

Article

The Impact and Mechanisms of Yangtze River Delta Regional Integration on the Green and Low-Carbon Development of Cities

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Abstract

Regional integration is a foundation for coordinated regional development and an important pathway for promoting the green and low-carbon development (GLD) (In this paper, GLD refers to green and low-carbon development, while YRD refers to the Yangtze River Delta) of cities. Based on a systematic analysis of the theoretical mechanisms through which regional integration affects the GLD of cities, this study uses changes in the spatial scope of Yangtze River Delta (YRD) regional integration as a quasi-natural experiment and constructs a multi-period DID model to examine its impact. The results show that YRD regional integration significantly improves the GLD efficiency of cities. This conclusion remains valid after a series of robustness tests, including the parallel-trends test, year-by-year PSM-DID, and modern staggered DID estimators. The heterogeneity analysis shows that the promoting effect of regional integration is more significant for megacities, core cities, and especially Shanghai, while its effects on medium-sized cities and cities in Anhui Province have not yet emerged in the short term. The mechanism tests further show that YRD regional integration improves the GLD efficiency of cities mainly by optimizing the energy consumption structure, promoting industrial restructuring, enhancing government attention to GLD, and improving green innovation. The findings provide useful empirical insights for fully leveraging the green and low-carbon effects of YRD regional integration and for promoting GLD in the Yangtze River Economic Belt and even across China.

Keywords: Yangtze River Delta regional integration; green and low-carbon development; multi-period DID; mechanism analysis



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1. Introduction

Against the background of accelerating global climate governance, regional integration has become an increasingly important pathway for promoting the low-carbon transition of urban agglomerations. In recent years, the global climate system has continued to warm. The years 2023 to 2025 were the three warmest years on record, with the three-year average temperature rise approaching the 1.5 °C threshold set by the Paris Agreement [1]. The year 2025 was also the third warmest year since global climate records began in the mid-nineteenth century [2]. At the same time, international climate governance has become more complex. Global consensus on the low-carbon transition has continued to strengthen, and clean energy technologies and emission reduction tools have advanced rapidly [3]. Yet the multilateral climate governance framework has also been affected by geopolitical tensions and policy uncertainty. The United States again initiated the process of withdrawing from the Paris Agreement in 2025, which further increased uncertainty in global climate

governance. In this context, traditional multilateral governance frameworks alone are no longer sufficient to address the complex challenges of urban low-carbon transition. Coordinated governance at the regional scale has therefore become more important.

Urban areas play a central role in advancing the transition toward GLD. As urbanization continues worldwide, cities already accommodate the majority of the global population, and their demographic share is projected to rise to nearly 70% by 2050. However, the low-carbon transition of cities cannot be achieved by individual administrative units alone. Power system allocation, industrial chain division, infrastructure connectivity, and environmental externality governance all have clear cross-regional attributes. If cities rely only on fragmented local governance, problems such as pollution transfer, fragmented standards, duplicated infrastructure investment, and insufficient diffusion of green technologies may arise. Regional integration can promote cross-regional factor mobility, coordination of market rules, infrastructure connectivity, and joint ecological and environmental governance [4]. It can also reduce institutional segmentation caused by administrative boundaries and provide a more effective spatial framework for the green and low-carbon transition of urban agglomerations [5].

For China, the green and low-carbon transition is particularly urgent. The time span between carbon peaking and carbon neutrality is much shorter than that of most developed countries. China also needs to address constraints related to energy resource endowments and the uneven regional distribution of low-carbon technologies [6]. In the field of power system reform, building a more unified, open, and efficient electricity market requires breaking administrative barriers and regional segmentation. Regional integration is therefore an important institutional foundation for optimizing energy resource allocation and advancing the green and low-carbon transition. The Action Plan for Carbon Dioxide Peaking Before 2030 issued by the State Council also emphasizes that each region should promote GLD based on major regional strategies, the regional coordinated development strategy, and the major function-oriented zoning strategy.

The YRD provides a representative empirical setting for exploring how regional integration affects urban GLD. Although it accounts for less than 4% of China's territory, this region is home to approximately 16% of the country's population and generates nearly one fourth of national economic output. It has therefore become one of China's most vibrant regions in terms of economic activity, openness, and innovation capacity. However, rapid agglomeration has also been accompanied by intensive energy use and considerable pressure to reduce carbon emissions, with the region contributing roughly 20% of China's total carbon emissions [7]. This combination of strong economic concentration and tightening ecological constraints highlights the necessity of institutionalized coordination across administrative boundaries to support the YRD's transition toward GLD.

The potential contributions of this study are as follows. First, in terms of research scope, this study uses the YRD regional integration city scope defined by national policies in 2010, 2016, and 2019 as the policy evaluation object. Compared with studies that focus only on the 2010 integration policy, this study further expands the spatial scope of research on YRD integration. Second, in terms of research perspective, this study examines the impact of the YRD regional integration process on cities from the perspective of urban GLD, thereby extending the existing literature. Third, in terms of research content, this study clarifies the connotation of YRD regional integration and constructs four mechanisms through which it affects urban GLD, including energy structure, industrial structure, governmental attention to GLD, and green innovation. It also examines heterogeneous effects across multiple dimensions, which enriches existing research. Overall, this research deepens the understanding of the relationship between YRD regional integration and urban GLD by examining both its overall effect and its underlying mechanisms. The findings provide

policy-relevant evidence for advancing coordinated regional development and supporting the transformation toward a greener and lower-carbon development model.

2. Literature Review

2.1. *International Research on Regional Integration*

Existing studies have widely examined how regional integration affects national economic and social development. Much of this literature focuses on the integration models of ASEAN, the African Union, and the European Union.

2.1.1. Regional Integration in ASEAN

(ASEAN is the abbreviation of the Association of Southeast Asian Nations, a regional intergovernmental organization in Southeast Asia). ASEAN regional integration places greater emphasis on gradual cooperation and open regionalism. This is closely related to the large development gaps among its member states, the diversity of political systems, and strong sensitivity to national sovereignty [8]. Unlike the European Union, which promotes deeper integration through binding rules, ASEAN tends to maintain cooperation through consensus, flexible participation, and incremental implementation while respecting differences among member states [9].

The ASEAN-X mechanism reflects this institutional logic. It allows some member states to fulfill economic commitments first, while others follow gradually according to their own conditions. This helps prevent large development gaps from slowing the overall integration process. At the same time, ASEAN integration is not a closed form of internal market integration. It has a strong feature of open regionalism [10]. ASEAN has gradually become deeply integrated into East Asian and Asia-Pacific production networks through ASEAN + 1 free trade agreements, participation in the Regional Comprehensive Economic Partnership, and cooperation with external partners, including China, Japan, South Korea, Australia, and New Zealand [11]. The establishment of RCEP has further consolidated ASEAN's position as a key hub of regional economic cooperation. It enables ASEAN to integrate existing external partnerships and reduce transaction costs caused by fragmented rules [12].

2.1.2. Regional Integration in the African Union

Regional integration led by the African Union has a stronger development orientation and a clear focus on continental market integration. Existing studies suggest that African integration is not simply an arrangement for trade liberalization. Rather, it is a development strategy rooted in historical foundations such as Pan-Africanism, national independence, and collective self-reliance. African countries have long faced market fragmentation, weak industrial foundations, inadequate infrastructure, and strong external dependence. Regional integration is therefore expected to expand market size, strengthen development autonomy, and enhance the overall competitiveness of the continent [13].

The Abuja Treaty provides a phased roadmap for building the African Economic Community. The advancement of the African Continental Free Trade Area further marks a shift in African integration from subregional cooperation toward the construction of a continent-wide unified market. Empirical studies find that regional organizations such as the Southern African Development Community and the Economic Community of West African States have promoted intraregional trade to some extent and generated trade creation effects [14]. However, the performance of integration varies significantly across regional organizations. Other studies also point out that the overlapping membership of African countries in multiple regional organizations may create institutional overlap and rule complexity, which can weaken the growth-enhancing effects of regional integration [15].

2.1.3. Regional Integration in the EU

The EU (EU) is one of the most representative cases in research on regional integration. Its integration process is characterized by strong institutional arrangements and a high degree of rule coordination [16]. Existing studies generally suggest that EU integration has promoted economic development in its Member States through the development of the Single Market, the discipline of common rules, and policy coordination among members [17]. However, these effects are not evenly distributed. They vary considerably across countries [18]. Some scholars examined GDP trends in all countries that joined the EU in 2004 and found that poorer new member states grew faster than wealthier new member states. This finding confirms the existence of heterogeneity, while also suggesting that integration can narrow income gaps between the two groups of countries and promote more balanced regional economic development [19]. However, as EU integration entered a more mature stage, developed member states began to experience negative externalities from cross-border industrial pollution generated by less developed member states [20]. This indicates that a development model focused solely on economic growth cannot ensure a benign convergence among member states [21]. Therefore, how to achieve GLD while maintaining stable economic growth has become an important concern in international research. Related studies suggest that the EU should impose requirements on pollution and carbon emissions among member states in line with the objectives of regional integration [22]. These studies further suggest that governance of building-sector energy efficiency should be strengthened. In particular, member states are encouraged to promote energy-saving retrofits, improve policy support for efficiency upgrades, and facilitate the diffusion of successful governance practices across countries [23].

The impact of EU integration on the economic and social development of its Member States is mainly realized through channels such as factor mobility, capital allocation, and trade linkages. These channels, in essence, all depend on the EU's strong capacity for institutional coordination. First, there is the labor mobility channel. Since the 1990s, population mobility among EU member states has continued to increase, and the demographic dividend associated with citizen mobility has gradually become evident. This suggests that EU integration has reduced the cost of cross-border labor mobility [24]. Moreover, many migrants have chosen to settle in rural areas, injecting momentum into sustainable rural economic development, promoting rural population growth, reducing certain social problems, and generating multiple benefits for local economic growth [25]. Second, there is the capital mobility channel. Because investment in new member states can generate higher returns, EU integration has increased the attractiveness of these countries to foreign investment and promoted the movement of capital among member states. Given the presence of significant spatial effects, increased investment in new member states can also generate positive economic spillovers for neighboring countries [26]. Third, there is the trade channel. Within a given period and geographical scope, EU integration can stimulate trade among member states. Its effects on transaction costs and market potential tend to be stronger for border member states than for central member states [27].

2.2. Research Progress on Regional Integration in China

2.2.1. The Logic Underlying Regional Integration in China

As economic globalization has deepened, China has progressively developed a more mature understanding of regional economic integration, partly under the influence of cross-regional capital mobility [28]. This evolution has contributed to the emergence of integrated urban agglomerations, represented by the YRD and the Pearl River Delta [29]. However, administrative boundaries, often described as an “invisible wall”, have hindered market integration [30]. To remove administrative barriers, cross-regional governance

among local governments is required [31]. This means resolving conflicts arising from administrative divisions through “compound administration” [32]. More specifically, government cooperation mechanisms can be improved by establishing unified market competition rules, creating cross-regional coordination agencies, and developing distinctive regional economies [33]. Appropriate compensation and incentive mechanisms, as well as effective governing bodies, are also needed to support this process [34]. Since then, the rapid development of transport infrastructure, including high-speed railways, has played a positive role in promoting regional economic integration in China [35,36]. As the temporal and spatial distance between cities has continued to shrink, urban boundaries have become increasingly blurred. This has greatly expanded the scope of factor mobility and strengthened the effect of urban integration [37]. Research on regional integration in China has generally developed along two strands. One strand examines integration within major river-basin regions, represented by the Yellow River Basin [38] and the Yangtze River Economic Belt [39]. The other strand focuses on urban agglomerations, such as the Beijing–Tianjin–Hebei region [40], the Guangdong–Hong Kong–Macao Greater Bay Area [41,42], the YRD [43,44], the Chengdu–Chongqing Economic Circle [45], and urban agglomerations in Central China [46].

2.2.2. Regional Integration in the YRD

Within China’s regional integration framework, the YRD urban agglomeration occupies a strategic position at the national level. This has led to a growing body of research evaluating its integration process and related policy outcomes. Existing studies have largely examined YRD regional integration from the perspectives of economic growth, talent mobility, urban innovation, and ecological governance. Regarding economic performance, the literature indicates that integration helps raise the level of high-quality development across the YRD urban agglomeration. Both incumbent cities and newly incorporated cities can benefit from this process, although the magnitude of the effect differs by city type. Such variation is generally attributed to the uneven balance between spillover effects and siphoning effects [47,48]. With respect to talent mobility, regional integration has been found to increase demand for high-quality public services, thereby motivating governments and social organizations to attract highly skilled talent and improve its spatial allocation. This effect is particularly evident in core cities and small and medium-sized cities [49,50]. For urban innovation, previous research suggests that intergovernmental coordination and market-based resource allocation are key pathways through which regional integration strengthens cities’ innovation capacity [51].

The environmental consequences of YRD regional integration have received increasing scholarly attention, particularly in the context of China’s dual carbon goals and its pursuit of high-quality development. Prior studies indicate that integration may lower aggregate carbon and pollutant emissions by reshaping industrial structures, enhancing cross-regional pollution control, and facilitating the spread of green technologies, thereby supporting regional green development [52]. Nevertheless, the green benefits generated by integration may not be evenly distributed across cities. Newly incorporated cities may become destinations for pollution-intensive industries relocated from original member cities. Although such industrial relocation can bring economic gains, it may also increase local energy demand and environmental pressure [53]. Thus, the environmental impact of YRD regional integration should be understood as heterogeneous rather than uniformly positive [54]. It can advance urban GLD through market integration [55], technology diffusion [56], and collaborative environmental governance [57], but it may also intensify pollution transfer through industrial relocation and core-periphery specialization [58].

Taken together, prior research has offered valuable insights into the economic and environmental consequences of regional integration, yet several gaps remain. First, much of the literature relies on single indicators, such as carbon emissions or pollutant emissions, to evaluate environmental outcomes. Relatively limited attention has been given to urban GLD efficiency, which integrates economic growth, resource inputs, pollution abatement, and carbon-emission constraints within a unified analytical framework. Second, many existing studies define YRD regional integration according to the spatial coverage established in 2010, thereby giving insufficient consideration to its subsequent staged expansion. Third, intra-regional differences within the YRD urban agglomeration remain underexplored, particularly across cities with different sizes, locations, and provincial affiliations. Uneven green benefits between core and peripheral cities, together with the potential for pollution transfer, also deserve further examination. To address these gaps, this study treats the spatial expansion of YRD regional integration as a quasi-natural experiment and investigates its effect on urban GLD efficiency, as well as the underlying mechanisms and heterogeneous impacts.

3. Development Background and Theoretical Analysis

3.1. Development Background

In China's broader modernization agenda, the YRD plays a leading role in driving the development of the Yangtze River Economic Belt and the country as a whole, supported by its strong advantages in technological innovation and industrial upgrading. Its regional integration process is also embedded in a rich policy context, making it a representative case for studying integrated development.

Since the Third Plenary Session of the 11th CPC Central Committee, the central government has continued to explore reform and development paths for China's economic system. At the end of 1982, the State Council approved the establishment of the Shanghai Economic Zone, with Shanghai as its core. The establishment of this zone was an important step in breaking the traditional segmentation between administrative departments and local governments. It also helped strengthen horizontal economic linkages and promoted an urban agglomeration development model. More importantly, it represented the first major attempt by the central government to promote YRD Regional Integration at the strategic level. However, the effect of this early attempt was limited. During its implementation, state-owned enterprises and traditional enterprises accounted for a relatively large share, and the industrial structure remained rather simple. As a result, emerging private enterprises could not fully benefit from the institutional advantages created by the Shanghai Economic Zone. Industrial development also lacked sufficient technological support and failed to generate economies of scale. Because the reform did not provide enough market autonomy, the overall effect of regional integration was not ideal.

The 2008 global financial crisis prompted a broader reassessment of the sustainability of the YRD's regional economic integration model. In September 2008, the State Council issued the Guiding Opinions on Further Promoting Reform, Opening-up, and Economic and Social Development in the YRD Region, the first national-level policy document specifically addressing the economic and social development of the YRD. This document called for coordinated urban–rural and regional development, together with stronger resource conservation and environmental protection. However, cities within the YRD differed substantially in their development stages and environmental regulatory intensity. As a result, carbon-intensive industries, such as steel and chemicals, could shift from more strictly regulated areas to places with relatively weaker regulation, thereby increasing the transformation burden on receiving cities. Issues such as cross-regional energy allocation, industrial relocation, and environmental externalities are difficult for any single city to

manage independently. A region-wide integration framework is therefore needed to strengthen coordination across administrative boundaries. Against this policy background, the National Development and Reform Commission clarified the functional positioning and spatial coverage of YRD regional integration in 2010, initially covering 16 cities (The scope included 16 cities, namely Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, Zhenjiang, Yangzhou, Taizhou in Jiangsu Province, Nantong, Hangzhou, Ningbo, Huzhou, Jiaxing, Shaoxing, Zhoushan, and Taizhou in Zhejiang Province), including Shanghai, Nanjing, and Suzhou. In 2016, the State Council approved the Development Plan for the YRD Urban Agglomeration, which incorporated another 10 cities (Another 10 cities were later added, namely Yancheng, Jinhua, Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou, and Xuancheng), including Yancheng, Jinhua, and Hefei, and emphasized the construction of a networked, open, and integrated development pattern. The Outline of the YRD Regional Integrated Development Plan, released in 2019, further extended the integration scope to the entire administrative areas of Shanghai, Jiangsu, Zhejiang, and Anhui. It also proposed improving institutional arrangements for integrated development and enhancing joint capacity for ecological and environmental protection and governance.

This study therefore takes the urban scope of YRD Regional Integration defined by national policy documents in 2010, 2016, and 2019 as the basis for policy evaluation. These policy documents provide a systematic national-level arrangement for the spatial scope and development direction of regional integration in the YRD. They also have strong policy authority and institutional representativeness. Compared with local regional economic coordination meetings, the city scope defined by national policy documents better reflects the institutional arrangement and policy boundary of the regional integration strategy. Accordingly, this study treats the spatial scope of YRD Regional Integration defined by national policy documents as a quasi-natural experiment. It identifies the impact of regional integration on urban GLD efficiency.

3.2. Theoretical Analysis

Advancing regional integration enables the YRD to explore new approaches to GLD in both development practices and policy design. It also helps the region assume a leading role in promoting energy transition, industrial transformation, and efficiency gains. In addition, regional integration can convert ecological and environmental endowments into broader socioeconomic advantages, thereby supporting the Yangtze River Economic Belt and China as a whole in moving toward more environmentally sustainable development pathways and a stronger balance between economic growth and environmental protection. Against the background of China's dual carbon goals and green development objectives, Figure 1 presents the main channels through which YRD regional integration influences urban GLD. These channels are discussed as follows:

First, regional integration may contribute to urban GLD by reshaping energy consumption patterns and reducing pollution-related pressures. The optimization of the energy structure is a key condition for advancing a low-carbon energy transition. China's recent progress in GLD has been closely associated with continuous efforts to adjust and upgrade its energy system. As energy provides the basic input for socioeconomic production and daily operation, improving energy efficiency, expanding the use of clean and renewable energy, and forming a cleaner low-carbon consumption structure are essential for promoting GLD [59]. In the context of regional integration, local governments can strengthen monitoring and evaluation mechanisms for the low-carbon energy transition and introduce incentive schemes that encourage green energy use. These policy arrangements may guide energy-intensive industries to reduce dependence on fossil fuels. In the short run, they help enterprises lower energy waste and improve energy-use efficiency. In the long run,

they may stimulate technological breakthroughs in clean-energy production, thereby accelerating the energy transition and supporting the coordinated development of regional green energy systems. Accordingly, this study proposes the following hypothesis:

Hypothesis 1. *Regional integration can optimize the urban energy consumption structure, improve energy use efficiency, increase the use of green and clean energy, and thereby promote urban GLD.*

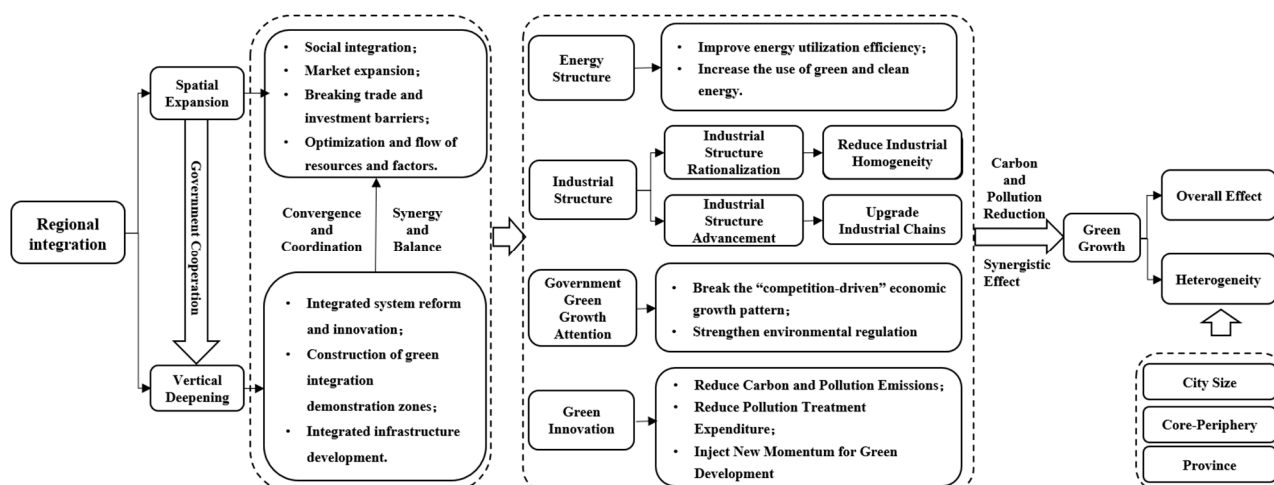


Figure 1. Linkage mechanism of regional integration and urban GLD in YRD.

Second, regional integration may enhance GLD efficiency by reorganizing the regional industrial structure. Industrial upgrading is commonly reflected in two interrelated dimensions: structural rationalization and structural advancement. Since China's reform and opening-up, the expansion of the export-oriented economy has stimulated investment demand within the YRD urban agglomeration. Although this process supported urban economic growth, it also produced a fragmented outward-oriented production system and intensified industrial homogenization. At the present stage, YRD regional integration is increasingly driven by region-wide consumption and investment demand. By promoting a more coordinated industrial layout, integration can weaken fragmented production patterns and reduce the duplication of similar industries across cities. In addition, the National Development and Reform Commission and related departments have specified the direction of industrial optimization and upgrading for urban agglomerations, including the YRD. Local governments may employ tax incentives, subsidies, and other policy tools to guide market actors away from industries characterized by high energy use, high emissions, and low efficiency, while encouraging the growth of sectors with lower energy consumption, fewer emissions, and higher efficiency. Such adjustments can increase technological intensity and facilitate upward movement along the value chain. Nevertheless, existing studies have reported mixed findings on the effects of industrial structure rationalization and advancement, partly because of differences in research regions, environmental quality indicators, and pollutant measurement standards [60–62]. Some scholars argue that both dimensions are conducive to improving urban GLD efficiency [63,64]. Others contend that the advancement of industrial structure may induce horizontal industrial competition among local governments, thereby generating adverse effects on GLD at the urban-agglomeration level. Moreover, policy incentives from the central government and regional coordination mechanisms often involve implementation lags and cyclical effects. Under time constraints and performance-based incentives, local governments may attach greater importance to the spatial reallocation of industries than to technology-driven upgrading. Therefore, the contribution of industrial structure optimization to GLD efficiency may arise more from spatial

redistribution than from technological progress [65]. Accordingly, this study proposes the following hypothesis:

Hypothesis 2. *Regional integration promotes the GLD of the overall urban agglomeration by adjusting the industrial structure within the region.*

Third, government attention reflects the priorities of local governance and the direction of policy allocation during a specific period. For many years, several YRD cities relied heavily on an extensive growth model, under which local governments tended to prioritize economic expansion and form performance-oriented competition centered on GDP growth. Regional integration can weaken this growth-first competition logic by promoting coordination in environmental standards, ecological evaluation systems, and governance rules. Such coordination requires cities at different development stages to move toward higher standards of green governance. Meanwhile, stricter environmental regulations adopted by core or more developed cities may be transmitted to medium-sized and less developed cities through regional coordination mechanisms, thereby strengthening the overall orientation of regional green governance. As local governments attach greater importance to GLD, policy attention can be converted into concrete governance measures, such as increasing green fiscal expenditure, promoting clean energy use, strengthening environmental law enforcement, and tightening constraints on pollutant emissions. These actions can improve environmental governance capacity and accelerate the low-carbon transition, ultimately enhancing cities' GLD efficiency. Prior research has shown that government attention to GLD exerts a positive influence on urban GLD [66]. In addition, stronger government attention may encourage local governments to reduce pollutant concentrations and improve labor productivity through stricter environmental regulation, thereby further advancing GLD [67]. Accordingly, this study proposes the following hypothesis:

Hypothesis 3. *Regional integration promotes GLD by increasing government attention to GLD.*

Fourth, regional integration can promote GLD by improving the level of green innovation. Green innovation, also referred to as environmental innovation, differs from general technological innovation in that it mainly involves environmentally friendly innovations in processes, procedures, systems, and products [68]. As one of China's most resource-rich regions for scientific and technological innovation, the YRD is home to two comprehensive national science centers and 104 national key laboratories. Supported by high-tech resources, the region has continuously improved production methods and the ecological environment. On the one hand, green innovation can reduce carbon emissions and pollutant emissions by improving production methods and technologies, thereby lowering pollution treatment costs. On the other hand, it can inject new momentum into economic development and improve economic efficiency [69]. Taken together, these effects help form a GLD pathway that aligns economic growth with resource conservation and environmental protection. Based on this logic, the following hypothesis is proposed:

Hypothesis 4. *Regional integration can promote GLD by enhancing urban green innovation capacity.*

4. Model Specification, Research Method, and Data Description

4.1. Model Specification

To evaluate the impact of YRD regional integration on urban GLD, this study constructs a multi-period difference-in-differences model for empirical analysis. The model is specified as follows:

$$Green_{i,t} = \alpha + \beta DID_{i,t} + \gamma X_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t} \quad (1)$$

where $Green_{i,t}$ denotes the GLD efficiency of city i in year t . $DID_{i,t}$ indicates whether city i had joined the YRD Urban Economic Coordination Conference in year t . $X_{i,t}$ represents a set of control variables. μ_i and τ_t denote city fixed effects and year fixed effects, respectively. $\varepsilon_{i,t}$ is the random error term. α , β and γ are model coefficients, where β captures the effect of regional integration on urban GLD efficiency.

4.2. Variable Selection

4.2.1. Dependent Variable: Green and Low-Carbon Development Efficiency

The measurement of GLD efficiency in the YRD urban agglomeration is not identical to conventional green total factor productivity indicators [70]. To capture the multidimensional nature of GLD, this study develops an input–output indicator system based on four objectives: carbon reduction, pollution reduction, ecological improvement, and economic growth, as reported in Table 1. On the input side, the indicator system covers labor, capital, natural resources, and energy, with natural resources mainly represented by land and water resources [71]. On the output side, desirable outputs are reflected by economic, social, and environmental benefits, which capture cities' performance in promoting ecological improvement and economic growth. Given the increasing importance of coordinated governance between industrial waste treatment and carbon reduction, carbon emissions are treated as an undesirable output. Together with sulfur dioxide emissions, soot emissions, and wastewater discharge, this indicator reflects the outcomes of carbon and pollution reduction [72]. Based on this framework, the SBM model with undesirable outputs is employed to estimate the GLD efficiency of each city from 2006 to 2023 [73]. The model is expressed as follows:

$$\rho = \min \frac{1 - \frac{1}{N} \sum_{n=1}^N \frac{s_n^x}{x_{k'n}^{t'}}}{1 + \frac{1}{M+I} \left(\sum_{m=1}^M \frac{s_m^y}{y_{k'm}^{t'}} + \sum_{i=1}^I \frac{s_i^b}{b_{k'i}^{t'}} \right)} \quad (2)$$

$$\text{s.t. } \sum_{t=1}^T \sum_{k=1}^K z_k^t x_{kn}^t + S_n^x = x_{k'n}^{t'}, \quad n = 1, \dots, N \quad (3)$$

$$\sum_{t=1}^T \sum_{k=1}^K z_k^t x_{km}^t + S_m^y = y_{k'm}^{t'}, \quad m = 1, \dots, M \quad (4)$$

$$\sum_{t=1}^T \sum_{k=1}^K z_k^t b_{ki}^t + S_i^b = b_{k'i}^{t'}, \quad m = 1, \dots, I \quad (5)$$

$$z_k^t \geq 0, S_n^x \geq 0, S_m^y \geq 0, S_i^b \geq 0, k = 1, \dots, K$$

where ρ denotes green development efficiency. N , M , and I represent the numbers of inputs, desirable outputs, and undesirable outputs, respectively. S_n^x , S_m^y , and S_i^b denote the slack variables for inputs, desirable outputs, and undesirable outputs, respectively. $x_{k'n}^{t'}$, $y_{k'm}^{t'}$, and $b_{k'i}^{t'}$ represent the input and output values of the k' decision-making unit in period t' . z_k^t denotes the weight of each decision-making unit. The value of the objective function ρ lies within the range $0 < \rho \leq 1$. When $0 < \rho < 1$, the efficiency of the decision-making unit can still be improved. When $\rho = 1$, the decision-making unit reaches the optimal efficiency frontier.

Table 1. Indicator system for measuring the GLD efficiency of cities.

Category	Primary Indicator	Secondary Indicator	Notes
Input indicators	Labor input	Number of employees in urban units at year-end (10,000 persons).	① Capital stock is measured using the perpetual inventory method, as follows: $K_{i,t} = K_{i,t-1}(1 - \delta_{i,t}) + I_{i,t}$, where $K_{i,t}$ denotes the capital stock of city i in year t, $\delta_{i,t}$ denotes the depreciation rate of capital, which is set at 9.6%, and $I_{i,t}$ denotes the current investment of city i. The initial capital stock is estimated using the base-period fixed-asset investment divided by the sum of the depreciation rate and the average investment growth rate. Fixed-asset investment is deflated to constant prices to ensure comparability across years. ② Total energy consumption is calculated by converting natural gas, liquefied petroleum gas, and electricity consumption into standard coal equivalent. The conversion coefficients are taken from the General Principles for Calculation of Comprehensive Energy Consumption. According to the units of the original data, the coefficients are 13.3 tce per 10,000 m³ for natural gas, 1.7143 tce per ton for liquefied petroleum gas, and 1.229 tce per 10,000 kWh for electricity. ③ Carbon dioxide emissions are obtained from the gridded emission estimates provided by the EDGAR database. In this study, city-level CO₂ emissions are obtained by spatially aggregating EDGAR grid-cell emission data within the administrative boundary of each city.
	Capital input	Capital stock (CNY 10,000).	
	Natural resource input	Built-up area (km ²); Total water resources (10,000 m ³).	
	Energy consumption input	Total urban energy consumption, 10,000 tons of standard coal;	
Desirable outputs	Economic benefits	Gross domestic product (CNY 10,000).	
	Social benefits	Total retail sales of consumer goods (CNY 10,000); Total wages of employed staff and workers (CNY 10,000)	
	Environmental benefits	Green coverage rate of built-up areas (%); Centralized treatment rate of wastewater treatment plants (%); Harmless treatment rate of domestic waste (%).	
Undesirable outputs	Environmental pollution	Carbon dioxide emissions (10,000 tons); Total industrial wastewater discharge (tons); Total industrial sulfur dioxide emissions (tons); Industrial soot emissions (tons).	

4.2.2. Core Explanatory Variable: Regional Integration Intervention

The empirical identification in this study relies on changes in the spatial coverage of YRD regional integration defined by relevant State Council policy documents. These policy adjustments are treated as a quasi-natural experiment, and a city is assigned to the treatment group once it is incorporated into the regional integration framework in a given year. This status is represented by the binary variable *DID*. The variable takes the value of 1 if the city has been included in the scope of regional integration in a given year. Otherwise, it takes the value of 0, indicating that the city belongs to the control group.

4.2.3. Mechanism Variables

To further examine the mechanisms through which YRD regional integration affects green development efficiency, this study selects energy structure, industrial structure transformation and upgrading, government attention to GLD, and green innovation as mechanism variables.

1. Energy structure (*energy*): Energy structure is measured by the proportion of coal consumption in a city's total energy consumption.
2. Industrial structure transformation and upgrading: This is mainly captured from two dimensions: industrial structure rationalization and industrial structure advancement. First, industrial structure rationalization (*structure1*): existing studies have used var-

ious methods to measure industrial structure rationalization. Following Yuan and Zhu [74], this study adopts the Theil index for measurement. The formula is as follows:

$$theil_{i,t} = \sum_{j=1}^3 y_{i,j,t} \ln \left(\frac{y_{i,j,t}}{l_{i,j,t}} \right), j = 1, 2, 3 \quad (6)$$

where $y_{i,j,t}$ denotes the share of the output value of industry j in city i in year t in the city's total output value. $l_{i,j,t}$ denotes the share of employees in industry j in city i in year t in the city's total employment. Industrial structure rationalization provides a comprehensive measure of the coordination between the three major industries and the employment structure of a city. A nonzero value indicates that the city's industrial structure is in an unbalanced state, whereas a value of zero indicates that the industrial structure is balanced.

Second, industrial structure advancement (*structure2*): Beyond industrial structure rationalization, industrial structure advancement represents another key dimension of industrial transformation and upgrading. It describes the evolution of industrial composition from the primary sector toward the secondary and tertiary sectors as YRD regional integration progresses and regional economic development deepens. In this study, industrial structure advancement is calculated according to the following formula:

$$X_0 = (x_{1,0}, x_{2,0}, x_{3,0}); X_1 = (1, 0, 0); X_2 = (0, 1, 0); X_3 = (0, 0, 1) \quad (7)$$

$$\theta_j = \arccos \left(\frac{\sum_{i=1}^3 (x_{i,j} \times x_{i,0})}{\sum_{i=1}^3 (x_{i,j}^2)^{\frac{1}{2}} \times \sum_{i=1}^3 (x_{i,0}^2)^{\frac{1}{2}}} \right), j = 1, 2, 3 \quad (8)$$

$$W = \sum_{k=1}^3 \sum_{j=1}^k \theta_j \quad (9)$$

where $x_{1,0}$, $x_{2,0}$, and $x_{3,0}$ denote the shares of the added value of the primary, secondary, and tertiary industries in total output, respectively, which together form a three-dimensional vector X_0 . θ_j denotes the angle between vector X_0 and vector X_j . W represents the level of industrial structure advancement. A larger value indicates a higher degree of industrial advancement.

3. Government attention to GLD (*attention*): Government attention to GLD is shaped by a range of policy and governance considerations. Conventional measures, such as pollution-control expenditure or environmental R&D investment, capture only limited aspects of environmental governance and cannot fully reflect the formulation and implementation of environmental regulation policies. To address this limitation, this study applies text-mining methods to government work reports and identifies terms associated with GLD [75]. The frequency of these terms is then divided by the total word count of each report to measure the degree of attention that each city government assigns to GLD. This ratio-based approach reduces potential bias caused by differences in report length. The selected terms are further grouped into five categories, as shown in Table 2.
4. Green innovation (*innovation*): Considering the lag between patent application and patent grant, this study measures green innovation using the number of green invention patent applications and green utility model patent applications submitted by each city in a given year [76]. The entropy method is then employed to construct a composite green innovation index, which is used to capture the level of urban green innovation [74].

Table 2. Green and low carbon development related terms.

Category	Keywords
Environmental Conservation	Environmental protection, Environmental conservation, Environment, Pollution prevention and control, Treatment, Pollution control, Pollution treatment, Remediation, Treatment of pollution, Greening, Green, Green development, Low carbon, Clean energy, Ecology, Wastewater treatment, Environmental impact assessment, Environmental inspection, Domestic waste harmless treatment, Environmental quality, Air quality.
Environmental Pollution	Carbon dioxide, Carbon dioxide emissions, PM2.5, Particulate matter, Ammonia, Nitrogen oxides, Sulfur dioxide, Air pollution, Chemical pollutants, Pollutants, Dust, Ash, Waste gas, Volatile organic compounds, Sewage, Emissions, Exhaust, Air, Chemical oxygen demand, Carbon dioxide, PM10, Haze, Greenhouse gases, Pollution, Discharge, Wastewater.
Energy Conservation	Water resources, Energy consumption, Consumption, Natural resources, Energy conservation, New energy, Clean energy, Coalbed methane, Coal gas, Coal-fired power generation, Renewable energy, Utilization of waste heat, Recycling, Conservation.
Environmental Co-governance	Environmental coordination, Coordinated development, Collaborative governance, Joint governance, Departmental cooperation, Public participation, Cross-regional cooperation, Sharing, Transfer, Joint prevention and control, Joint monitoring and control, Joint governance, Regional coordinated development, Integrated management of river basins, Regional cooperation, Benefit sharing, Collaborative action, Joint promotion, Multi-stakeholder participation, Cooperative governance, Sustainable.
Other	Blue sky, Clear water, Clean soil, Green mountains, Forests, Rivers, River basins, Lakes, Lake basins, Wetlands, Paddy fields, Residential areas, Buildings, Species, Green waters and lush mountains, Ecological barriers, Water scarcity, Soil conservation, Afforestation, Land degradation control, Natural forests.

4.2.4. Control Variables

Considering that GLD efficiency may be influenced by other city-specific factors, this study includes the following control variables: ① Economic development level (*ln_pgdp*): Measured by per capita GDP. ② Industrial structure (*industry*): Measured by the share of secondary industry value added in GDP. ③ Foreign direct investment (*fdi*): Measured as the ratio of actual utilized FDI in a given year to city GDP. FDI denominated in US dollars is converted to RMB using the average annual exchange rate. ④ Technological innovation (*ln_patent*): Measured by the number of patents granted in the city. ⑤ Population density (*ln_population*): Measured as the number of people per square kilometer. ⑥ Urbanization level (*urban*): Measured as the ratio of urban resident population to total city population. ⑦ Human capital (*human*): Measured as the proportion of the population enrolled in general higher education institutions relative to total city population. ⑧ Financial development (*financial*): Measured as the ratio of total loans from financial institutions to city GDP.

4.2.5. Sample Selection and Data Description

This study uses data from 281 prefecture-level cities in China from 2006 to 2023 as the initial sample. The 41 cities included in the expanded scope of YRD Regional Integration in 2010, 2016, and 2019 are treated as the treatment group, while the remaining 240 cities are used as the control group. The data are obtained from the *China City Statistical Yearbook* from 2007 to 2024, the *China Urban Construction Statistical Yearbook* from 2007 to 2024, government work reports of prefecture-level cities, local statistical yearbooks, EDGAR database, and the CNRDS database. Some missing values are supplemented using data from the corresponding local statistical yearbooks. Descriptive statistics for the variables are reported in Table 3.

Table 3. Descriptive statistics for variables.

Variable	Description	Sample Size	Mean	Standard Deviation	Min	Max
<i>Green</i>	Green and low-carbon development efficiency	5058	0.388	0.329	0.000	1.000
<i>DID</i>	Regional integration policy intervention	5058	0.089	0.285	0	1
<i>ln_pgdp</i>	Economic development level	5058	10.535	0.713	4.605	13.125
<i>industry</i>	Industrial structure	5058	0.457	0.113	0.117	0.918
<i>fdi</i>	Foreign direct investment	4884	0.018	0.019	0.000	0.201
<i>ln_patent</i>	Technological innovation	5038	7.709	1.625	1.946	12.352
<i>ln_population</i>	Population density	5058	8.012	0.721	5.517	10.023
<i>urban</i>	Urbanization level	5038	0.538	0.161	0.153	1.000
<i>financial</i>	Financial development	5058	0.993	0.620	0.075	9.715
<i>human</i>	Human capital	5058	0.021	0.025	0.001	0.155
<i>energy</i>	Energy structure	4496	0.814	0.147	0.040	0.997
<i>structure1</i>	Industrial structure rationalization	5058	0.330	2.914	0.000	208.403
<i>structure2</i>	Industrial structure advancement	5058	6.504	0.358	5.517	7.844
<i>attention</i>	Government attention to GLD	5058	0.015	0.007	0.000	0.262
<i>innovation</i>	Green innovation	5029	0.018	0.053	0.000	0.913

5. Empirical Results and Analysis

5.1. Baseline Regression

Table 4 presents the baseline estimates for the effect of YRD regional integration on urban GLD efficiency. Column (1) reports the specification without year fixed effects or control variables. Column (2) incorporates year fixed effects, while control variables are still excluded. Column (3) further introduces the full set of control variables on the basis of Column (2). Across these specifications, the estimated coefficient of regional integration remains positive and statistically significant, indicating that the integration process in the YRD contributes to higher urban GLD efficiency. In Column (3), the coefficient of DID is estimated at 0.147. This result suggests that, after accounting for city fixed effects, year fixed effects, and relevant control variables, YRD Regional Integration exerts a significant positive impact on urban GLD efficiency (To address potential standard error bias caused by a limited number of clusters, this study further applies the wild cluster bootstrap method to test the robustness of the baseline regression results. The results show that the wild-bootstrap *p*-value of the core explanatory variable remains within conventional significance levels. This suggests that the baseline conclusion is highly robust).

Table 4. The impact of regional integration policies on the GLD efficiency of cities.

Variable	(1) <i>Green</i>	(2) <i>Green</i>	(3) <i>Green</i>
<i>DID</i>	0.198 *** (0.036)	0.160 *** (0.038)	0.147 *** (0.040)
Control variables	NO	NO	YES
City fixed effects	YES	YES	YES
Year fixed effects	NO	YES	YES
Observations	5058	5058	4872
R-squared	0.508	0.532	0.532

Notes: *** $p < 0.01$. Standard errors are reported in parentheses and clustered at the city level.

5.2. Robustness Test

5.2.1. Parallel Trend Test

A common pre-policy trend between the treatment group and the control group is a necessary condition for the validity of the regression results from the staggered DID model. Since the treatment cities were included in the scope of YRD Regional Integration at different times, this study constructs dummy variables based on the relative time to each city's inclusion in the integration scope. The specific model is specified as follows:

$$Green = \alpha + \beta_1 pre5_{i,t} + \beta_2 pre4_{i,t} + \beta_3 pre3_{i,t} + \beta_4 pre2_{i,t} + \beta_5 current + \beta_6 after1_{i,t} + \beta_7 after2_{i,t} + \beta_8 after3_{i,t} + \beta_9 after4_{i,t} + \beta_{10} after5_{i,t} + \gamma X_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t} \quad (10)$$

here, *pre*, *current*, and *after* represent dummy variables for the *n* years before, the year of, and the *n* years after a city in the treatment group is incorporated into the regional integration framework, respectively. For cities in the control group, these dummy variables take the value of 0. The meanings of α , α , $X_{i,t}$, μ_i , τ_t , $\varepsilon_{i,t}$ are the same as in Equation (2). Since the study period covers 2006–2023 and the critical points for regional integration are 2010, 2016, and 2019, the time span before and after policy implementation is relatively long. Therefore, the time dummy variables are truncated, retaining only five periods before and after each critical point. The period immediately preceding policy implementation is excluded and used as the reference group to avoid multicollinearity. Figure 2 indicates that the estimated coefficients for the pre-policy time dummies are near zero and statistically insignificant. This suggests that, before the implementation of YRD regional integration, there was no systematic difference in GLD efficiency between the treatment and control groups. Therefore, the parallel trends assumption is supported. In the post-policy period, the coefficients are mostly positive and statistically significant, implying that YRD regional integration improves urban GLD efficiency and further supports the reliability of the baseline estimates.

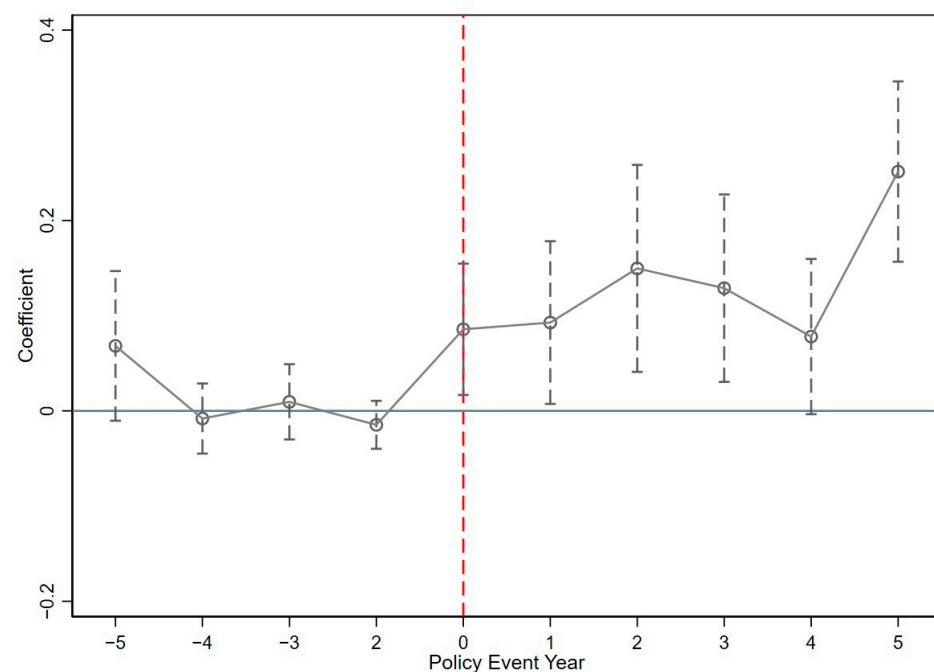


Figure 2. Parallel trend test results.

5.2.2. Placebo Test

In the baseline regression, this study controls for factors related to the economy, human capital, and education of cities. However, some unobservable factors may still

affect the estimated policy effect of YRD Regional Integration. To address this concern, this study further conducts a placebo test by randomly assigning policy timing and treated cities. Unlike a standard DID setting, the staggered DID design involves multiple policy implementation years. It is therefore not appropriate to directly draw the same number of treated cities from the full sample. This study randomly generates a pseudo policy shock variable, $post^{random}$, and a pseudo treatment group variable, $treat^{random}$. Specifically, 1000 random simulations are conducted using the full city sample. In each simulation, pseudo treated cities are randomly selected according to the actual number of cities and timing in the three treatment groups. This generates 1000 sets of pseudo DID variables, DID^{random} , defined as $post^{random} \times treat^{random}$. Finally, this study plots the kernel density distribution of the 1000 estimated β^{random} values and their p -values. The results are shown in Figure 3. The figure shows that the β^{random} values generated from the 1000 random treatments are mainly concentrated around zero. By contrast, the true DID coefficient is 0.147 and lies clearly outside the right tail of the simulated coefficient distribution. This indicates that the positive policy effect identified in the baseline regression is unlikely to be explained by random treatment assignment or sample randomness.

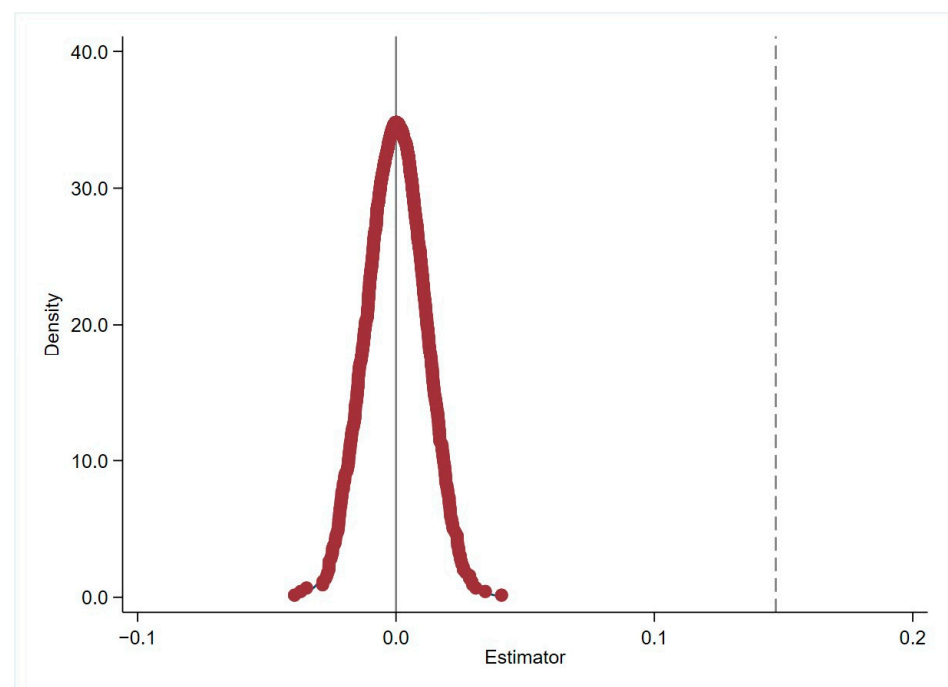


Figure 3. 1000 placebo test results.

5.2.3. PSM-DID Test

Because YRD Regional Integration does not constitute a natural experiment in the strict sense, integrated and non-integrated cities may differ systematically in observable characteristics, which may lead to sample selection bias. If such differences are not addressed, the estimated policy effect from staggered DID may be biased. Propensity score matching helps reduce this concern by selecting control cities that are comparable to treated cities in observable characteristics, except for their treatment status. Therefore, this study further applies a year-by-year PSM-DID strategy to re-estimate the policy effect. With the caliper set at 0.05, Columns (1), (2), and (3) of Table 5 present the results based on 1:2, 1:4, and 1:6 nearest-neighbor matching, respectively. The corresponding coefficients are 0.086, 0.087, and 0.085, and all are significantly positive. These findings suggest that, after alleviating potential sample selection bias, YRD Regional Integration continues to exert a significant positive effect on cities' GLD efficiency.

Table 5. Year-by-Year PSM-DID test and exclusion the influence of neighboring cities.

Variable	PSM-DID			Excluding the Influence of Neighboring Cities
	(1) <i>Green</i>	(2) <i>Green</i>	(3) <i>Green</i>	(4) <i>Green</i>
<i>DID</i>	0.086 * (0.047)	0.087 ** (0.041)	0.085 ** (0.040)	0.145 *** (0.040)
Control variables	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
Observations	1488	2156	2552	4610
R-squared	0.541	0.514	0.516	0.528

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Standard errors are reported in parentheses and clustered at the city level.

5.2.4. Excluding the Influence of Neighboring Cities

To address the concern that spatial spillovers from YRD Regional Integration may affect the estimated results, an additional robustness check is conducted by removing neighboring cities outside the YRD from the sample. Specifically, the baseline model is re-estimated after excluding 15 adjacent cities, including Rizhao, Linyi, and Zaozhuang. As shown in Column (4) of Table 5, the coefficient of the regional integration variable remains positive and statistically significant, both with and without control variables. This result suggests that the baseline estimates are unlikely to be driven by spillover effects from nearby cities. It also provides further evidence that YRD Regional Integration contributes to improving urban GLD efficiency.

5.2.5. Controlling for the Effects of Other Policies

Other policy interventions related to GLD may have occurred during the sample period in parallel with YRD Regional Integration. To strengthen the credibility of the baseline results, this study further incorporates controls for relevant concurrent policies into the baseline specification. First, the Low-Carbon City Pilot policy was designed to explore low-carbon development pathways and facilitate the low-carbon transition through mechanisms such as technological innovation. The National Development and Reform Commission introduced two batches of low-carbon provincial and city pilots in 2010 and 2012, and the pilot coverage was further extended in 2017. Second, the Emissions Trading Scheme pilot policy affects the low-carbon development of the manufacturing sector by directly restricting firm-level carbon emissions and defining carbon emission rights through market-based mechanisms. This study sets 2013 and 2016 as the effective response years for this policy. Third, the Green Finance Reform and Innovation Pilot Zone policy aims to strengthen financial support for green technology R&D, clean production, and low-carbon industries through the development of green financial products and the expansion of green financing channels. In 2017, China introduced this pilot policy in nine cities, including Guangzhou and Huzhou, and Lanzhou was subsequently included as a Green Finance Reform and Innovation Pilot Zone in 2019. Fourth, the River Chief System affects urban ecological improvement by clarifying responsibilities for river and lake governance, strengthening cross-regional water environment governance, and improving pollution prevention and control. Since 2008, Zhejiang Province has taken the lead in exploring the River Chief System at the provincial level. Other local governments have also carried out similar practices, and the system was eventually implemented nationwide in 2016. Fifth, the National Ecological Civilization Construction Demonstration Zone policy aims to improve the efficient and circular use of resources, promote energy conservation and emission reduction, and reduce carbon emission intensity. Since 2017, China has gradually established a number of National Ecological Civilization Construction Demonstration Zones.

Based on the above considerations, five policy dummy variables are constructed. Columns (1)–(5) of Table 6 present the corresponding estimation results. After each of these policy controls is introduced separately, the estimated coefficient of YRD Regional Integration remains positive and statistically significant at the 1% level. This finding indicates that the baseline results are unlikely to be explained by other concurrent green and low-carbon policies. It further supports the conclusion that YRD Regional Integration contributes to higher urban GLD efficiency.

Table 6. Results after controlling for the effects of other policies.

Variable	(1) <i>Green</i>	(2) <i>Green</i>	(3) <i>Green</i>	(4) <i>Green</i>	(5) <i>Green</i>
<i>DID</i>	0.149 *** (0.040)	0.153 *** (0.039)	0.147 *** (0.040)	0.123 ** (0.049)	0.146 *** (0.040)
<i>did_carbon</i>	0.022 (0.028)				
<i>did_trade</i>		0.049 (0.044)			
<i>did_fin</i>			0.035 (0.102)		
<i>did_river</i>				0.065 (0.046)	
<i>did_stwm</i>					0.016 (0.053)
Control variables	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
Observations	4872	4872	4872	4872	4872
R-squared	0.533	0.533	0.532	0.533	0.532

Notes: *** $p < 0.01$, ** $p < 0.05$. Standard errors are reported in parentheses and clustered at the city level.

5.2.6. Heterogeneous Treatment Effects

Because the treatment cities entered the YRD Regional Integration framework in different years, the coefficient estimated by a conventional staggered DID model represents, in essence, a weighted average of treatment effects across cohorts and time periods. When treatment effects vary across groups, however, some comparisons may be assigned inappropriate or even negative weights, even though the total weights add up to one. This issue may weaken the credibility of the staggered DID estimates. To assess whether the baseline results are affected by this weighting problem, this study employs the Goodman-Bacon decomposition [77]. Figure 4 shows that the main identifying variation comes from comparisons between treated cities and never-treated cities, which account for 92.73% of the total weight. In contrast, comparisons among groups treated at different times contribute 5.32%, while comparisons within treated groups account for only 1.95%. These decomposition results indicate that potentially problematic comparisons play only a limited role in the overall estimates. Thus, the baseline findings are unlikely to be driven by the weighting structure of the staggered DID model and can be considered robust.

To further address potential bias arising from heterogeneous treatment effects, four modern staggered DID estimators are adopted. First, following Callaway and Sant’Anna [78], this study estimates group-time average treatment effects and further evaluates the dynamic treatment patterns. Columns (1)–(4) of Table 7 present the overall average treatment effect and the group-specific average treatment effects for the 2010, 2016, and 2019 cohorts, respectively. Figure 5 displays the corresponding dynamic effects, showing that the pre-treatment trends are broadly comparable. Second, the imputation estimator

proposed by Borusyak et al. is used [79]. This estimator relies on a two-step procedure and avoids using earlier-treated units as controls, thereby improving the reliability of the robustness check. Third, following Sun and Abraham [80], group-period dynamic effects are estimated and then aggregated into average dynamic effects by event time. Fourth, from the perspective of stacked regression, this study applies the stacked DID estimator proposed by Cengiz et al. [81], where each stack contains observations from the treated cohort and the never-treated control group within the same event window. Columns (5)–(7) of Table 7 report the results from the latter three estimators. Across these alternative estimators, the coefficients remain consistent with the baseline estimates, suggesting that the main conclusion is not sensitive to heterogeneous treatment effects.

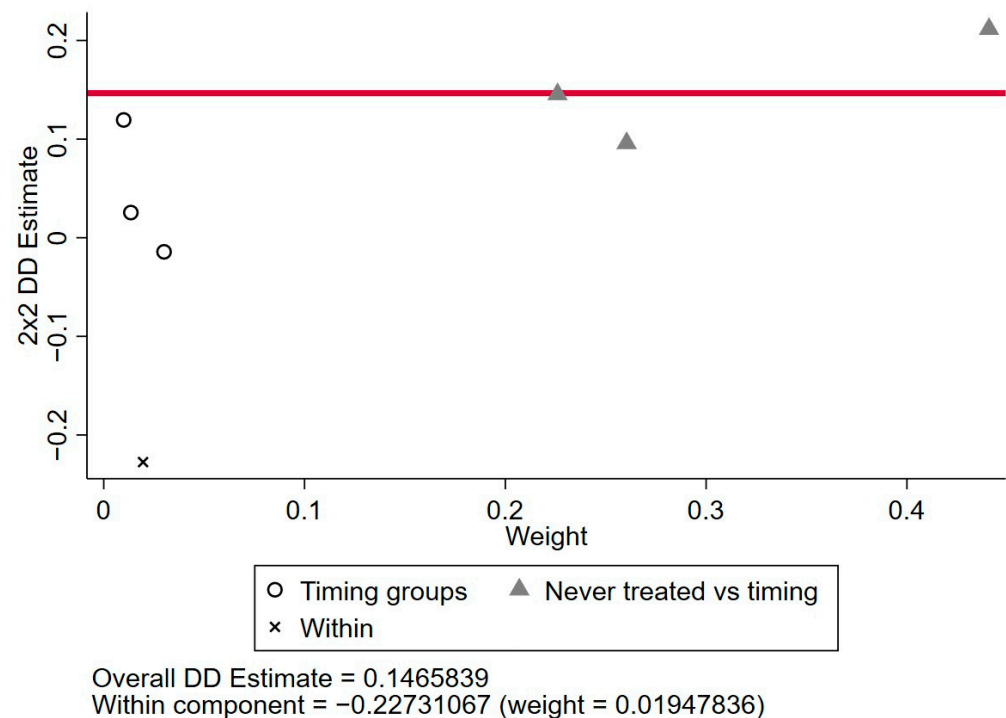


Figure 4. Multi-period DID weight share test.

Table 7. Results of heterogeneous treatment effects.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	<i>csdid</i> <i>Green</i>	<i>csdid</i> <i>Green</i>	<i>csdid</i> <i>Green</i>	<i>csdid</i> <i>Green</i>	<i>did_imputation</i> <i>Green</i>	<i>eventstudyinteract</i> <i>Green</i>	<i>stackeddev</i> <i>Green</i>
<i>DID</i>	0.192 *** (0.033)	0.204 *** (0.055)	0.174 ** (0.070)	0.154 * (0.089)	0.093 *** (0.032)	0.188 *** (0.033)	0.155 *** (0.039)
Control variables	YES	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES	YES
Observations	-	-	-	-	-	4872	13,140
R-squared	-	-	-	-	-	0.533	0.546

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Standard errors are reported in parentheses and clustered at the city level. The *csdid* and *did_imputation* regressions do not report items other than the estimated results. The larger sample size in Column (7) is due to the *stackeddev* command, which stacks the sample for estimation.

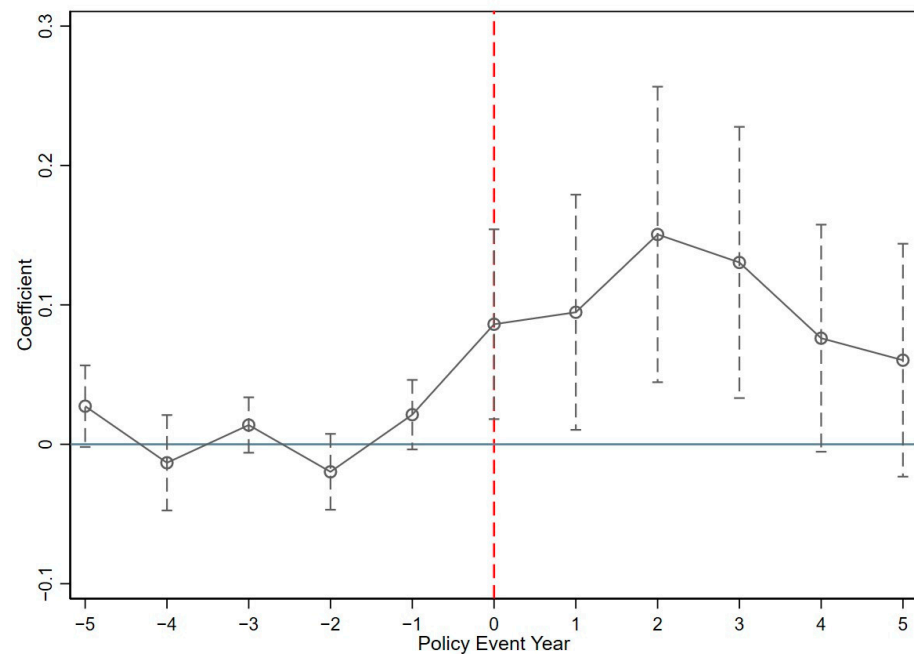


Figure 5. Overall parallel trend test.

5.3. Heterogeneity Analysis

5.3.1. Differences Across Cities of Different Sizes

Cities with different population scales may respond differently to regional integration policies, leading to heterogeneous policy effects. This study therefore examines whether the impact of regional integration on urban GLD efficiency varies across city-size groups. The corresponding results are presented in Table 8. Overall, YRD Regional Integration is found to improve GLD efficiency across different city-size categories, although the magnitude of the effect differs substantially. The coefficient is highest for megacities, implying that these cities benefit most from regional integration in terms of GLD efficiency improvement. Type I large cities also show a relatively strong positive response, suggesting that they are able to convert the institutional coordination and market integration advantages brought by regional integration into better GLD performance. In contrast, the coefficient for medium-sized cities is positive, but the corresponding promoting effect has not yet become fully evident.

Table 8. The impact of Yangtze River Delta regional integration on the GLD efficiency in different sizes cities.

Variable	(1) Megacity (>10 Million)	(2) Extra-Large (5–10 Million)	(3) Type I Large (3–5 Million)	(4) Type II Large (1–3 Million)	(5) Medium (0.5–1 Million)
	Green	Green	Green	Green	Green
<i>DID</i>	0.397 *** (0.079)	0.135 ** (0.061)	0.298 *** (0.079)	0.144 ** (0.059)	0.026 (0.074)
Control variables	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
Observations	4188	4206	4260	4440	4314
R-squared	0.549	0.554	0.546	0.545	0.552

Notes: *** $p < 0.01$, ** $p < 0.05$. Standard errors are reported in parentheses and clustered at the city level.

These results indicate that the effect of regional integration on the GLD efficiency of cities does not simply increase with city size. Instead, megacities benefit the most, followed

by type I large cities, while the effect on medium-sized cities appears more delayed. On the one hand, megacities usually have stronger industrial agglomeration capacity, technological innovation capacity, and environmental governance capacity. They can respond more quickly to regional integration policies and convert the institutional and market advantages brought by integration into GLD performance. On the other hand, medium-sized cities may also benefit from improved market accessibility and factor inflows under regional integration. However, their innovation capacity, industrial absorption capacity, and green governance foundation are relatively weaker. As a result, the policy effect may take longer to emerge and has not yet become significant. It is worth noting that the policy effect is significantly positive for type II large cities, and the estimated coefficient for medium-sized cities is not negative. This suggests that regional integration has not reduced the GLD efficiency of smaller cities. One possible explanation is that regional integration has raised environmental governance standards across the region. When smaller cities receive industries and participate in regional industrial specialization, they are often subject to stricter environmental standards. This can offset the potential negative effects of pollution transfer. In addition, some highly polluting and high-emission industries may have been transferred to cities outside the scope of YRD Regional Integration. This also helps explain why the estimated effects remain positive.

5.3.2. Differences Across Cities by Location

The YRD urban agglomeration shows clear center-periphery characteristics. The Guiding Opinions of the State Council on Promoting the Development of the Yangtze River Economic Belt by Relying on the Golden Waterway, hereafter referred to as the Opinions, also states that the region will form a multi-triangle and radial pattern of integrated development, namely a multi-center development pattern. This study defines Shanghai, Nanjing, Hangzhou, Hefei, Wuxi, Suzhou, Changzhou, and Ningbo as central cities, and the remaining 33 cities as non-central cities. The results are reported in Columns (1) and (2) of Table 9. The coefficients are significantly positive for both groups, suggesting that the green and low-carbon effects of regional integration are not limited to core cities. However, the effect is stronger for central cities. This indicates that central cities are better able to absorb and transform the institutional dividends and factor mobility advantages brought by regional integration. Future YRD Regional Integration should place greater emphasis on narrowing the green development gap between central and non-central cities.

Table 9. The impact of YRD regional integration on the GLD efficiency in central-peripheral cities.

Variable	(1) Central Cities	(2) Peripheral Cities	(3) Shanghai	(4) Jiangsu	(5) Zhejiang	(6) Anhui
	<i>Green</i>	<i>Green</i>	<i>Green</i>	<i>Green</i>	<i>Green</i>	<i>Green</i>
<i>DID</i>	0.290 *** (0.071)	0.122 *** (0.044)	0.489 *** (0.029)	0.216 *** (0.044)	0.262 *** (0.057)	0.031 (0.065)
Control variables	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES
Observations	4278	4728	4152	4368	4332	4422
R-squared	0.545	0.540	0.552	0.541	0.550	0.551

Notes: *** $p < 0.01$. Standard errors are reported in parentheses and clustered at the city level.

5.3.3. Differences Across Provinces

To examine whether the policy effect differs across provincial units, this study conducts a heterogeneity analysis for Shanghai, Jiangsu, Zhejiang, and Anhui. The estimation results are presented in Table 9. Clear provincial variation is observed in the impact of YRD

Regional Integration on urban GLD efficiency. The coefficient for Shanghai reaches 0.489 and is statistically significant at the 1% level, suggesting that Shanghai gains the largest GLD efficiency improvement from regional integration. The estimated coefficients for Jiangsu and Zhejiang are 0.216 and 0.262, respectively. The stronger effect observed in Zhejiang relative to Jiangsu may be associated with its more developed private economy and stronger digital economy foundation. In contrast, the effect for Anhui is relatively limited and has not yet become fully evident. As a late-developing province within the YRD, Anhui has received industrial relocation and factor inflows during the integration process. However, its comparatively weaker environmental governance capacity may expose some cities to greater environmental pressure. This may help explain why the GLD effect of regional integration has not yet fully materialized in Anhui. Future policy efforts should further facilitate the diffusion of green technologies, innovation resources, and environmental governance experience to late-developing cities in Anhui, thereby better aligning industrial relocation with green transition and improving the coordination and sustainability of regional integration.

6. Mechanism Analysis

The preceding results indicate that regional integration improves GLD in the YRD urban agglomeration overall and across different city groups within the region. To clarify the channels underlying this effect, this study further tests and compares several potential mechanisms using the empirical data. The corresponding results are reported in Tables 10 and 11.

Table 10. Mediation effect test (I).

Variable	(1) <i>Green</i>	(2) <i>Green</i>	(3) <i>Green</i>	(4) <i>Green</i>	(5) <i>Green</i>
<i>DID</i>	−0.064 *** (0.023)	0.130 * (0.076)	0.034 (0.024)	0.003 * (0.002)	0.022 *** (0.007)
Control variables	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
Observations	4400	4872	4872	4872	4846
R-squared	0.714	0.002	0.950	0.360	0.690

Notes: *** $p < 0.01$, * $p < 0.10$. Standard errors are reported in parentheses and clustered at the city level.

First, energy structure. The results in Column (1) of Tables 10 and 11 show that the coefficients are negative and significant at the 1% level. This suggests that YRD Regional Integration helps reduce dependence on highly polluting and high-carbon energy sources. It also promotes the optimization of the energy consumption structure, which provides important support for improving the GLD efficiency of cities. Hypothesis 1 is supported.

Second, industrial structure. The results in Columns (2) and (3) of Tables 10 and 11 suggest that YRD Regional Integration affects cities' GLD efficiency mainly through industrial reallocation and changes in regional industrial specialization, whereas the industrial upgrading channel has not yet obtained significant empirical support. In both tables, the coefficient reported in Column (2) is significantly positive. This result can be explained by the fact that, as regional integration advances, administrative barriers among cities are gradually reduced and the cross-city movement of industries and production factors becomes more efficient. Central cities or cities with strong production capacity may relocate part of their industrial activities to peripheral and late-developing cities, which can induce short-term changes in local industrial structures. Such reallocation may also improve resource-use efficiency in receiving cities, thereby contributing to higher GLD efficiency. By

contrast, the coefficient in Column (3) is positive but statistically insignificant in both tables, indicating that technological upgrading and changes in production modes may require a longer period to materialize. Therefore, Hypothesis 2 is mainly supported through the industrial restructuring mechanism.

Table 11. Mediation effect test (II).

Variable	(1) <i>Green</i>	(2) <i>Green</i>	(3) <i>Green</i>	(4) <i>Green</i>	(5) <i>Green</i>
<i>energy</i>	−0.328 *** (0.079)				
<i>structure1</i>		0.001 *** (0.000)			
<i>structure2</i>			0.058 (0.076)		
<i>attention</i>				0.989 ** (0.423)	
<i>innovation</i>					1.390 *** (0.168)
Control variables	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
Observations	4400	4872	4872	4872	4846
R-squared	0.549	0.527	0.527	0.527	0.543

Notes: *** $p < 0.01$, ** $p < 0.05$. Standard errors are reported in parentheses and clustered at the city level.

Third, government attention to GLD. The results in Column (4) of Tables 10 and 11 show that regional integration has a positive effect on government attention to GLD. As regional development goals and a coordinated environmental governance system gradually take shape, local governments attach greater importance to GLD. Inter-city competition has also shifted from a narrow focus on economic growth to a broader competition that also considers green performance and low-carbon transition. Hypothesis 3 is supported.

Fourth, green innovation. The results in Column (5) of Tables 10 and 11 indicate that regional integration policies significantly stimulate urban green innovation, thereby contributing to improvements in GLD efficiency. By enlarging market size, facilitating knowledge diffusion, and deepening cross-city innovation collaboration, regional integration creates more favorable conditions for the development and application of green technologies. Stronger green innovation can also upgrade production technologies, lower pollution-control costs, and improve resource-use efficiency. In this sense, green innovation serves as a key mechanism through which regional integration advances GLD. Thus, Hypothesis 4 is supported.

Overall, the two-step regression results indicate that YRD Regional Integration enhances cities' GLD efficiency mainly through energy structure adjustment, industrial restructuring, greater government attention to GLD, and stronger green innovation.

7. Discussion and Conclusions

This study takes cities within the YRD regional integration framework as the research sample and employs a multi-period difference-in-differences model to evaluate the effect of regional integration on urban GLD. It further examines the mechanisms through which this effect operates. The empirical results show that YRD regional integration significantly improves urban GLD efficiency and contributes to the transition toward low-carbon urban growth. The policy effect is heterogeneous, with more pronounced impacts in megacities and core cities. The mechanism analysis further indicates that regional integration

promotes GLD mainly through energy structure optimization, industrial restructuring, stronger government attention to GLD, and green innovation. Based on these findings, this study proposes the following policy implications for deepening regional integration and advancing urban GLD in the YRD.

First, regional green integration should be further strengthened. The empirical evidence suggests that regional integration is an effective pathway for improving urban GLD efficiency and can support the achievement of carbon peaking and carbon neutrality goals under the combined pressures of pollution reduction and high-quality development. Future policies should place greater emphasis on deepening green coordination across cities, improving ecological governance, and building more livable and environmentally friendly urban spaces. Specifically, the responsibilities and regulatory boundaries of each city in ecological governance should be clarified, with greater attention given to collaborative pollution prevention and control. Unified standards for ecological governance and restoration should be implemented more strictly, and monitoring and evaluation systems related to environmental protection, carbon reduction, and pollution control should be improved to strengthen mutual supervision among cities. In addition, ecological compensation and incentive mechanisms should be further explored. Subsidies or other forms of support can be provided to enterprises or local governments that generate positive environmental externalities, thereby encouraging broader participation in environmentally beneficial practices.

Second, the leading role of central cities should be further strengthened to support GLD in late-developing cities. The heterogeneity analysis shows that the coefficients for medium-sized cities and cities in Anhui are positive but not yet statistically significant. Therefore, a cross-provincial negative list for industrial relocation should be established. Core cities should concentrate on R&D, headquarters functions, design services, and high value-added manufacturing, whereas peripheral cities should apply strict standards for environmental carrying capacity, energy efficiency, and total pollutant control when undertaking manufacturing relocation. Such arrangements can help prevent the transfer of low-end and pollution-intensive industries and guide regional integration from simple spatial expansion toward coordinated green development.

Third, policy efforts should focus on the key mechanisms that drive GLD. The empirical results show that regional integration improves urban GLD efficiency mainly through energy structure optimization, industrial rationalization, stronger government attention, and green innovation. Future integration policies should promote the wider use of low-carbon energy in transportation, construction, agriculture, industry, services, and household consumption, while increasing the R&D and application of renewable and clean energy sources such as wind, solar, and biomass. In addition, a green industrial system with lower energy consumption and lower pollution intensity should be developed by reducing the share of high-energy and high-pollution sectors and expanding low-energy and low-pollution industries. Local governments should also strengthen ecological awareness and align policy implementation with green development objectives, so that ecological protection can be better integrated with economic growth. Furthermore, urban green innovation should be promoted by mobilizing regional resources, concentrating innovation factors, and developing green industrial chains, thereby supporting the YRD in becoming a world-class demonstration region for green innovation.

This study has several limitations that provide directions for future research. First, although a robustness test is conducted by excluding neighboring cities, the direction, intensity, and spatial range of spillover effects require further examination. Second, the analysis focuses on the YRD, a region with distinctive institutional arrangements, industrial characteristics, and governance capacity. Whether the conclusions can be extended to other

regional integration contexts should therefore be assessed by considering differences in development stages and policy environments. Third, future studies may conduct comparative analyses across multiple urban agglomerations to further explore how regional integration influences GLD efficiency in different types of urban agglomerations.

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