50% of total emissions, while cell manufacturing contributes 13% to 20%. Module encapsulation accounts for 15% to 29%, with equipment and facility operations contributing roughly 10% and 5%, respectively. This structure defines the focal points for coordinated emission reductions in the Yangtze River Delta region: Anhui should prioritize energy-saving technological upgrades in polysilicon production, Jiangsu should optimize manufacturing efficiency in module assembly, and Zhejiang can leverage digital technologies to enhance carbon management across the entiremanagement across the entire supply chain. By transferring Shanghai-developed N-type cell and perovskite technologies to manufacturing bases in Jiangsu, Zhejiang, and Anhui, the Yangtze River Delta is transforming its technological edge into low-carbon competitiveness. Jiangsu Times' "Lighthouse Factory" alone achieved a 38% energy efficiency boost through intelligent management.

Industrial chain synergy is the core competitiveness of the Yangtze River Delta's photovoltaic industry. A tiered division of labor has emerged within the region: Jiangsu dominates manufacturing segments such as modules, wafers, and cells; Shanghai focuses on cutting-edge R&D through the Yangtze River Delta National Technology Innovation Center; while Zhejiang and Anhui complement the ecosystem with specialty materials and application-oriented innovations. This synergy manifests in resource integration—optimizing power allocation through bundled transmission of wind, solar, and thermal energy—technological innovation—deploying distributed PV power forecasting systems covering over 900,000 households—and green transformation—where 40 enterprises achieved 57 million MWh of renewable energy utilization in 2024, reducing carbon dioxide equivalent emissions by over 32.55 million tons. Through industrial chain synergy, the Yangtze River Delta is transforming individual enterprises' carbon reduction efforts into systemic advantages across the entire value chain. This approach not only consolidates its leading position in photovoltaic manufacturing but also provides a replicable regional collaboration model for global energy transition.

Figure 12: Photovoltaic Industry Chain Structure in the Yangtze River Delta Region



(2)Build an end-toend industrial ecosystem for the electrification and hydrogenationend-use energyOfconsumption, spanning the entire chain from core materials to key components to end applications.

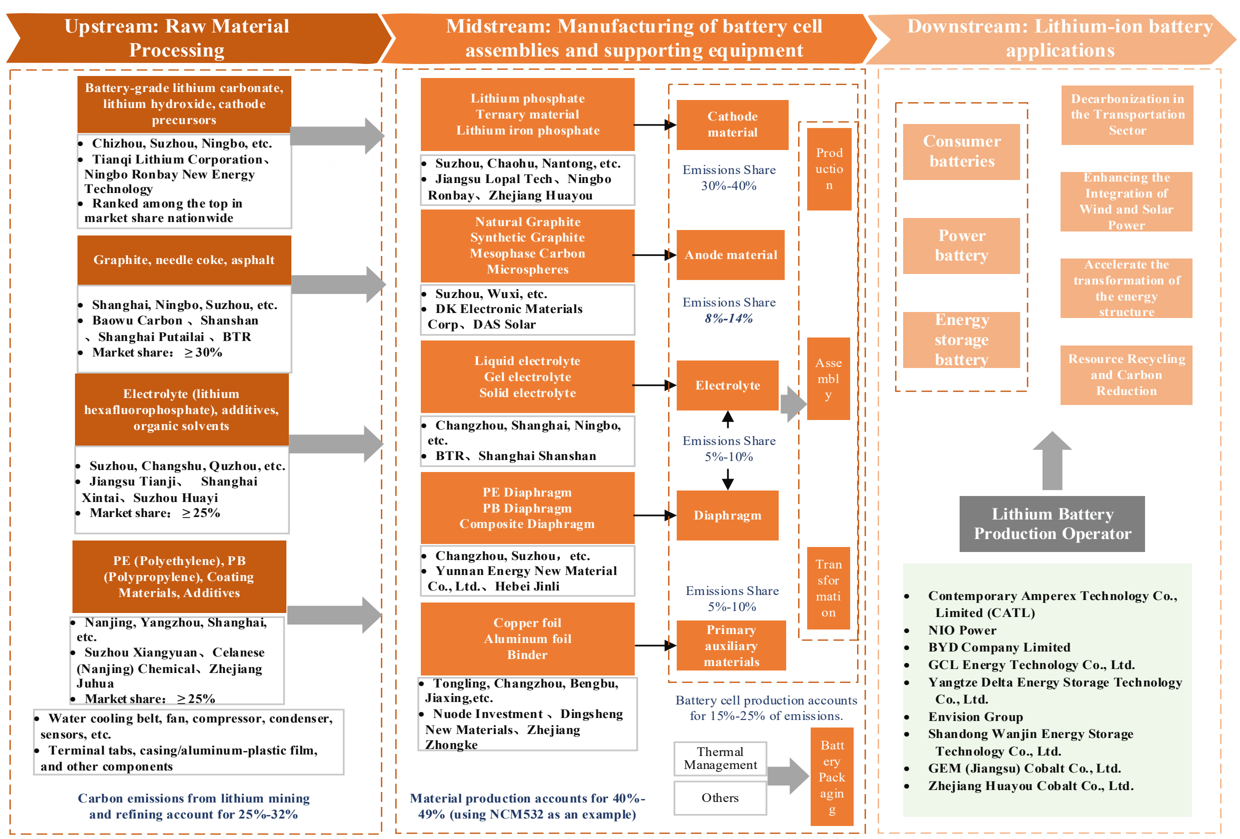
The emissions reduction process in the Yangtze River Delta region is rooted in its massive industrial and transportation energy consumption base, with the core focus being revolutionary substitutions in end-use energy patterns. The goal is to build an application ecosystem centered on electricity and hydrogen energy, comprehensively replacing fossil fuels across major energy-consuming sectors such as industry, transportation, and buildings. Its comprehensive manufacturing system presents both an emissions reduction challenge and a testing ground for the large-scale application of electrification and hydrogen technologies. The lithium battery industry serves as the pivotal lever for this energy consumption transformation. This not only lays the foundation for transportation electrification but also requires deep integration with traditional manufacturing, becoming the core support for the region's achievement of its dual carbon goals.

The lithium battery industry chain in the Yangtze River Delta region has preliminarily formed a closed-loop system encompassing "upstream materials—midstream manufacturing—downstream applications—end-of-life recycling." Taking Anhui as an example, Guoxuan High-Tech has established partnerships with automakers such as JAC Motors and Chery; Jiangsu has attracted clusters of upporting enterprises for positive and

negative electrode materials, electrolytes, and separators through battery manufacturers like CATL and Zhongxin Innovation; Zhejiang has strengthened its supply of ternary materials and cobalt-nickel resources by leveraging Rongbai Technology and Huayou Cobalt; Shanghai, meanwhile, has leveraged the traction of automakers like Tesla and SAIC to drive the coordinated development of batteries and vehicles.

The carbon emissions issue inherent to the lithium battery industry has become a critical juncture linking "industrial development" with the "dual carbon goals." Carbon emissions in lithium battery production primarily concentrate in raw material extraction, cathode material manufacturing, and cell assembly. Analyzing carbon emissions across lithium battery production stages reveals that mining and refining account for approximately 25%–32% of total emissions. The remaining emissions are distributed as follows: cathode materials (30%–40%), anode materials (15%–20%), electrolyte solutions (5%–10%), and cell manufacturing (15%–20%). In response, the Yangtze River Delta region is implementing measures such as promoting green manufacturing, improving recycling systems, and introducing renewable energy to reduce carbon emissions intensity per unit of production. By driving green industrial upgrades, the region is strengthening the foundation for its own low-carbon transition and safeguarding national energy security.

Figure 13: Structure of the Lithium Battery Industry Chain in the Yangtze River Delta Region



(3)Establish a three-in-one industrial digitalization and intelligent empowerment hub integrating high endchips, industrial software, and artificial intelligence.

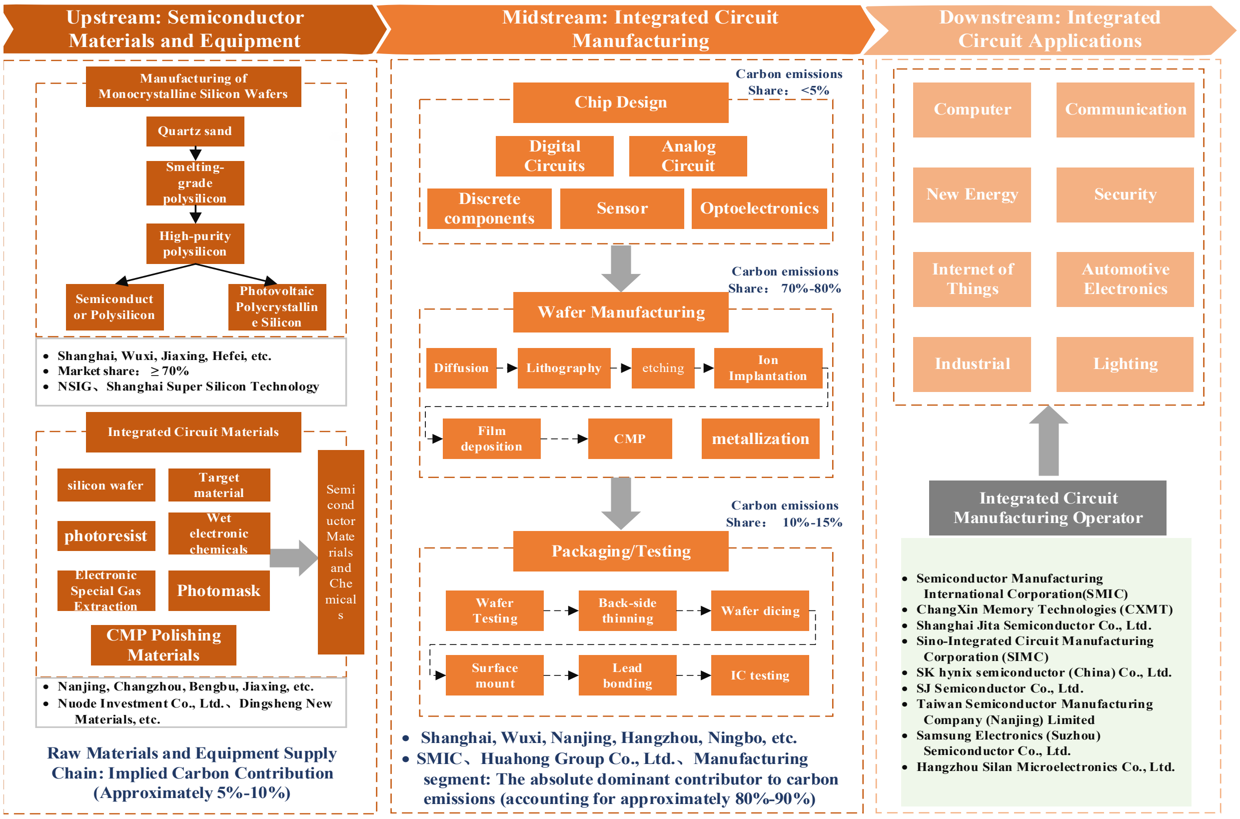
The optimal alignment of energy systems with the overall operational efficiency of the economy and society is a core challenge in the low-carbon transition process. The strategic value of the integrated circuit industry in the Yangtze River Delta region extends far beyond that of a single high-tech sector; at its core, it serves as the "central nervous system" underpinning the region's low-carbon transformation. Whether it involves the precise dispatch of smart grids, the optimization of terminal energy efficiency, or the intelligent manufacturing of emerging industries, all rely on the support of high-efficiency computing power, reliable sensing, and intelligent algorithms. Integrated circuits serve as the material carrier and technological foundation for realizing these functions. The industrial synergy pattern formed in the Yangtze River Delta—where "design is centered in Shanghai, packaging and testing in Jiangsu, materials in Zhejiang, and storage in Anhui"—has established an irreplaceable industrial foundation for fulfilling this enabling role. Priority should be given to developing core components such as power semiconductors, application-specific integrated circuits (ASICs), and sensors. These will provide essential control units for new energy generation, ultra-high voltage transmission, smart distribution grids, and energy storage systems, driving comprehensive digital and intelligent upgrades of energy infrastructure. Leveraging technologies like industrial internet and digital twins, we will digitally transform traditional high-energy-consumption industries throughout their entire lifecycle. By deploying high-density sensors and edge computing nodes in production environments, we will optimize process parameters in real time, predict equipment energy consumption, and achieve cascaded utilization of residual heat and pressure. This will maximize energy efficiency at the manufacturing stage and enable source control of carbon emissions.

Integrated circuit manufacturing plays a vital role in building a green and low-carbon society. It can contribute to achieving the dual carbon goals by optimizing energy efficiency, supporting renewable energy grid integration, and advancing smart grid technologies. First, at the product level, domestically produced high-end chips can reduce carbon emissions per unit of computing power or energy consumption by 15% to 30% in downstream applications such as data centers, new energy vehicles, and smart grids. Second, at the manufacturing level, regional collaboration has compressed the spatial radius of the "design-manufacturing-packaging and testing-equipment and materials" chain to within 150 kilometers. By 2025, this is expected to shorten average logistics distances by 20%, directly reducing transportation CO2 equivalent emissions by approximately 500,000 tons. Third, in the recycling phase, the Yangtze River Delta Semiconductor Resource Comprehensive Utilization Center—jointly established by Shanghai, Wuxi, Suzhou, and Hefei—has already increased the recovery rate of waste acid and waste copper liquid to 90% in 2023, corresponding to an annual reduction of 42,000 tons of carbon dioxide emissions.

The Yangtze River Delta has established a chain-based collaborative framework featuring "Shanghai's high-tech leadership, Jiangsu's manufacturing and packaging/testing, Zhejiang's analog and power sectors, and Anhui's storage and display industries." Shanghai dominates chip design and advanced manufacturing, with 2022 industry sales exceeding ¥300 billion, hosting leaders like SMIC and Hua Hong Group. Jiangsu possesses global competitiveness in packaging and testing, with companies such as Jiangsu Changjiang Electronics Technology and Tongfu Microelectronics ranking among the world's top ten. In the first three quarters of 2023, the packaging and testing sector generated revenue of ¥112.46 billion. Zhejiang focuses on semiconductor materials and design, with materials accounting for 41.4% of its 2022 output and Hangzhou's design sector contributing 84% of the province's total. Anhui has achieved breakthroughs in memory chips, with companies like Changxin Memory Technologies completing the regional industrial chain. This division of labor—Shanghai for design, Jiangsu for packaging and testing, Zhejiang for materials, and Anhui for memory—has laid the foundation for coordinated development in the integrated circuit industry.

Wafer fabrication is the primary source of carbon emissions in the integrated circuit industry. Examining carbon emissions across various stages of IC production reveals that the raw materials and equipment supply chain accounts for approximately 5% to 10% of emissions. Chip design, wafer fabrication, and packaging/testing contribute 3% to 5%, 70% to 80%, and 10% to 15% of emissions, respectively. Therefore, the core of carbon reduction in the integrated circuit industry lies in wafer fabrication. Due to the complexity and high energy-density processes such as lithography, thin-film deposition, and etching, this stage not only accounts for the highest proportion of the industry's overall energy consumption but also represents a key breakthrough point for achieving carbon reduction through technological optimization (e.g., application of energy-saving equipment, iteration of process parameters, substitution with green electricity). Its carbon reduction effectiveness directly determines the overall progress of the industry's low-carbon transformation. By establishing cross-provincial energy efficiency standards, sharing green energy supplies, and jointly developing low-carbon processes, the Yangtze River Delta region is transforming its industrial chain synergy into carbon reduction momentum, offering a "Chinese solution" for the global semiconductor industry's green transition.

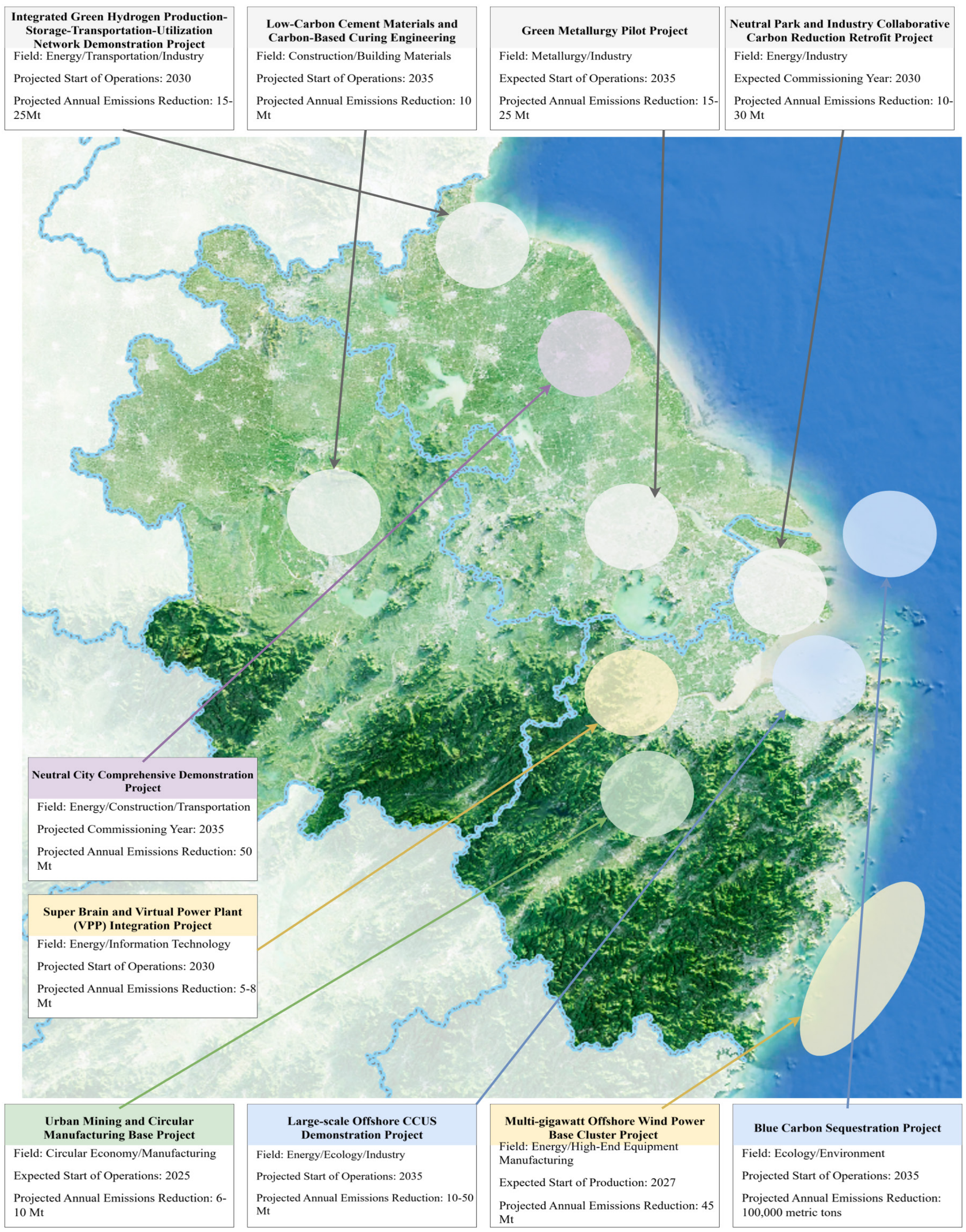
Figure 14: Integrated Circuit Production Industry Chain Structure in the Yangtze River Delta Region



3.5 Major Climate Engineering

Accelerate the implementation of a series of systemic and landmark climate projects. Based on the energyresource endowments and industrial characteristics of the Yangtze River Delta region, plan and implement maiorclimate projects with leading significance as key supports and pathway demonstrations for advancing the region'sachievement of its dual carbon goals.

Figure 15: Distribution of Major Climate Engineering Projects in the Yangtze River Delta Region



Yangtze River Delta Regional Integration Green Hydrogen "Production-Storage-Transportation-Utilization" Network Demonstration Project. Centered on constructing GW-scale water electrolysis hydrogen production plants and a regional hydrogen energy network, this initiative leverages offshore wind power and coastal photovoltaic bases to establish high-pressure gaseous and liquid hydrogen transmission pipelines between key industrial parks (e.g., chemical, steel) and port hubs. It also deploys a hydrogen refueling station network to achieve systematic hydrogen energy application demonstrations in industrial and transportation sectors. Key implementation measures include: constructing electrolytic hydrogen production plants, building hydrogen transmission and distribution networks along with refueling stations, and promoting demonstration applications of hydrogen in heavy-duty trucks, port machinery, metallurgical chemical processes, and distributed power generation. This will form a closed-loop regional hydrogen ecosystem encompassing production, storage, transmission, and utilization. This project serves as both a strategic initiative to transform energy consumption patterns and a core engine for high-end equipment manufacturing and green economic development: with a total investment of approximately 100-200 billion RMB, it is projected to replace fossil fuels in industrial and transportation sectors, achieving carbon dioxide emissions reductions of tens of millions of tons; It is projected to stimulate GDP growth of approximately 150-250 billion yuan and create 50,000 to 80,000 jobs. Simultaneously, it will drive the development of the entire industrial chain for electrolytic cells, hydrogen storage tanks, fuel cells, and hydrogen energy equipment, serving as a key solution for decarbonizing hard-to-abate industries.

Large-scale Offshore CCUS Demonstration Project in the Yangtze River Delta Region. Scheduled for implementation between 2025 and 2035, this initiative aims to establish an integrated offshore carbon sequestration system encompassing "capture-transport-storage-monitoring" for key emission sources in the Yangtze River Delta coastal areas, including thermal power plants, steel mills, chemical plants, and offshore oil and gas platforms. It seeks to address the challenge of deep emission reductions in coastal energy-intensive industries, support the region's carbon neutrality goals, and ensure the coordinated development of energy security and ecological conservation. Core initiatives include: deploying 20 carbon capture stations (with capture rates exceeding 90%) in key coastal zones; constructing 300 kilometers of subsea carbon transport pipelines and deploying 10 transport vessels to deliver CO_2 to deep saline aquifers in the Yangtze River Estuary and Hangzhou Bay (with over 1 billion tons of storage capacity) and abandoned oil and gas fields; installing subsea sensing and satellite monitoring systems for full lifecycle management; and establishing ecological buffer zones through numerical modeling with restoration and compensation measures. The project's total investment and industrial chain are projected to stimulate RMB 50-100 billion in GDP growth for the Yangtze River Delta region and create 25,000-45,000 jobs. It will annually sequester 10-50 million tons of carbon dioxide, ultimately establishing replicable technical standards and operational models. This initiative will serve as a national demonstration for coastal emissions reduction and solidify the Yangtze River Delta's leadership in low-carbon technologies.

Zero-Carbon Industrial Park and Industry Synergy Carbon Reduction Transformation Project in the Yangtze River Delta Region. Focusing on systematic zero-carbon transformation of industrial parks, 10–15 representative parks (e.g., chemical, steel, integrated circuit) will be selected. By deploying distributed wind-solar-storage systems, building park-level smart energy networks, and promoting efficient utilization of waste heat/pressure and material recycling, the initiative aims to achieve over 80% green electricity self-sufficiency within parks while driving collaborative carbon reduction among upstream and downstream enterprises in the industrial chain. The project will actively build distributed renewable energy and energy storage facilities, establish a smart energy management platform for the parks, and promote the recovery of waste heat and pressure as well as the recycling of industrial by-products. This will create a demonstration model for green energy self-sufficiency and collaborative carbon reduction across industrial chains. This initiative serves as both a strategic move for the industrial park's low-carbon transformation and a new engine for economic and employment growth: with a total investment of approximately RMB 80-180 billion, it is projected to reduce annual carbon dioxide equivalent emissions by 10-30 million tons, stimulate GDP growth of about RMB 250-350 billion, create 60,000-120,000 jobs, and foster emerging industries such as integrated energy services, energy-saving retrofits, and carbon management consulting.

Yangtze River Delta Zero-Carbon City Comprehensive Demonstration Project. This initiative tackles the two major carbon emission sources—buildings and transportation—through a systematic approach, creating a model for urban low-carbon transformation. Building Sector: Advance (near) zero-carbon retrofits for existing buildings, promote electricity substitution for gas, direct photovoltaic power supply, and intelligent control systems. Implement full-lifecycle (near) zero-carbon demonstrations in public buildings like schools and hospitals, utilizing low-carbon building materials and prefabricated construction. Integrate "photovoltaic-storage-direct-flexible" power systems and explore virtual power plant participation in peak shaving. Transportation Sector: Construct a three-dimensional coordinated network of "nodes-trunk lines-hubs"; deploy distributed PV-storage systems in zero-carbon logistics parks to achieve green energy self-sufficiency;

advance rail electrification and promote new energy medium-heavy trucks along zero-carbon freight corridors; upgrade clean energy facilities and green ground support equipment at zero-carbon ports and airports; establish a comprehensive carbon monitoring system. The total project investment and industrial chain are projected to stimulate 250-350 billion yuan in GDP for the Yangtze River Delta region, creating 60,000-120,000 professional jobs. Annual savings of billions in energy and environmental management expenditures will provide a replicable model for China's urban low-carbon development, serving regional high-quality growth and ecological security.

The Yangtze River Delta Region's Multi-Gigawatt Offshore Wind Power Base Cluster Project. Leveraging the region's abundant offshore wind resources (with near-shore technical potential exceeding 100 gigawatts), this initiative will establish a cluster of offshore wind farms spanning Yancheng and Nantong in Jiangsu, Ningbo and Wenzhou in Zhejiang, and Lingang in Shanghai. This will create a comprehensive system encompassing "offshore power generation—onshore consumption—industrial upgrading." By 2027, the Yangtze River Delta's nearshore wind power grid-connected capacity will exceed 30 gigawatts, with deep-sea demonstration projects reaching 5 gigawatts. Key initiatives include expanding megawatt-scale bases in Rudong and Dafeng, Jiangsu, piloting floating offshore wind power in Shengsi and Daishan, Zhejiang, and concurrently constructing supporting facilities like offshore substations and flexible DC transmission lines. Leveraging leading enterprises like Shanghai Electric and Goldwind, industrial parks for wind power equipment manufacturing will be established in Nantong, Yancheng, and other locations. This will achieve a domestic production rate exceeding 90% for core equipment including megawatt-class turbines (12 MW+), intelligent operation and maintenance systems, and submarine cables. Explore the "offshore wind power + marine ranching" model by deploying artificial reefs and deep-water fish cages around turbine foundations, achieving dual benefits of ecological conservation and economic returns. This initiative is projected to reduce annual carbon dioxide emissions by approximately 45 million tons, replace 13.5 million tons of coal-fired power generation, drive an annual industrial chain output value exceeding 200 billion yuan, and create over 100,000 jobs.

Yangtze River Delta Blue Carbon Carbon Sequestration Enhancement Project. Scheduled for implementation from 2026 to 2035, this initiative aims to systematically restore and expand coastal ecosystems such as the Yangtze Estuary salt marsh wetlands and seagrass beds. It seeks to significantly enhance their carbon sequestration capacity and ecological resilience, establishing a nationally leading blue carbon demonstration zone to support the Yangtze River Delta's carbon neutrality goals. The project will establish an integrated carbon sequestration system encompassing "survey and monitoring—

ecological restoration—carbon accounting—value realization," facilitating the conversion of blue carbon resources into ecological assets. It will conduct baseline surveys of blue carbon resources in the Yangtze Estuary, deploying over 100 monitoring stations to precisely track carbon flux and storage in salt marshes and seagrass beds; Focus on restoring 5,000 hectares of degraded wetlands in areas like Chongming East Beach and Jiuduan Sand, artificially planting dominant carbon-sequestering vegetation such as Spartina alterniflora and Phragmites australis to rebuild healthy food chains; Develop localized, high-precision carbon sink monitoring and accounting methodologies to create certifiable, tradable blue carbon products; Establish a blue carbon management and trading platform to integrate carbon credits into regional carbon markets, innovating ecological compensation and green finance models. The project's total investment and related industrial chain are projected to stimulate ¥10-20 billion in GDP growth across the Yangtze River Delta, creating 10,000-20,000 jobs in research, engineering, and conservation. By the project's completion, annual carbon sequestration capacity is expected to exceed 100,000 tons, significantly enhancing climate resilience and protecting biodiversity.

The Yangtze River Delta Region Energy "Super Brain" and Virtual Power Plant (VPP) Integration Project. Centered on building a region-wide smart energy dispatch and trading platform, this initiative leverages a "cloud-edge-end" architecture to aggregate distributed PV, energy storage units, EV charging stations, smart appliances, and industrial flexible loads into a multi-gigawatt virtual power plant capable of real-time interaction with the main grid. This enables intelligent management and efficient dispatch of the regional energy system. Installing smart terminals for millions of distributed energy sources and flexible loads establishes a comprehensive data collection, forecasting, and optimization control system. This creates a closed-loop regulatory capability for VPP-grid interaction, enhancing renewable energy integration capacity and system operational flexibility. This project serves as both a strategic initiative to enhance energy system intelligence and renewable energy integration, and a core engine for high-end technology industry development. With a total investment of approximately RMB 50-100 billion, it will indirectly reduce carbon emissions from thermal power peak shaving by about 5-8 million tons annually through intelligent dispatch. It is projected to stimulate regional GDP growth by approximately 60 to 90 billion yuan and create 20,000 to 40,000 jobs. Concurrently, it will accelerate the development of related industries such as high-end chips, communication modules, industrial software, and artificial intelligence algorithms, thereby enhancing regional energy technology competitiveness and industrial value-added.

Yangtze River Delta Urban Mining and Circular Manufacturing Base Project. Centered on establishing cross-city reverse logistics, high-purity recycling, and remanufacturing hubs, the initiative will designate 3-4 regional sites for prioritized development of electronics, batteries, copper, aluminum, and steel industries. It will establish a "re-certification standards + remanufacturing index" system and create a regional circular materials trading platform to achieve efficient recovery and recycling of urban mining resources. Construction will include reverse logistics networks, recycling and sorting centers, high-purity material extraction facilities, and remanufacturing production lines. This will drive efficient recovery and reuse of electronic waste, spent batteries, and metal materials, forming a closed-loop industrial system covering collection, processing, remanufacturing, and trading. This initiative serves as both a strategic measure to enhance resource utilization efficiency and circular economy standards, and a core driver for high-end manufacturing and green economic development: With a total investment of approximately RMB 30-70 billion, it is projected to achieve annual CO_2 equivalent emissions reductions of 6-10 million tons by 2035; It will stimulate 40–70 billion yuan in output value for the recycled metals and remanufacturing equipment industries, create 30,000–50,000 jobs, and simultaneously advance regional circular economy development and green industrial chain upgrades.

Low-Carbon Cement Materials and Carbon-Curing Engineering in the Yangtze River Delta Region. Focusing on reducing the clinker ratio, promoting the substitution of blended cementitious materials, and establishing a carbon dioxide-cured prefabricated component base (for prefabricated construction), this initiative covers Anhui, Zhejiang, and Jiangsu provinces. By integrating industrial symbiosis and waste heat recovery technologies, it achieves systematic upgrades across the cement and building materials industry chain. Establish low-carbon cement production and CO_2 curing prefabricated component bases to advance prefabricated construction applications. Integrate waste heat recovery and industrial symbiosis solutions to form a full-process low-carbon building materials system spanning raw material production, processing, and assembly applications. This project represents both a crucial strategic initiative for the low-carbon transformation of the construction and building materials industry and a vital engine for green economic and emerging industry development. With a total investment of approximately RMB 30-60 billion, it is projected to achieve annual CO_2 equivalent emissions reductions of 10-15 million tons by 2035. It will stimulate a market output value of 50 to 80 billion yuan in low-carbon building materials and prefabricated engineering contracting, create 20,000 to 30,000 jobs, and simultaneously advance the upgrading of the green building and building materials industry chain.

Green Metallurgy Pilot Project in the Yangtze River Delta Region. Centered on establishing 3 to 5 sets of 2-3 million-ton-scale green hydrogen direct reduced iron (H_2-DRI) and electric arc furnace (EAF) short-process production lines, this initiative spans Shanghai, Jiangsu, Zhejiang, and Anhui. By replacing traditional blast furnace long-process production with direct green power supply and waste heat recovery, it drives the low-carbon transformation of the steel industry. The project involves constructing green hydrogen direct reduced iron (DRI) production lines and scrap steel electric arc furnace (EAF) short-process lines, supported by direct green electricity supply and waste heat recovery systems. This will advance the electrification of steel production processes and hydrogen substitution while enhancing scrap steel recycling and circular utilization systems, thereby forming a closed-loop green steel industry chain. This project represents both a critical strategic initiative for carbon reduction and industrial upgrading in the steel sector and a core engine for green equipment manufacturing and circular economic development. With a total investment of approximately RMB 80-150 billion, it is projected to achieve annual CO_2 equivalent emissions reductions of 15-25 million tons by 2035. It will stimulate approximately 100-150 billion yuan in output value across electrolytic cells,hydrogen storage and transportation, EAF equipment, and scrap steel recycling industries, creating 30,000 to 50,000 jobs while advancing the steel sector's green transformation and high-end equipment upgrades.

Table 2:Top Ten Key Carbon Reduction Projects (2025–2035)

Serial Number	Project Name	Construction Site	Investment scale (in billions)	Departmental Areas	Projected Year of Production Production Production Production	Projected Emission Reduction (10,000 tons)	drive job creation (10,000 people)	GDP Growth(in billions of yuan)
1	Yangtze River Delta Regional Integration Green Hydrogen "Production-Storage-Transportation-Utilization" Network Demonstration Engineering	Key coastal industrial parks and port hubs	1000~2000	Energy, Transportation, Industrial Transportation, Transportation, Industrial	2030	1000	5~8	1500~2500
2	Large-Scale Demonstration Project for Offshore Carbon Capture, Utilization, and Storage in the Yangtze River Delta Region	Yangtze River Estuary, Hangzhou Bay Coastal	1000~1500	Energy, Industry, Ecology	2025~2035	1000~5000	2.5~4.5	500~1000
3	Zero-Carbon Industrial Parks and Collaborative Carbon Reduction Transformation Project in the Yangtze River Delta Region	10–15 industrial parks (e.g., chemical, steel, integrated circuit, etc.)	800~1800	Industry, Energy	2030	1000~3000	6~12	2500~3500

Serial Number	Project Name	Construction Site	Investment scale (in billions)	Departmental Areas	Projected Year of Production Production Production Production	Projected Emission Reduction (10,000 tons)	drive job creation (10,000 people)	GDP Growth(in billions of yuan)
4	Yangtze River Delta Zero-Carbon City Comprehensive Demonstration Project	Urban (Architecture and Transportation Sector)	1500~2500	Architecture, Transportation	2035	5000	6~12	2500~3500
5	Yangtze River Delta Region's Multi-Gigawatt Offshore Wind Power Base Cluster Engineering	Yancheng and Nantong in Jiangsu Province; Ningbo and Wenzhou in Zhejiang Province; Lingang in Shanghai; etc.	2500~3500	Energy, High-End Equipment Manufacturing	2027	4500	>10	2000
6	Blue Carbon in the Yangtze River Delta Region Increased Foreign Exchange Earnings Project	Yangtze River Estuary salt marsh wetlands, seagrass beds, and other coastal ecosystems	75~150	Ecology, Environment	2026~2035	Over 100,000	1~2	100~200
7	Yangtze River Delta Region Energy "Super Brain" and Virtual Power Plant (VPP) Integrated Engineering	Yangtze River Delta region	500~1000	Energy, Information Technology	2030	500~800	2~4	600~900
8	Yangtze River Delta Urban Mining and Circular Manufacturing Base Project	Key Cities in the Region	300~700	Circular Economy, Manufacturing	2025	600~1000	3~5	400~700
9	Low-Carbon Cement Materials and Carbon Curing in the Yangtze River Delta Region Engineering	Anhui, Zhejiang, and Jiangsu regions	300~600	Construction, Building Materials	2035	1000~1500	2~3	500~800
10	Green Metallurgy Pilot Project in the Yangtze River Delta Region	Yangtze River Delta region	800~1500	Metallurgy, Industry	2035	1500~2500	3~5	1000~1500

3.6 Funding Requirements

Capital investment is the key support for ensuring the timely achievement of the dual carbon goals. Systematically calculating and optimizing the scale and composition of capital investment facilitates the scientific allocation of resources, coordinates low-carbon transition demands across energy, industry, and technology sectors, and provides robust financial backing for the green transformation and implementation of the dual carbon goals in the Yangtze River Delta region.

From 2025 to 2030, the Yangtze River Delta region is projected to require a total of 7.05 trillion yuan to achieve its carbon neutrality goals. The energy sector will be the largest source of funding demand, reaching 3.67 trillion yuan and accounting for over 50% of the total demand. This indicates that optimizing the energy structure and investing in clean energy technologies are core tasks during the initial phase of carbon neutrality. The industrial and construction sectors follow, with funding requirements of 1.32 trillion yuan and 0.93 trillion yuan respectively. This

Figure 16: Cumulative Capital Requirements Under the Enhanced Carbon Neutrality Scenario, 2020–2060 (trillion RMB)

reflects that green transformation of industrial production processes and enhancing building energy efficiency represent key carbon reduction directions during this period. In contrast, carbon removal technologies receive relatively limited investment at this stage, as related technologies remain in their infancy or R&D phase, with large-scale application yet to commence.

From 2031 to 2060, the total funding requirement for achieving carbon neutrality in the Yangtze River Delta region will surge significantly to 63 trillion yuan. Compared to the previous phase, funding needs across all sectors will increase substantially. The energy sector remains the primary driver of funding demand, reaching 2.89 trillion yuan. Notably, funding requirements for transportation and carbon removal technologies will surge dramatically. Transportation funding will skyrocket to 9.72 trillion yuan, signaling accelerated electrification, intelligent transportation system development, and widespread adoption of new energy vehicles during this period. Funding requirements for carbon removal technologies have surged from 44.2 billion yuan in the previous phase to 1.59 trillion yuan. As technologies mature, negative emission techniques like CCUS will become indispensable tools for deep decarbonization. Overall, this structural shift in funding demands indicates that as the carbon neutrality process deepens, the focus of emissions reduction will gradually expand beyond the initial energy transition to broader sectors such as transportation and carbon removal.

Table 3: Estimated Cumulative Capital Requirements for the Yangtze River Delta Region Under an Enhanced Carbon Neutrality Pathway, 2025–2060 (RMB billion)

Departmental Areas	2025~2030	2031~2060
Industrial	13222	100548
Architecture	9326	72657
Transportation	4980	97249
Energy	36731	289284
Agriculture	5794	54346
Carbon removal	442	15913
Total	70500	630000

IV

Policy Recommendations

04

POLICY IMPLICATIONS

(1)Establish a new integrated regional carbon management system under the new circumstances

Pioneer the establishment of a new regional system for total emissions control and market-based allocation inthe Yangtze River Delta region, featuring a three-tiered coordination mechanism of "regional carbon budgetmetropolitan carbon credits enterprise carbon guotas," This initiative aims to create a pressure testing zone fordeepening national carbon market reforms and a high ground for institutional innovation.

First, at the regional level, establish the nation's first cross-provincial "Yangtze River Delta Carbon Budget Management System." Set aggregate targets to achieve net-zero growth during the 15th Five-Year Plan period and comprehensive reduction during the 16th Five-Year Plan period. These aggregate targets will be broken down into tradable "metropolitan carbon credits."

Second, at the metropolitan area level, an innovative "bubble mechanism" for carbon totals has been introduced. In major metropolitan areas (including the Nanjing, Hangzhou, Suzhou-Wuxi-Changzhou, Hefei, Ningbo, and Shanghai metropolitan areas), the metropolitan area is designated as the smallest governance unit. This approach aligns with the Yangtze River Delta's unique "cooperative-competitive integration" model, overcoming the limitations of existing carbon markets that only cover the enterprise level. It allows for mutual quota assistance and optimized allocation between metropolitan areas while connecting to the national carbon market, achieving dual-level linkage between the enterprise and regional levels. This approach connects enterprises to the national carbon market, activates local governments' motivation for emission reductions at the metropolitan level, and enables cross-provincial coordination at the regional level. It establishes a three-tiered management model: "enterprise carbon compliance → metropolitan carbon pool → regional carbon clearing."

Finally, to ensure the system operates efficiently, establish market and regulatory infrastructure. Leverage Shanghai's financial hub advantages to build the "Yangtze River Delta Carbon Credit Trading and Clearing Center," providing real-time matching, risk hedging, and green finance services to form a complete closed-loop system encompassing "carbon price discovery—carbon credit circulation—carbon debt clearing." The "bubble-based" total control approach allows flexible internal adjustments within regions, ensuring rigid adherence to overall targets while stimulating local innovation. A digital supervision platform for carbon budget execution in the Yangtze River Delta will be built, integrating IoT monitoring, blockchain evidence storage, and big data analytics to achieve full visibility, verifiability, and traceability throughout the carbon budget implementation process.

(2) Innovating a new model for coordinated emissions reduction across the entire industrial chain, driven by leading enterprises

Establish a "chain-leader-driven industrial chain carbon governance system" based on advantageous industr ialclusters, Leverage the carbon responsibility system of chain-leading enterprises to drive systematic decarbonizationacross supply chains, thereby building a strategic fulcrum for enhancing the green competitiveness of China'sindustrial chains.

The core initiative involves implementing an innovative "carbon chain leader system" management mechanism within strategic industrial clusters such as photovoltaics, lithium batteries, and integrated circuits in the Yangtze River Delta region, based on the national carbon footprint management strategy. Leading enterprises serve as "carbon chain leaders," assuming primary responsibility for driving coordinated emissions reduction across the entire industrial chain. The core mechanism involves establishing a "Key Segment Carbon Coefficient" management system. This system focuses on high-emission critical segments, enabling low-cost control of the entire chain's carbon footprint through a small number of highly sensitive parameters. Chain-leading enterprises are responsible for ensuring their Tier 1 and Tier 2 suppliers meet key segment carbon coefficient targets, achieve specified green electricity usage rates, and maintain unit product carbon intensity benchmarks. They transmit emission reduction pressure through market-based tools such as "green procurement agreements, technology empowerment platforms, and supply chain carbon finance."

To ensure the sustainability of this model, the government provides differentiated policy incentives. Leading enterprises in the supply chain can obtain priority access to carbon quotas, guaranteed green electricity supply, and subsidies for technological upgrades. Qualified suppliers benefit from preferential energy usage rights and reduced financing costs. Establish a "Chain Carbon Performance Index" to integrate it into corporate Environmental, Social, and Governance (ESG) ratings and government industrial policy evaluations, creating a virtuous cycle of "chain leader traction—supplier responsiveness—government incentives—market recognition." Shift from "one policy per enterprise" to "one policy per industrial chain," driving systemic emissions reduction through an industrial ecosystem lens. This approach reduces compliance costs for SMEs while reinforcing the global competitive edge of critical industrial chains.

This model deeply integrates regional governance with industrial governance, using metropolitan areas as governance units. It simultaneously incorporates key carbon coefficients into urban industrial policies, factor allocation, and financial incentives (such as green electricity consumption, energy rights, and technical renovation loans), forming a closed-loop transmission system of "chain leader—supplier—metropolitan area." Within the Yangtze River Delta's highly homogeneous industrial landscape characterized by pronounced competition and cooperation, this approach achieves higher-intensity systemic emissions reductions at lower costs.

(3) Forging a new international framework for climate technology and carbon standards that connects the world

Establish the Yangtze River Delta region as a global climate technology hub for dual circulation and aninternational carbon standard export hub, building a technology sovereignty system that integrates "technologyintroduction and assimilationocal innovation standard export-global promotion."

Transform the Yangtze River Delta region into a "two-way converter" connecting global and Chinese climate technologies and a "source of standards." To promote the "internal circulation," establish an international climate technology launch platform. Benchmarking against cutting-edge European and American technologies such as hydrogen energy, CCUS, and virtual power plants, create dedicated technology sandbox zones in the Yangtze River Delta. These zones will provide real-world scenarios, open data access, and fault-tolerant mechanisms to accelerate the localized validation and scaled application of international technologies, serving as testing grounds before nationwide rollout. To lead the "external circulation," China will focus on building an "international certification system for Chinese carbon standards." Successful national practices in areas like zero-carbon transformation of industrial parks, carbon management across industrial chains, and urban carbon management will be distilled into proprietary technical standards, certification systems, and comprehensive solutions. Leveraging platforms such as the Belt and Road Green Development International Alliance, China will promote its standards as international norms. Establish a complete chain of "technology introduction—scenario validation—standardization—international export," complemented by the establishment of the "Yangtze River Delta Climate Technology Property Rights Exchange" and the "International Carbon Standard Certification Center." By securing control over standard-setting and certification authority, achieve a strategic shift from technology follower to rule leader. Transform the Yangtze River Delta into a base for exporting "Chinese solutions" within the global climate governance system, enhancing China's voice in shaping global carbon markets and green trade rules.

V

Research Methods

05

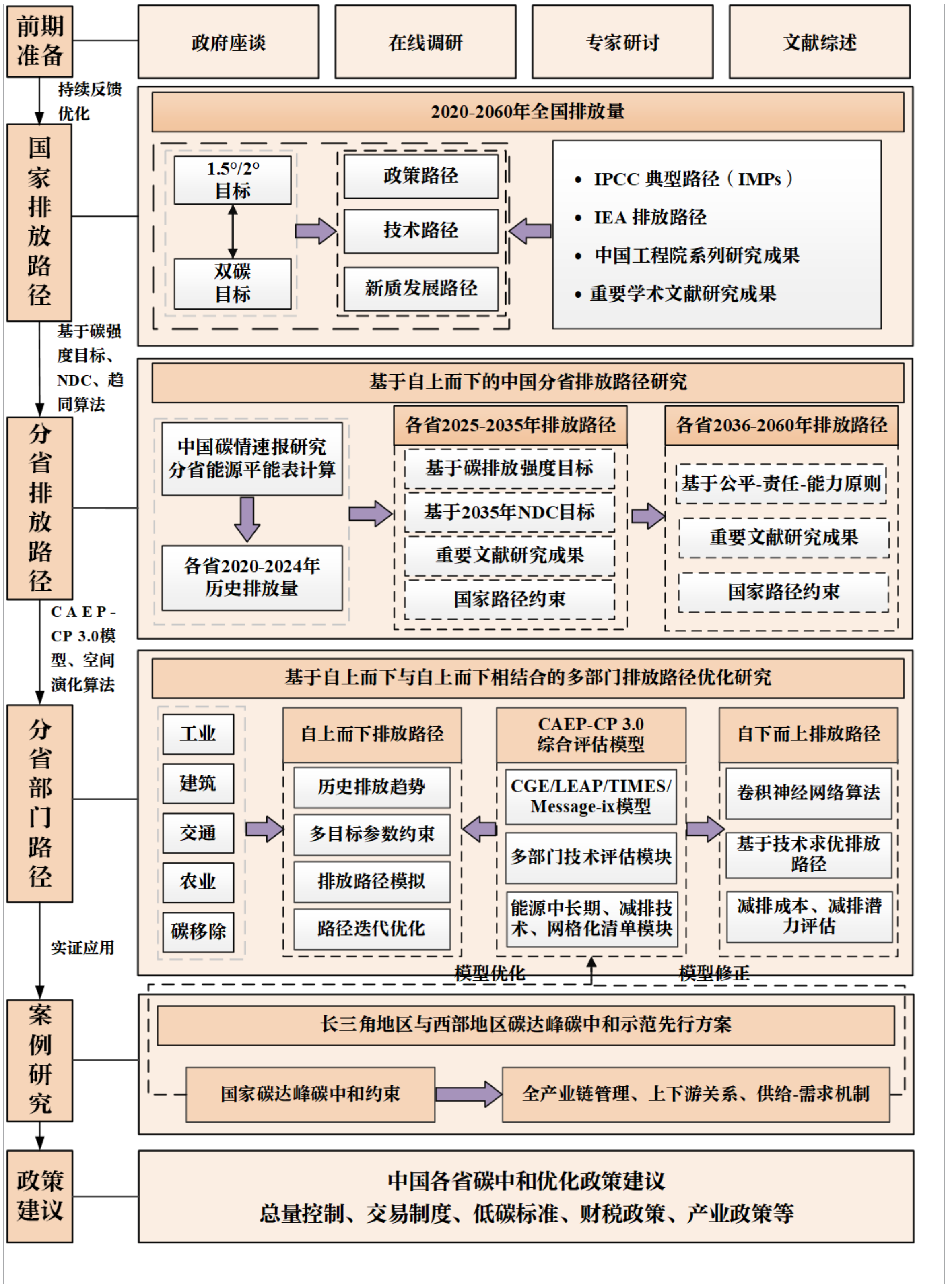
METHODS

This study represents a core applied outcome of the special project "Major Fundamental Scientific Issues and Countermeasures for National Carbon Neutrality" (72140004). It addresses practical implementation challenges in regional carbon emission pathway research. The study innovatively proposes a multi-level emission pathway optimization methodology system spanning "national-provincial-sectoral" tiers, establishing the China Comprehensive Assessment Model for Regional Coordination of Peak Carbon and Carbon Neutrality Pathways (CAEP-CP 3.0). This model integrates multidisciplinary theories with cutting-edge artificial intelligence technologies and incorporates the CGE (Contingent General Equilibrium) framework to analyze the comprehensive impact of macroeconomic policies and industrial restructuring on regional carbon emissions. Through dynamic simulation, technical optimization, scenario analysis, and emission reduction assessment functions, it establishes a standardized, scientific evaluation system that provides robust support for advancing China's dual carbon goals.

5.1 Research Technical Approach

The research methodology systematically integrates cutting-edge findings from authoritative domestic and international institutions such as the IPCC, IEA, and the Chinese Academy of Engineering, within the framework of national carbon peaking and carbon neutrality goals alongside socioeconomic development. It comprehensively considers multidimensional factors including historical emission characteristics, GDP growth rates, industrial structure, upstream-downstream industrial linkages, emission reduction technologies, energy consumption patterns, and renewable energy development. Methodologically, it employs a dual constraint of cost-optimality and social equity, coupling a bottom-up model grounded in spatial evolution theory with a top-down approach based on the CGE model. Notably, the integration of the CGE model enables deeper simulation of how factors like carbon market pricing mechanisms and resource endowment conditions impact the economic system, thereby facilitating more accurate assessments of socioeconomic costs and benefits across different emission reduction pathways.Furthermore, through field research, government interviews, and expert workshops, the model underwent iterative validation and optimization. This culminated in the development of multi-scale emission optimization pathways for 2020–2060 covering national, provincial, and key sectoral levels (e.g., industry, buildings, transportation, agriculture). Based on model simulations and case studies, the research provides scientific support for the National Carbon Neutrality Pilot Demonstration Zone Special Plan and further proposes policy recommendations for regional resource optimization and coordinated management.

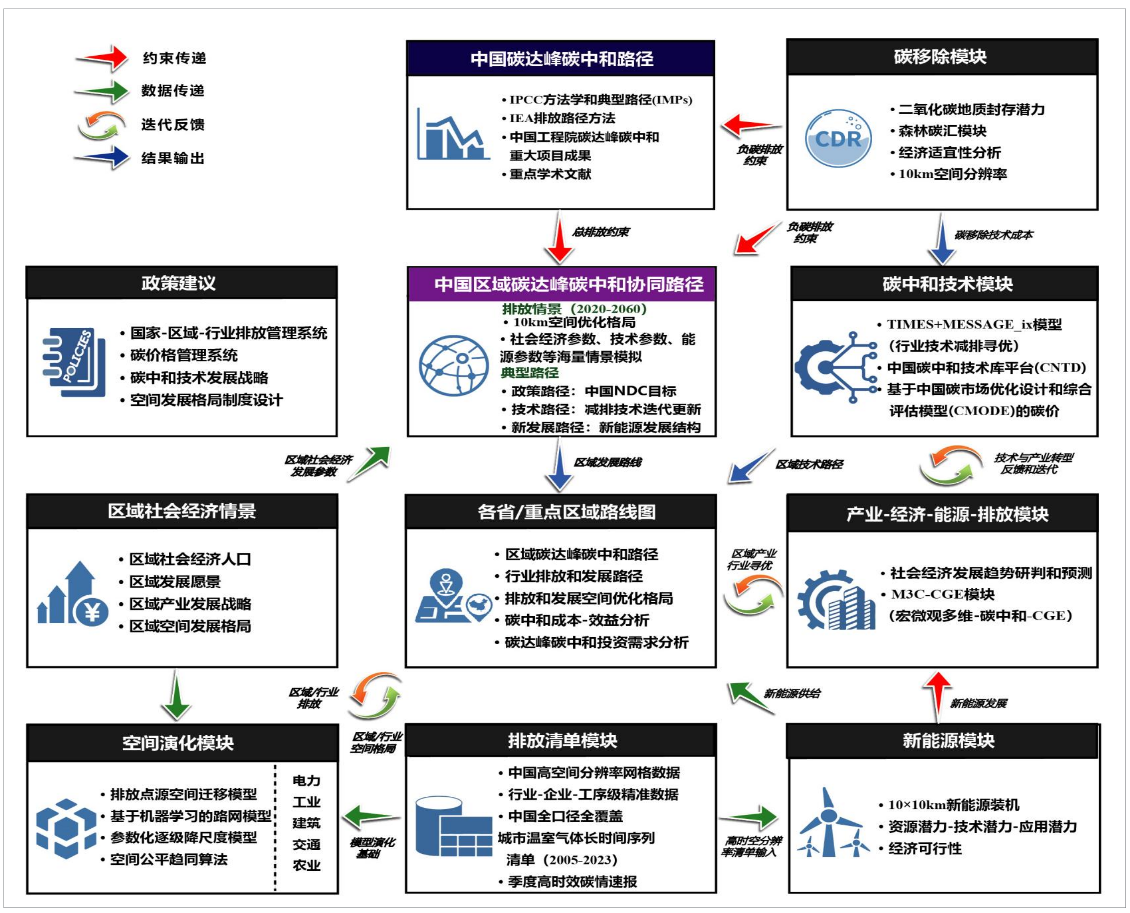
Figure 17: Technology Roadmap



5.2 Comprehensive Evaluation Model for Optimizing Regional Coordination Pathways Toward China's Carbon Peaking and Carbon Neutrality Goals

Adopting a combined top-down and bottom-up optimization analysis approach, with the national carbon peaking and carbon neutrality pathway as the overarching constraint, we establish a dynamic coordination mechanism for regional (provincial) and sectoral carbon emissions. This forms a three-tiered, interconnected optimization framework—national, regional, and sectoral—to scientifically evaluate and optimize China's progress toward achieving its national carbon peaking and carbon neutrality goals. We analyze the coordination among regions (provinces, autonomous regions, and municipalities) Solve for regional coordinated emission reduction strategies that maximize cost efficiency or social welfare under multiple constraints, ensuring macro-level consistency and micro-level feasibility.

Figure 18:CAEP-CP 3.0 Model Framework

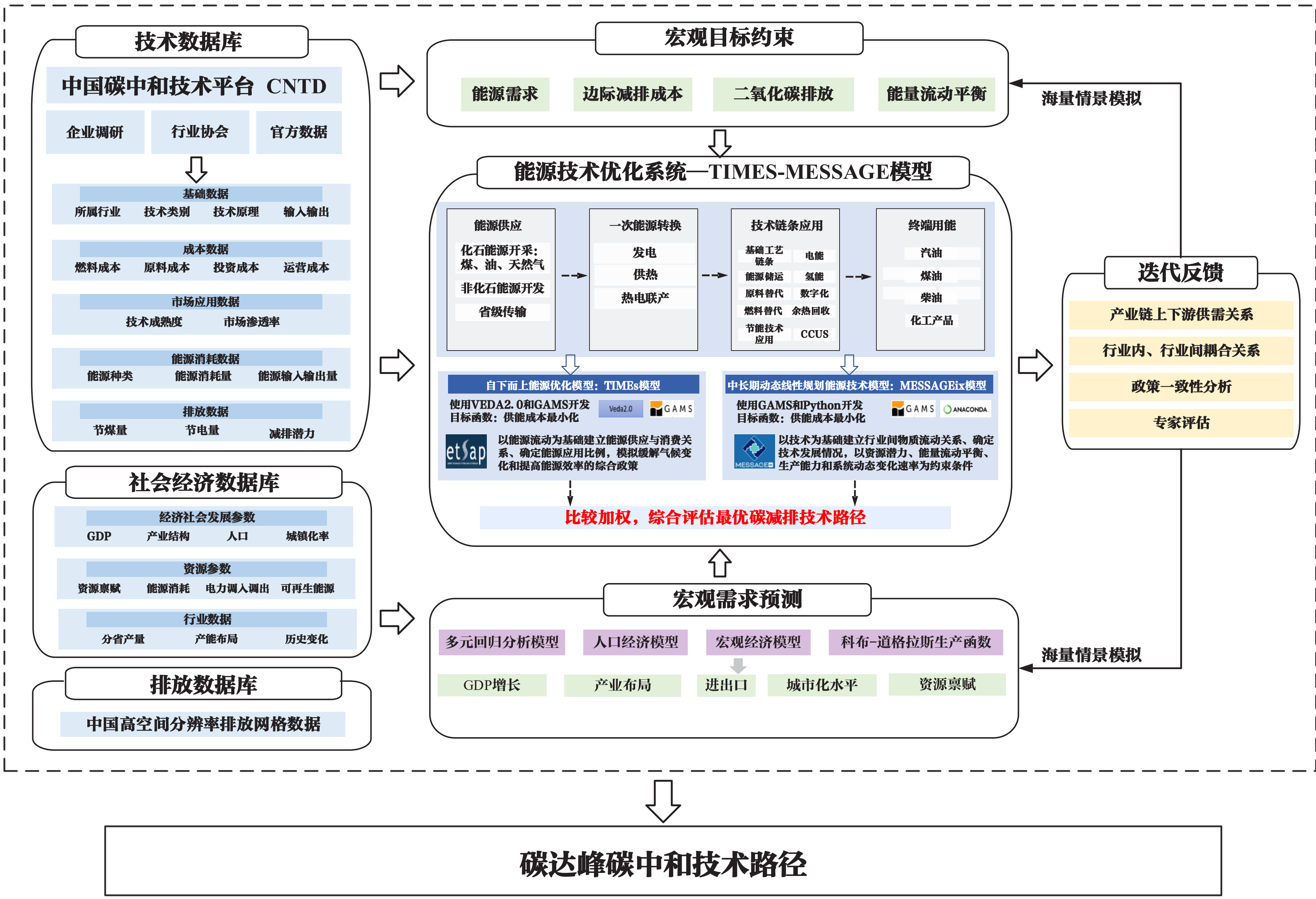


Coupling and Iterative Feedback of Top-down and Bottom-up Methods

Region: Top-down constraints are established at the national level through emission pathways and targets. Authoritative methodologies and findings—including IPCC representative pathways (IMPs), research outcomes from the Chinese Academy of Engineering's major project on carbon peaking and carbon neutrality, and key academic literature—are integrated to provide strategic constraints for regional pathway optimization. Employ the M3C-CGE (Macro-Micro Multi-scale Carbon Neutrality and CGE) module and carbon neutrality technology module to iteratively optimize regional pathways through top-down integration of population dynamics, economic development visions, industrial restructuring, and technological advancement trajectories. Recognizing regional variations in carbon peak and neutrality pathways, establish adynamic optimization mechanism for provincial carbon reduction targets, enabling adaptive alignment between regional trajectories and national strategy. Through a top-down/bottom-up feedback mechanism guided by national objectives, spatial coordination and dynamic optimization of regional emission reduction pathways are achieved. Ultimately, differentiated regional implementation pathways are designed by analyzing regional carbon peak and neutrality trajectories, sectoral emissions and development paths, spatially optimized emission-economic configurations, carbon neutrality cost-benefit assessments, and investment requirements for carbon peaking and neutrality.

Sectors and Technologies: Based on the internationally mainstream TIMES+MESSAGE_ix technology model, combined with the China-specific Technology Database (CNTD), this framework meticulously characterizes the costs, efficiencies, potentials, and penetration processes of various low-carbon/zero-carbon/negative-carbon technologies. It conducts bottom-up analyses of regional energy structure and industrial transformation characteristics and trends, identifies key technological factors influencing regional carbon peaking and neutrality pathways, and determines regional output constraints for key sectors like thermal power, steel, and cement under different pathways. The carbon removal module evaluates negative carbon emission potential and spatial patterns, integrating it as a critical negative emission approach within the overall framework to achieve carbon neutrality goals. The new energy module focuses on high spatiotemporal resolution simulations of wind and solar resources, with spatial accuracy down to 10 km, providing data support for precise, large-scale deployment of new energy industries.

Figure 19: Emission Reduction Technology Path Optimization Model



Spatial Grid: Building upon China's High-Resolution Emission Grid Database (CHRED), this approach employs a bottom-up methodology. It integrates machine learning, spatial econometric models (such as emission source migration models and parameterized road network/built-up area models), and spatial coupling algorithms. Based on emission source characteristics and adhering to specific rules and constraints, it autonomously evolves emission patterns across different stages. This constructs an emission pathway model grounded in spatial evolution theory, encompassing point source emission evolution models and line source emission evolution model, and area source emission evolution model. Top-down approaches, constrained by sectoral and regional emission targets, enable precise spatial selection and technical deployment of sectoral/regional emission reduction pathways.

- **Strong Coupling and Feedback Loops**

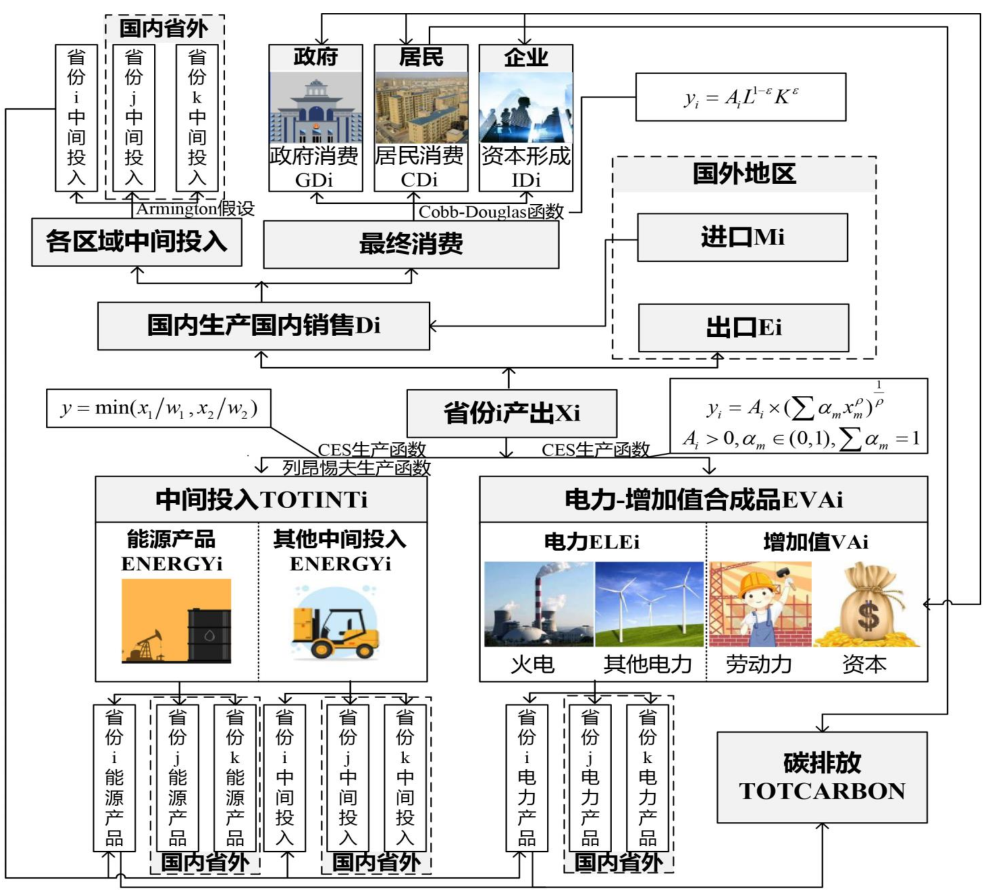
Coupling model approaches of different types (CGE, spatial models, technology models, etc.), different scales (national, regional, grid), , and different emphases (technological, economic, spatial). It integrates multiple key dimensions—socioeconomic scenarios, technological development, industrial economic evolution, energy system transformation, carbon emissions accounting, spatial pattern evolution, and carbon removal—to transcend the limitations of single models or disciplines, comprehensively capturing the complexity of the carbon-neutral transition. Explicit input-output relationships and feedback loops exist between internal modules, capturing interactions and dynamic adjustments across systems. Outcomes from the carbon neutrality technology module (e.g., technology costs, emission reduction potential) feed back into the central "synergistic pathways" module for iterative optimization. A "technology-industry transition feedback and iteration" mechanism exists between the "industry-economy-energy-emissions module" and the "carbon-neutral technology module"; spatial evolution outcomes influence emissions inventory calculations, which in turn shape regional pathway planning.

Macro-Micro Multidimensional—Carbon Neutrality—CGE (M3C-CGE) Model Based on Computable General Equilibrium (CGE) modeling, this framework integrates the interconnections among environmental, economic, and social systems. It facilitates interactions and feedback loops between diverse economic entities across regions, thereby quantifying the impacts of various emission reduction scenarios on economic, social, and environmental dimensions under the dual carbon goals. The model employs extensive mathematical equations to characterize the production, consumption, investment, and import/export behaviors of different economic agents (enterprises, households, government, investors, importers/exporters, etc.) in production, consumption, investment, and trade. Under constraints of household utility maximization, firm profit maximization, cost minimization, and resource/budget limitations, it derives the supply and demand for production factors or other goods at market equilibrium, thereby obtaining equilibrium prices. Based on market price changes and the mutual influences among economic agents, the model comprehensively reveals the relationships between economic development, energy demand, industrial structure, and greenhouse gas emissions.

The study utilizes 2020 provincial input-output tables as socioeconomic baseline data, integrating 2020 provincial energy balance sheets, provincial statistical yearbooks, and provincial carbon emissions to establish baseline year data. The model encompasses 40 sectors, including production modules, domestic and international trade market modules, government and household income-expenditure modules, and carbon emission modules. With a one-year time step, it dynamically simulates provincial industrial economic trends, industrial structure shifts, energy consumption, and carbon emission changes under various emission constraint scenarios from 2020 to 2060. This enables exploration of optimal emission reduction pathways for each province in the future.

Figure 20: Macro-Micro Multidimensional—Carbon Neutrality—CGE Model (M3C-CGE)

Note: Jointly developed by the Carbon Peaking and Carbon Neutrality Research Center of the Environmental Planning Institute under the Ministry of Ecology and Environment, the Center for Forecasting Science of the Chinese Academy of Sciences, and the School of Economics and Management of the University of Chinese Academy of Sciences.



Big Data-Driven Scenario Analysis and Path Optimization for Decision-Making

Using China's high-resolution spatial grid data, industry-enterprise-plant-level precision data, and comprehensive urban greenhouse gas inventories covering all sources and periods (2005–2024) as inputs, this study employs a comprehensive assessment model framework to systematically simulate regional industrial structure and energy mix shifts, carbon emission trajectories, and their spatial evolution across grid zones under various scenarios from 2020 to 2060. By integrating regional technical feasibility, economic affordability, and potential policy orientations, the study proposes tiered and orderly peak-emission pathways for different regions. Guided by the objective of formulating scientifically sound, effective, and coordinated dual-carbon strategies for each region, the research focuses on regulatory requirements while fully considering national strategic planning, regionally differentiated development paths, and sectoral technological advancement potential. This enables quantitative analysis of regional pathway optimization, investment demand assessment, and policy effectiveness evaluation.

Key Parameters

Table 4 : Parameters for Each Stage in the Yangtze River Delta Region

Note: Based on the latest World Population Prospects 2024 released by the United Nations Population Division, as well as materials such as the Internal Logic, Trend Characteristics, and Countermeasures of Negative Population Growth and the China Population Projections Report 2023 Edition published by the China Population and Development Research Center, this analysis incorporates objective population evolution patterns, migration trends, natural population growth, and national/local policies. It provides macro-level analyses of population dynamics in the Yangtze River Delta region of China: long-term (2030–2060) perspectives. China Economic Update, World Economic Outlook (2025–2026), Yangtze River Delta Regional Integration Development Plan Outline, and Long-Term Growth and Short-Term Fluctuations (Analysis and Forecast of China's Macroeconomic Situation), this study conducts a macro-level analysis of GDP growth in China's Yangtze River Delta region from 2025 to 2060.

stage	Population (millions)	GDP (trillion yuan)
2024 年	238.00	33.17
2025~2030 年	238.29 (growth rate 0.1% to 0.3%)	45.12 (growth rate 4.5% to 6%)
2030~2050 年	236.15 (growth rate -0.3% to -0.6%)	75.89 (growth rate 1.5% to 3.5%)
2050~2060 年	235.09 (growth rate -0.3% to -0.6%)	99.78 (growth rate 1.5% to 3.5%)