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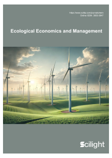

Article

A Study on the Statistical Measurement and Determinants of China’s Energy Transition from a Justice Perspective

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Abstract: Currently, research on measuring energy transition fairness at the provincial level is still insufficient. Therefore, in this paper, based on the dual carbon goals, we used panel data from 31 Chinese provinces from 2010 to 2023 to build a comprehensive evaluation system that combines transition outcomes with energy fairness. We applied the entropy method, DEA model, and TOPSIS model to calculate the energy transition fairness level of each province, and then used a two-way fixed effects panel model to identify the driving mechanisms. The results show that the national level of energy transition fairness has steadily improved, but there are significant regional differences: first, the western region has the best overall transition foundation, while the eastern region leads in transition efficiency; second, economic development has a stage-specific negative impact on transition fairness, while per capita fiscal capacity is a crucial positive driving factor; third, the impact of various factors differs across regions. Based on the findings of this study, it’s recommended to adopt targeted policies, such as region-specific support, optimizing green financial investments, and setting up a dynamic provincial monitoring system, so that energy use can be both efficient and fair during the transition.

Keywords: justice perspective; energy transition; statistical measures; influencing factors

1. Introduction

1.1. Research Background and Practical Significance

As we all know, the green and low-carbon transition of energy is an important way to tackle global climate change. In China’s energy transition practice, the coal consumption intensity per unit of GDP has been steadily decreasing, as shown in Figure 1. This change indicates that China’s energy efficiency is steadily improving, and the energy structure is continuously being optimized—it’ s a clear reflection of the phased achievements in energy transition. However, it’s important to note that energy transition is not just about upgrading technology and industry; it also involves the reorganization of interests, risks, and power. China has a massive population, and its energy transition is huge and very complex. During the transition, it’ s not only about driving economic growth and achieving common prosperity, but also about paying attention to fairness in energy transition. How to fairly allocate emission reduction responsibilities, and narrow the gap in energy acquisition and utilization between regions, remains a practical problem that needs to be solved.

In this context, the concept of “energy justice” has gained increasing attention: it advocates that the benefits and costs resulting from the energy transition should be fairly distributed among populations, regions, and generations. China’s energy transition not only has to deal with the complexity caused by its “huge population size”, but also needs to take into account the modernization goal of “harmonious coexistence between humans and nature”. Therefore, it cannot only focus on efficiency improvement, but must also incorporate the dimension of justice into policy design. Current research is insufficient in terms of how to measure "energy justice" and its driving factors at the provincial level, and this is precisely the practical issue that this article intends to address.

Therefore, this study attempts to construct a comprehensive evaluation index system that integrates "transformation effectiveness" and "fairness dimension". By using methods such as entropy value method, DEA model, and TOPSIS comprehensive measurement, it calculates the energy fair transition level of 31 provinces across the country from 2010 to 2023. At the same time, it analyzes the temporal and spatial changes and influencing factors. Theoretically, this paper integrates multiple dimensions such as distribution fairness, procedural fairness, and sustainable fairness with the transformation effectiveness indicators, and builds a quantitative analysis framework tailored to China's national conditions, bringing new measurement ideas and methods to the study of energy fairness; Practically, the research results are beneficial for governments at all levels to identify the shortcomings in the transformation process of each province, providing empirical data for designing regional policies that balance efficiency and fairness, facilitating the smoother and more inclusive implementation of energy transformation, and contributing to the achievement of the "dual carbon" goals and the implementation of the common prosperity strategy.

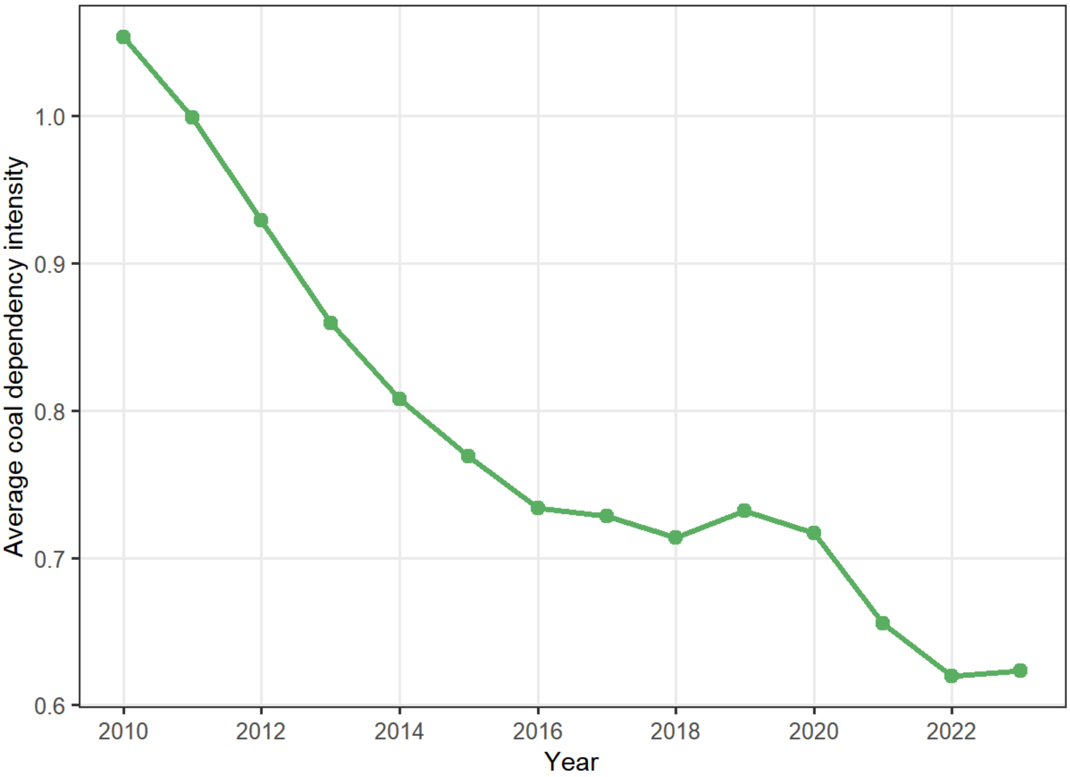

Figure 1. Changes in the national average coal dependency intensity.

1.2. Research Status and Literature Review

The energy just transition, as a key issue under the "dual carbon" goal, has received much attention within the scope of energy economy and sustainable development. There have been numerous studies on its theoretical connotation, measurement methods, influencing mechanisms, and policy practices, which have provided a solid foundation for this research.

With the continuous advancement of the dual-carbon strategy, research on energy transition has increasingly emphasized social equity, making energy justice an important research focus. Some scholars have explored the impact of air pollution control on people's livelihoods during the energy transition, analyzing its actual effects on residents' daily energy burdens [1]. At the same time, domestic scholars continue to explore practical paths for low-carbon transitions in energy systems. Using Guangzhou as a case study, they focus on the energy system transformation issues in megacities, carrying out targeted research on optimizing transition paths, providing a reference plan for similar cities in the country to improve their energy transition systems [2]. Domestic research has concentrated on the effectiveness of policy implementation, systematically examining the significant changes in the energy consumption structure of urban and rural households following the implementation of low-carbon city pilot programs [3]. At the industry transition level, some scholars have dialectically analyzed the conflict between the demand for decarbonization and the retention of traditional technologies, examining the multiple impacts of this interaction on low-carbon development in the global transportation sector [4]. From the perspective of urban sustainable development, numerous studies have confirmed that green technologies and clean energy can effectively regulate the relationship between urbanization and climate change [5]. To promote a fair transition, academia has begun to focus on addressing energy poverty, continuously exploring feasible pathways for a just transition to a low-carbon society [6]. From the viewpoint of residential space differences, varying property attributes result in clear stratification of household energy use and carbon emissions, further widening social disparities in energy consumption [7]. Grassroots governance conditions and regional development capabilities have also been confirmed as essential foundational conditions for ensuring the smooth and fair advancement of energy transition at the local level [8]. On an international scale, studies using G7 countries as a sample indicate that fluctuations in energy markets and levels of social equity directly affect the overall effectiveness of coordinated development between energy transition and ecological protection [9].

At the level of theoretical improvement and empirical measurement, academic research results are increasingly abundant. Aybudak and others conducted empirical analyses based on samples from multiple countries, confirming that strict environmental policies can create a synergistic effect with renewable energy and green technologies, together helping energy-transition economies achieve environmental sustainability [10]. Taking into account the national development context of China, scholars have established a policy-oriented quantitative evaluation system for social justice in energy transition, making fairness assessments more standardized and reasonable [11]. The academic community generally believes that a just energy transition is not simply a structural adjustment; a complete evaluation system is required to achieve precise quantitative assessments [12]. Relying on the perspectives of social equity and energy justice, optimized evaluation models can scientifically conduct comprehensive benefit assessments of various domestic energy transition policies [13]. Based on the overall framework of carbon neutrality and considering multiple socioeconomic factors, it is possible to outline a development approach for energy justice transition that better fits China’s development circumstances [14]. Using public value theory can broaden the research perspective on energy justice and better clarify the decision-making logic of various actors in the energy transition process [15]. From the perspective of the global development pattern, energy development models vary significantly across countries, and the resulting social equity issues urgently need coordinated solutions [16]. By optimizing and improving quantitative indicators and calculation methods, the accuracy of energy justice assessment results can be greatly enhanced [17]. The practical experience of transforming traditional industrial regions also provides mature and feasible approaches for other regions to avoid unbalanced energy transitions [18]. In terms of theoretical innovation, the introduction of the concept of restorative justice has refreshed academic understanding of development issues inherited from the fossil energy era [19]. Based on a critical perspective on energy justice, it is also possible to clearly identify various real contradictions hidden within current mainstream low-carbon transition models [20].

Overall, existing research still has room for expansion in the following areas: the integration of justice dimensions with transition outcomes remains insufficiently in-depth, with discussions largely focused on theoretical explanations and a comprehensive quantitative measurement system yet to be established; research scales remain generally macro-level, with relatively limited work utilizing provincial-level long-term panel data to conduct spatiotemporal differentiation and heterogeneity analyses; the identification of impact mechanisms and policy design also remain rather general, with a prevalence of national-level analyses and a scarcity of empirical studies on regional differences, resulting in limited support for the implementation of policies. To address these shortcomings, this paper uses China’s 31 provinces from 2010 to 2023 as a sample to construct a comprehensive energy transition measurement model that incorporates equity considerations. It systematically analyzes spatiotemporal characteristics and influencing factors, aiming to provide more granular empirical support and policy references for China’s just energy transition.

1.3. Research Content and Methodological Approach

In recent years, we have been in a crucial stage where the “dual carbon” goal is being deeply advanced and the energy structure is undergoing a profound transformation. Energy transition is no longer merely focused on improving efficiency; its underlying fairness attribute has gradually become an important issue for resolving the pain of the transition and ensuring the sustainable development of the social economy. Each province, as the core carrier of energy production and consumption and the implementation site of transformation policies, presents significant imbalances in the process of energy fair transition due to differences in economic foundation, resource conditions, and policy support intensity among different regions and provinces. Based on the above analysis, the core content of this research is to construct a measurement system for provincial energy fair transition and analyze its temporal and spatial characteristics (see Figure 2). Currently, most of the research focuses on the national macro level, and the measurement dimensions are mostly single-pointed at the effectiveness of the transition, without attaching importance to the core values of fairness dimensions such as distribution fairness, procedural fairness, and sustainable fairness. This research breaks through the limitations of traditional measurement and relies on the multi-dimensional framework of energy fairness to build a comprehensive evaluation index system that combines transition effectiveness and fairness dimensions. Specifically: The transition effectiveness dimension takes the substitution of clean energy and the improvement of energy efficiency as the two core directions; the fairness dimension is further divided into three sub-dimensions of distribution fairness, procedural fairness, and sustainable fairness, covering both the efficiency and fairness dual goals of energy transition in an all-round way.

The current studies lack systematic understanding of the logical effects of various influencing factors and the heterogeneity mechanism. Particularly, there are shortcomings in the analysis of the collaborative effects of multiple dimensions of factors at the provincial scale. This study utilizes the classic analysis framework of energy transition influencing factors, selects core explanatory variables from five aspects: economy, policy, technology, resources, and society, and introduces control variables to build a two-way fixed effect panel data model. This model has been verified to have good applicability in empirical research on energy transition and will conduct robustness tests, group heterogeneity regression analysis, etc. to accurately identify the net effects and action pathways of each factor, providing solid empirical support for the formulation of differentiated and precise energy fair transition policies.

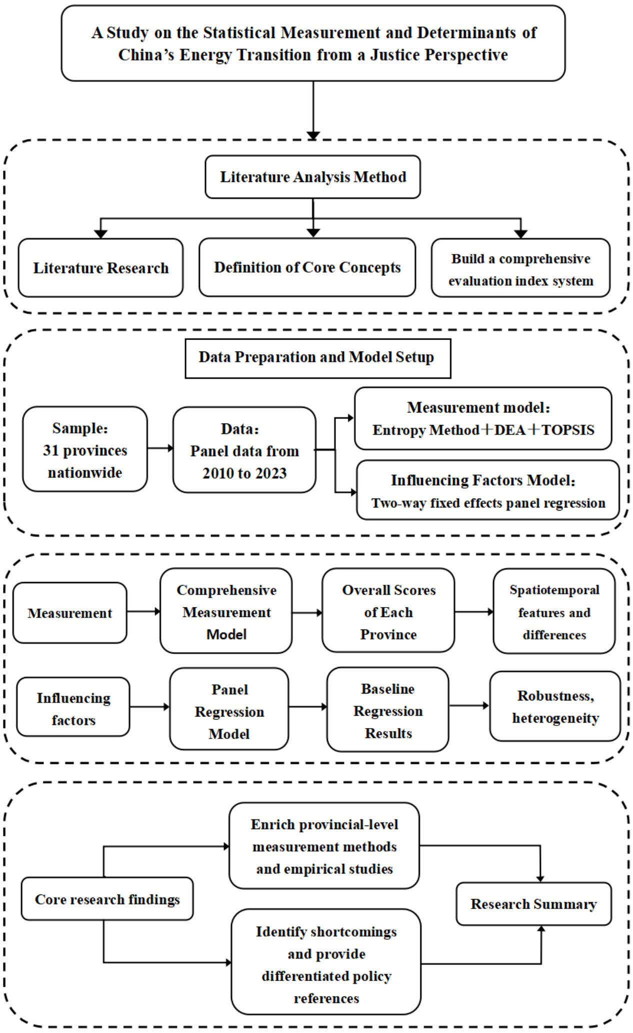

Figure 1. Technology road map

1.4. Research Innovations

This research aims to make breakthroughs in theoretical perspectives, analytical scales, methodological systems, and policy applications. Existing studies on energy transition measurement mostly focus on technical efficiency and economic performance, with insufficient attention paid to the social equity dimension during the transition process and scattered measurement methods. This research breaks the traditional limitation of only emphasizing effectiveness while neglecting equity, and systematically integrates the three core dimensions related to energy justice theory, namely distributive justice, procedural justice, and sustainable justice, with transition effectiveness indicators such as clean substitution and energy efficiency improvement. It has established a comprehensive evaluation framework with both transition effectiveness and equity dimensions as the core. This framework not only expands the quantitative connotation of energy transition but also provides a new theoretical analysis perspective for coordinating efficiency and equity and promoting inclusive transformation under the "dual carbon" goals.

The existing empirical studies mostly treat the country as the unit for macro analysis, making it difficult to reveal the micro heterogeneity of the transformation process and the related issues of justice. This study lowers the observation scale to the provincial level and conducts measurement and attribution analysis based on the national 31 provincial panel data from 2010 to 2023. The choice of this scale can more accurately capture the differences and fairness shortcomings in the transformation of provinces under different resource endowments, development stages, and policy environments. For example, problems such as employment impacts faced by resource-based provinces and the poor accessibility of clean energy in underdeveloped regions, which fill the gap in the empirical research on the energy justice transformation system at the provincial level.

Meanwhile, this study overcame the limitations of a single measurement method by establishing a comprehensive quantitative measurement and testing system that integrates multiple methods. It employed entropy method, data envelopment analysis, and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach to scientifically assess the overall level of energy just transition. In terms of mechanism testing related work, it utilized the construction of a two-way fixed effect panel model, and employed the instrumental variable method to address endogeneity issues, conducting multi-dimensional robustness tests and heterogeneous group regressions. This methodological system systematically analyzed the complex interaction patterns of multiple factors such as economic development, policy regulations, and technological innovation on just transition, thereby enhancing the robustness and reliability of the research conclusions.

Finally, this study not only conducts phenomenon measurement and mechanism verification, but also attaches great importance to the value of the transformation of outcomes and policies. Based on conducting heterogeneity analysis, it reflects the differentiated paths and constraints of eastern, central and western regions, as well as resource-based and non-resource-based provinces in promoting fair transformation. The policy recommendations proposed here focus on improving the mechanism of interest distribution, optimizing the public participation procedures, and enhancing the social security during the transformation process. The goal is to provide empirical evidence for the government to develop differentiated and precise policy toolboxes that are both efficient in transformation and inclusive in society, so as to drive China's energy transformation from a stage of "prioritizing speed" towards a high-quality development stage that balances fairness and efficiency.

2. Conceptual Definitions and Theoretical Analysis

2.1. Definition of Concepts Related to Energy Just Transition

From a fair perspective, the energy transition refers to the process in which the energy system undergoes a transformation towards green and low-carbon, with the systematic integration of the concepts of fairness and justice. The aim is to achieve the coordinated development of transition efficiency and social equity. It not only pursues a clean energy structure and improved energy efficiency, but also emphasizes the reasonable distribution of transition costs, benefits, and risks among individuals, regions, and generations.

Its core connotation generally covers three aspects: distribution justice focuses on the fair enjoyment of energy resources and transition dividends, especially the accessibility and affordability for disadvantaged groups and underdeveloped regions; procedural justice emphasizes the openness and transparency of the energy decision-making process and the participation of multiple stakeholders, ensuring the rights of stakeholders to understand the situation and express their opinions; sustainable justice will coordinate the long-term stability of environmental health, social inclusiveness, and economic resilience, emphasizing intergenerational equity and ecological protection efforts.

In China, fair energy transition has been given specific localized goals. It must serve the "dual carbon" goals and the common prosperity strategy, make efforts to solve the energy service gap between urban and rural areas and regions, ensure that workers in traditional energy industries and other groups can transition fairly, and reflect the "harmonious coexistence of man and nature" advocated by Chinese-style modernization. Therefore, this study will be based on the three-dimensional framework of "distribution–procedure–sustainability" of fairness, combine the transition effectiveness indicators, and build a comprehensive evaluation system, using this as empirical evidence for statistical measurement and impact mechanism analysis.

2.2. Theoretical Analysis of Energy Just Transition

This study takes the theory of energy justice as the core ethics and analytical framework. This theory transcends the traditional perspective of efficiency and establishes the fair distribution of energy benefits and costs, the inclusiveness and participation of decision-making, as well as the respect for the rights and cultures of different groups as the basic criteria for evaluating the transformation process. It provides direct theoretical references for building a multi-dimensional measurement index system that balances efficiency and fairness for this study.

From the perspective of development motivation, the theory of green new quality productive forces plays a key supporting role in understanding the driving mechanism of just transformation. This theory emphasizes that the new productive force, with technological innovation as the core driving force, green industries as the carrier, and resource efficient allocation as the basic feature, not only drives the technological innovation and structural optimization development of the energy system, but also uses channels such as creating high-quality employment, improving energy accessibility, and optimizing benefit distribution to become a fundamental factor in jointly promoting the efficiency of transformation and social fairness, laying a theoretical foundation for the selection of the core explanatory variables and the analysis of the influencing mechanism of this study.

From the perspective of system coordination, the theory of regional coordinated development and the theory of sustainable development jointly provide guidance for the spatial and temporal dimensions of just transformation: The former emphasizes eliminating the heterogeneity of geography and economy, requiring transformation policies to respond to the differences in resource endowment, development stage, and bearing capacity of different regions, in order to achieve the reasonable sharing of transformation responsibilities and the common enjoyment of development dividends; the latter focuses on intergenerational fairness and ecological constraints, advocating that energy transformation should be placed within the framework of "harmonious coexistence between humans and nature", ensuring that contemporary development does not affect the ability of future generations to meet their own energy needs and environmental well-being. These two theories together support the examination of the spatial and temporal differentiation characteristics and the sustainable just dimension in this study.

3. Development of the Indicator System and Data Notes

3.1. Construction of the Indicator System

This study constructs a comprehensive evaluation index system for energy just transition from two aspects: transformation effectiveness and fairness. It covers 3 input indicators and 4 output indicators (see Table 1):

Table 1. Construction of the Indicator System.

Dimension	No.	Indicator Name	Calculation Method	Unit	Direction
Transformation Effectiveness	E1	Per capita regional GDP	GDP_ pc	yuan	Positive ↑
	E2	Per capita electricity consumption	elec _cons × 10^8 ÷ (pop × 10^4)	kWh/person	Positive ↑
	E3	Coal Dependency	Coal consumption ÷ Total GDP	10,000 tons per 100 million yuan	Negative ↓
Fairness Dimension	J1	Per capita fiscal revenue	fiscal _rev	100 million yuan	Positive ↑
	J2	Per capita water consumption	water _use_ pc	cubic meters per person	Positive ↑
	J3	Total Water Resources	water _total	billion cubic meters	Positive ↑
	J4	Environmental Investment/GDP	env_ gdp _ratio	%	Positive ↑

Note: The upward arrows indicate that the indicator is a positive dimension; the downward arrows represent a negative dimension.

3.2. Notes on the Data

The dataset used in this study covers relevant data from 31 provinces across the country from 2010 to 2023, including 434 observations. The data mainly comes from the China City Statistical Yearbook and the EPS global data statistics platform. Some of the original panel data had missing values, which were all filled in using linear trend extrapolation. At the same time, all the indicators in this study follow the unified accounting standards of the official national statistical yearbooks.

4. Research Methods and Statistical Measures

4.1. Descriptive Statistical Analysis

To clearly understand the overall distribution and dispersion characteristics of each core variable, this paper first conducts descriptive statistical analysis on each indicator, and the results are shown in the following table (see Table 2).

Table 2. Descriptive Statistics.

Variable	N	Mean	Median	Minimum	Maximum
GDP per capita (yuan)	434	60,184	52,333	13,119	200,278
Electricity Consumption (billion kWh)	434	2087	1578	20	8502
Coal consumption (10,000 tons)	434	14,465	11,487	0	63,707
Per capita fiscal revenue (billion yuan)	434	2758	2090	37	14,105
Total Population (in thousands)	434	4469	3857	300	12,706
Total Water Resources (billion cubic meters)	434	919	610	8	4750
Per capita water consumption (cubic meters per person)	434	512	438	161	2657
Environmental Investment as a Percentage of GDP (%)	434	1	1	0	5

4.2. DEA-Based Assessment of Energy Just Transition Efficiency

This study uses an output-oriented variable returns to scale (VRS) DEA model to measure the relative efficiency of each province in achieving an energy just transition. The input indicators are chosen to reflect the basic support conditions for an equitable energy transition: total population indicates the scale of regional energy consumers, environmental governance investment represents the capital input from local governments for a low-carbon transition, and coal dependence intensity shows the constraints of being locked into traditional energy paths. The output indicators focus on the economic and livelihood energy benefits brought by the transition, with per capita GDP showing the overall economic development progress of the region and per capita electricity consumption measuring the level of basic energy services accessible to residents. These indicators align with our study's evaluation logic, which balances efficiency and fairness in the energy transition.

It should be noted that under the output-oriented setting, the interpretation of efficiency values is different from conventional understanding: when the efficiency value is exactly 1, it means that the province is on the production frontier and is relatively efficient; once the efficiency value is greater than 1, the higher the value, the lower the efficiency. It measures "how much more output is needed to reach the frontier level". For example, an efficiency value of 1.762 indicates that, with unchanged inputs, the output of this province needs to increase by 76.2% to reach the effective frontier.

Figure 3 illustrates the temporal changes in the national average DEA efficiency for energy just transition from 2010 to 2023. Under an output-oriented framework, an efficiency value greater than 1—and the higher the value—indicates lower efficiency. The average efficiency remained above 1 throughout the sample period, indicating that the national average efficiency has not yet reached the production frontier, and there is still room for improvement in output levels. Specifically, the average efficiency was highest in 2010, approaching 2.0, corresponding to the low point of the national average transition efficiency, when the need for output improvement was most pressing. Subsequently, the efficiency value declined in a stepwise manner; after 2014, the amplitude of fluctuations narrowed significantly, and after 2018, it fluctuated within a narrow range of 1.55 to 1.65, reflecting a gradual improvement in transition efficiency and a gradual narrowing of the scope for output improvement. This trend is highly correlated with key milestones such as the implementation pace of energy policies and industrial restructuring, clearly illustrating the phased evolution of China's just energy transition efficiency.

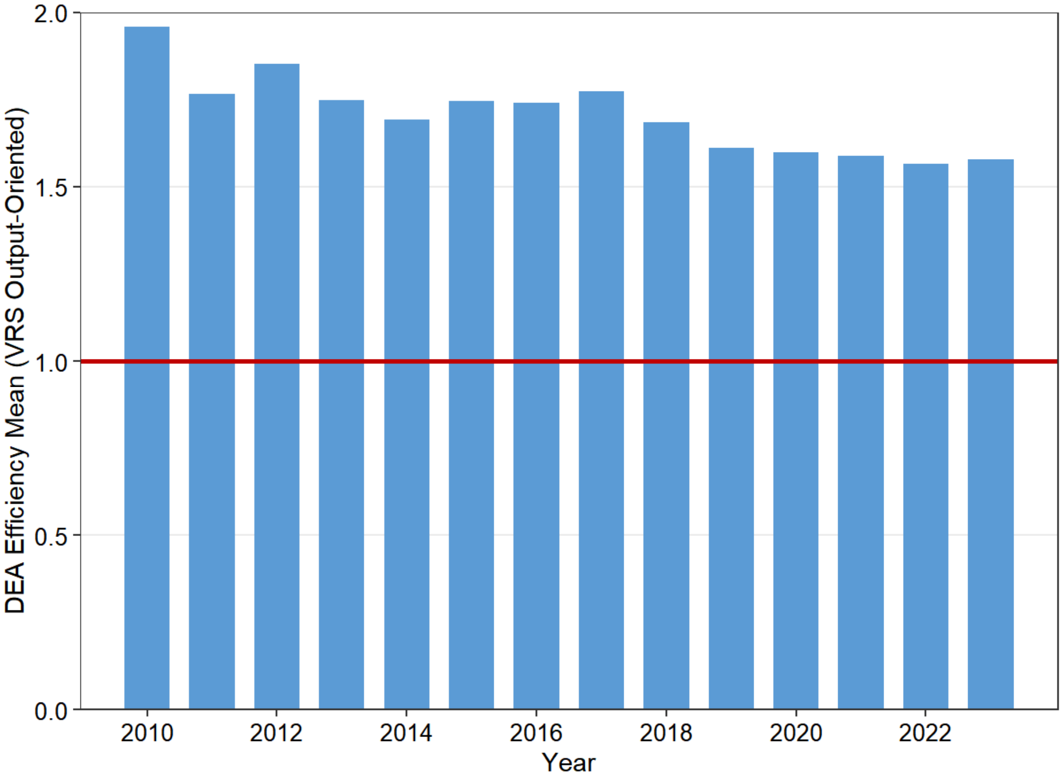

Figure 3. Changes in the Mean DEA Efficiency of National Energy Transition (2010–2023).

4.3. Measurement of Energy Justice Transition Level Based on TOPSIS

The entropy method determines weights based on the information content of each indicator's data, thereby avoiding subjective weighting biases. The specific steps are as follows:

Step 1: Normalization. Positive indicators are standardized using range normalization, while negative indicators (E3) are standardized using reverse range normalization, mapping all indicators uniformly to the [0,1] interval.

Step 2: Calculate information entropy. After converting the standardized matrix into a proportion matrix, calculate the information entropy $e_j = -(1/\ln n)\bullet\sum(p_{ij}\bullet\ln p_{ij})$ column-wise, where n is the sample size (n = 434).

Step 3: Determine weights. The coefficient of variation is calculated as $d_j = 1 - e_j$, and after normalization, the weights for each indicator are obtained as $w_j = d_j/\sum d_j$.

The specific calculation results are presented in Table 3:

Table 3. Weighting Results Using the Entropy Method.

No.	Indicator Description	Information Entropy e_j	Coefficient of Variation d_j	Weight w_j
E1	Per capita GDP (yuan)	0.9666	0.0334	0.1047
E2	Per capita electricity consumption (kWh/person)	0.9645	0.0355	0.1115
E3	Coal dependency intensity (10,000 tons per 100 million yuan)	0.9918	0.0082	0.0256
J1	Per capita fiscal revenue (100 million yuan)	0.9448	0.0552	0.1733
J2	Per capita water consumption (cubic meters per person)	0.9234	0.0766	0.2403
J3	Total water resources (billion cubic meters)	0.9232	0.0768	0.2410
J4	Environmental Investment as a Percentage of GDP (%)	0.9670	0.0330	0.1036

Note: J2 (per capita water consumption) and J3 (total water resources) have very high weights, reflecting significant differences in water resource endowments across provinces; E3 (coal dependency intensity) has the lowest weight, indicating that this indicator provides relatively limited information across provinces.

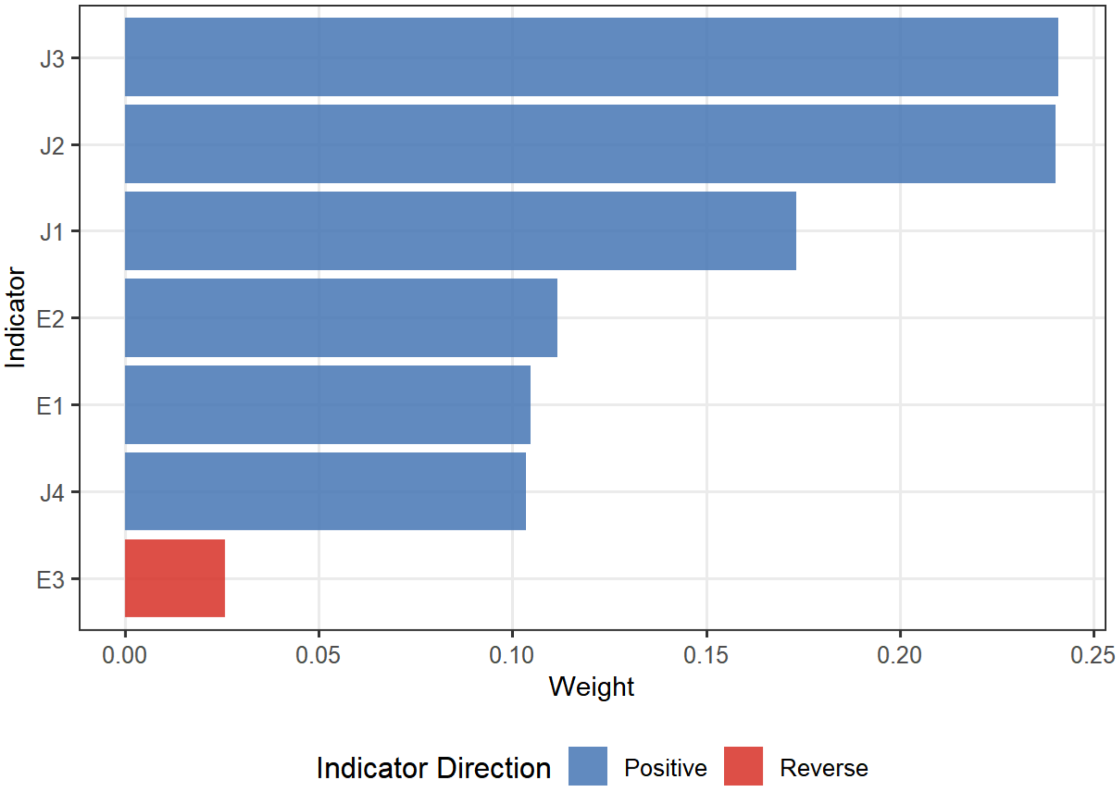

Figure 4. Weights of indicators in the entropy method.

Based on the weights provided by the entropy method, the proximity scores were obtained by calculating the Euclidean distances between the observed values of each province in each year and the positive and negative ideal solutions. These scores were then linearly normalized to the range [0, 1], yielding the comprehensive score for energy just transition.

As can be seen from the graph (see Figure 4), the overall performance of the national energy just-transition TOPSIS comprehensive score from 2010 to 2023 shows that although there were short-term fluctuations, there was a steady upward trend over a long period. During the sample period, the score was always within the range of 0.35 to 0.46, with an overall level that was acceptable and continuously improving in a positive direction. There was a phased decline in 2010–2011, and then it rebounded rapidly after 2011; from 2012 to 2014, it entered a small-scale adjustment stage, with the score fluctuating within the range of 0.39 to 0.41; starting from 2015, it entered a continuous upward trend, and after 2016, the growth trend became stable, although there was a slight decline in some years, the overall trend was upward, and in 2023, it reached the highest value within the sample period.

This trend indicates that the process of energy just-transition in China is affected by factors such as early policy alignment and market fluctuations. There are short-term adjustment phenomena, but since the mid-term of the “12th Five-Year Plan”, with the gradual realization of energy structure optimization, the implementation of energy conservation and emission reduction policies being in place, and the improvement of regional coordinated development mechanisms, the level of energy just-transition has entered a gradually upward stage, and the long-term positive development situation has been basically established (see Figure 5).

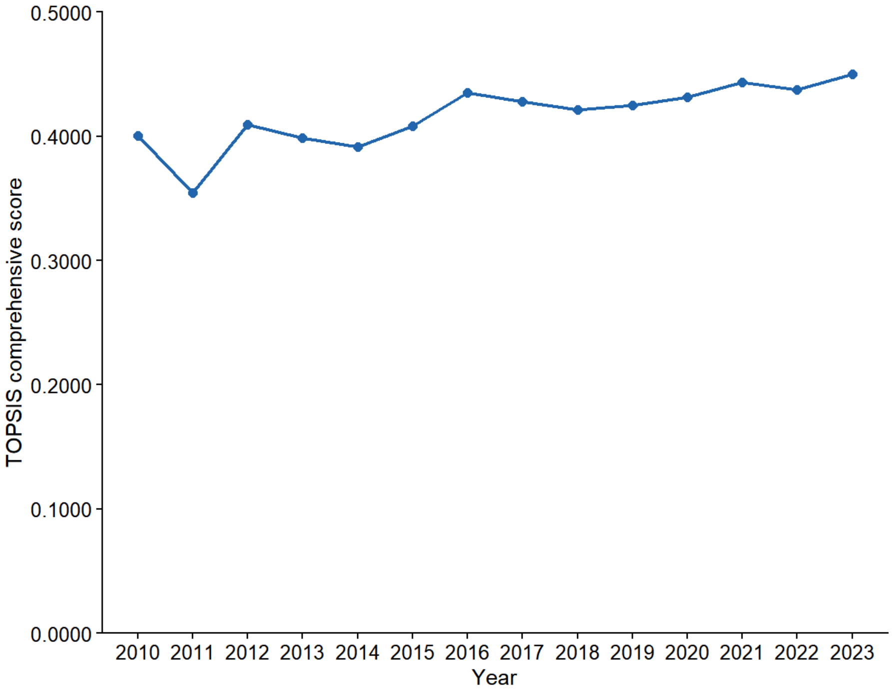

Figure 5. Average National Comprehensive Score for Energy Just Transition (2010–2023).

4.4. Regional Differences in Energy Just Transition

At the regional level, a pattern of significant divergence has emerged:

As shown in Table 4: The comprehensive score of TOPSIS gradually decreases from west to east. The western region leads all the other regions with an average value of 0.500. The central region ranks second, and the eastern region has the lowest value. This indicates that the western region has a relative advantage in the overall transformation conditions. The mean value of DEA efficiency shows an opposite ranking: central > western > eastern. Considering the meaning of the output-oriented model that "the larger the value, the lower the efficiency", the mean value of efficiency in the eastern region is closest to 1, indicating that its output efficiency is the highest under the given input conditions. While the efficiency value of the central region is the highest, meaning that the space for output development is the largest and the pressure on transformation efficiency is the most obvious.

Table 4. Regional Patterns.

Regional	Provincial Composition	TOPSIS Average	DEA Efficiency Mean
Eastern	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan	0.315	1.240
Central	Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan	0.432	2.270
Western	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	0.500	1.770

Although the eastern region does not have an advantage in the comprehensive score, its performance in transformation efficiency is the best. The western region leads other regions in the comprehensive score of each region and has an average efficiency performance at a medium level. The central region faces a situation where the comprehensive score is not very low, but has the dual predicament of low transformation efficiency. It becomes a weak aspect of energy fair transformation, indicating the imbalance characteristics of the three regions in terms of transformation basic conditions and actual efficiency.

From the temporal changes in the comprehensive TOPSIS scores of the three regions, Figure 6 shows that the score of the western region remained at the highest level throughout the sample period, fluctuating slightly within the range of 0.48 to 0.53 on the whole, leading the country consistently and demonstrating the continuous advantages of the west in terms of energy resources endowment and transformation foundation conditions. The score of the central region was second, fluctuating within the range of 0.34 to 0.49. The fluctuation was relatively large in the early stage and gradually stabilized within the range of 0.43 to 0.47 in the later stage. The score of the eastern region remained at the lowest level for a long time, but showed a distinct trend of first experiencing low-level fluctuations and then continuously and steadily rising. It gradually increased from approximately 0.21 in 2011 to around 0.40 in 2023, significantly narrowing the gap with the central and western regions.

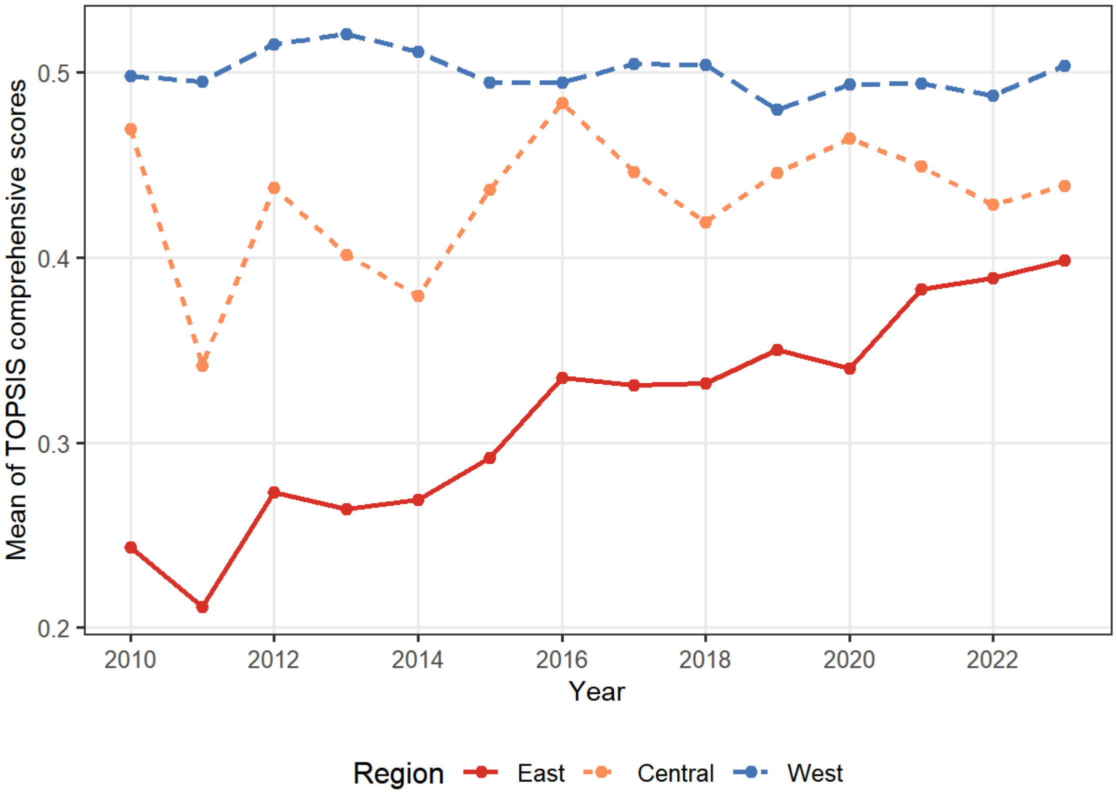

Figure 6. Temporal changes in just energy transition scores across three regions (2010–2023).

Overall, the scores of the three major regions reflect a pattern of "the West leading, the Central region in the middle, and the East catching up." While regional disparities are evident, the pace of transformation in the Eastern region is accelerating, and in the long term, regional gaps are converging.

The TOPSIS comprehensive scores of energy just-transition in each province in 2023 indicate significant differences among provinces. Overall, it presents a gradient distribution pattern. The western regions are generally in the first tier, with Xinjiang having the highest score. This indicates that these provinces have relatively good conditions for transformation. The internal division in the eastern regions is quite obvious. Guangdong and Jiangsu rank at the forefront, while Tianjin, Liaoning, and Hainan are at the bottom. Many central provinces are in the middle tier. The gap between provinces is relatively smaller. Heilongjiang, Jiangxi, Hunan have outstanding scores. Hebei, Anhui, etc., are in the middle to rear range.

As shown in Figure 7, from the perspective of regional comparison, the differences in the transformation scores of the three major regions are very obvious. Western provinces are in a leading position. This is mainly because they have abundant renewable energy resources and a relatively small transformation base. There are inherent favorable factors for energy supply-side transformation. The internal performance of eastern provinces is very different. This is mainly due to the different economic development models: coastal developed regions drive transformation with the favorable conditions of technology and capital, while some traditional industrial and resource-based provinces still have strong path dependence and transformation difficulties. Many central regions are areas with traditional energy production and heavy industry concentration. The overall transformation foundation is relatively unstable, and the scores are in the medium range. They lack the resource conditions of the west and the technological and capital advantages of the east, which are the current relative shortcomings in the transformation process.

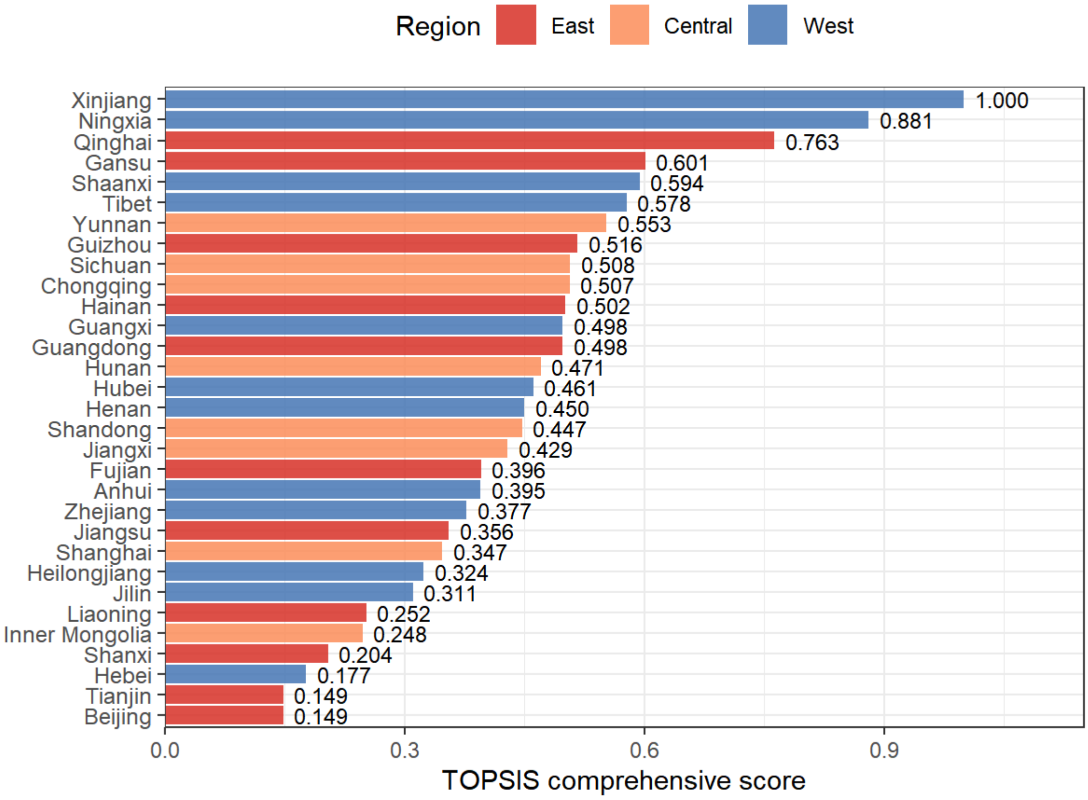

Figure 7. Provincial scores of just energy transition (2023).

Regarding the gap between provinces, the dispersion of just-transition scores in 2023 is relatively high. There is a significant gap between the highest and lowest scores, indicating the imbalance in the spatial distribution of energy just-transition in China. This differentiation situation shows that resource endowment, industrial structure, and economic development levels jointly determine the initial conditions for transformation in each province. In the future, when developing rational energy transformation, attention should be paid to implementing policies based on regional conditions: Western provinces should focus on ensuring the fair distribution of transformation benefits, eastern provinces should provide more guidance for the transformation of high-energy-consuming industries, and central provinces should increase the intensity of transformation support to gradually narrow the distance between regions and promote the coordinated and balanced development of energy just-transition.

5. Empirical Analysis

5.1. Establishing a Panel Regression Model

Using the comprehensive measure of energy just transition levels based on TOPSIS ($Score_{it}$) as the dependent variable, a two-way fixed-effects panel data model was constructed:

$$\begin{aligned}Score_{it} &= \alpha + \beta_1 \bullet \ln(gdp\_pc)_{it} + \beta_2 \bullet \ln(fiscal\_rev)_{it} + \beta_3 \bullet \ln(pop)_{it}\\ &+ \beta_4 \bullet coal\_share_{it} + \beta_5 \bullet water\_stress_{it} + \mu_i + \lambda_t + \varepsilon_{it}\end{aligned}$$

where μ_i represents the provincial fixed effect, λ_t represents the year fixed effect, and ε_{it} represents the random error term. Cluster-robust standard errors at the provincial level are used. Model selection is determined based on the results of the Hausman test.

5.2. Analysis of Benchmark Regression Results

To systematically examine the impact of factors such as economic development, fiscal capacity, and resource endowments on the just energy transition, this study constructs a two-way fixed-effects panel data model for empirical estimation. In the model specification, the comprehensive score for the just energy transition (TOPSIS measure results) is first set as the dependent variable, and core explanatory variables and control variables are gradually introduced to observe the robustness of the effects of each factor. Model (1) employs mixed OLS estimation, incorporating only core explanatory variables to preliminarily examine the relationships among variables; Model (2) controls for provincial and time fixed effects based on Model (1) to account for inter-provincial heterogeneity that does not change over time and common time trends, yielding more reliable estimates; Model (3) further incorporates control variables such as population size, coal dependency intensity, and water resource pressure to form a complete two-way fixed-effects model, thereby identifying the net effects of each factor on the just energy transition.

Regarding estimation methods, given the potential for auto-correlation in the disturbance terms across different years within the same province and the issue of heteroscedasticity across provinces, all models in this study employ cluster-robust standard errors at the provincial level to ensure the validity of statistical inferences. The results of the Hausman test support the superiority of fixed-effects models over random-effects models; therefore, this study adopts the two-way fixed-effects model as the benchmark estimation strategy.

Table 5 presents the estimation results of the two-way fixed effect model for provinces and years. The standard errors are calculated using the provincial clustering robust standard errors. The overall fit of the model is good, with an intra-group R^2 of 0.1225 and a sample size of 434 observations.

Table 5. Benchmark regression results.

Variables	(1)	(2)	(3)
	Level of Energy Justice Transition	**Level of Just Energy Transition**	**Level of Just Energy Transition**
ln (GDP per capita)	−0.0773 **	−0.2723	−0.2765 ***
	(0.0254)	(0.0409)	(0.0419)
ln (per capita fiscal revenue)	0.0059	0.2122 ***	0.1909 ***
	(0.0126)	(0.0341)	(0.0378)
ln (Total Population)	—	—	0.1420
			(0.1351)
Coal Dependency Intensity	—	—	0.0015
			(0.0037)
Water Resource Pressure (per capita water use/total water resources)	—	—	−0.0004
			(0.0011)
Provincial fixed effects	No	Yes	Yes
Time-invariant effect	No	Yes	Yes
Control variable	No	No	Yes
Observation	434	434	434
R^2	0.0284	0.1182	0.1225
Adjusted R^2	0.0238	0.0160	0.0131
Number of provinces	31	31	31

Note: Significance notation: *** $p < 0.001$, ** $p < 0.05$; no notation indicates no significance.

(1) The energy transition towards justice is significantly negatively affected by the level of economic development. According to model (1), the coefficient of ln (per capita GDP) is −0.0773, which is statistically significant at the 5% level. After adding the two-way fixed effects, the coefficient in model (2) increases to −0.2723, and further stabilizes at −0.2765 in model (3), and is highly significant at the 1% level. This result contrasts with the theoretical intuition, indicating that in the overall national sample, the better the economic development situation, the lower the comprehensive score of the energy transition. This phenomenon can be explained by the characteristics of the transition stage: at present, the provinces in the eastern region with the leading economic development level generally are in the "painful stage" of energy transition. There is considerable pressure for the exit of traditional high-energy-consuming industries, and the cost of energy structure adjustment is very high. In the short term, it actually leads to a decrease in the overall performance of the transition; while the resource-based provinces in the central and western regions have the advantage of taking the lead in developing renewable energy, the transition conditions are more favorable, resulting in a phased characteristic that "the higher the economic development level, the lower the overall transition performance". The absolute values of the coefficients in models (2) and (3) are significantly larger than those in model (1), indicating that after controlling for provincial heterogeneity and time trends, the adverse impact of economic development is more significantly manifested externally. The mixed OLS estimation has a relatively obvious omitted variable error.

(2) The local fiscal capacity plays a prominent positive driving role in the energy just transition. In Model (1), the coefficient of ln (per capita fiscal revenue) is 0.0059. After incorporating the fixed effects, it rises to 0.2122 in Model (2) and 0.1909 in Model (3), and both are statistically significant at the 1% level. This change indicates that after controlling for the unobservable heterogeneity across provinces, the effect of fiscal capacity is effectively identified: for every 1% increase in per capita fiscal revenue, the comprehensive score of energy just transition increases by approximately 0.0019 units on average. When local fiscal resources are relatively abundant

and the government has more capacity to increase investment in environmental governance, energy infrastructure construction, and supporting measures for the transition, it can provide stable financial guarantees for the energy just transition. It should be emphasized that this variable has no significant feature in Model (1), but after controlling for the fixed effects, its significance significantly increases. This indicates that the influence of fiscal capacity has prominent provincial differences, and conducting a mixed regression would mask its true effect.

(3) The results of the full-sample regression indicate that population size, coal dependency, and water resource pressure do not play a significant role in energy just transition. In Model (3), the coefficient for $\ln$ (total population) is 0.1420, the coefficient for coal dependency is 0.0015, and the coefficient for water resource pressure is −0.0004; none of these passed the standard significance test. Under the conditions of a two-way fixed-effects model, this result is not difficult to interpret: long-term inter-provincial differences in variables such as population size and resource endowments have largely been absorbed by individual fixed effects, making it difficult to effectively identify their net effects over time; Since the national sample encompasses provinces in the eastern, central, and western regions at different stages of development and with varying resource conditions, the effects of the aforementioned variables may offset each other in the overall estimation, resulting in statistical insignificance. However, this should not be taken to imply that these factors are unimportant; rather, this result suggests that their impacts likely exhibit significant regional heterogeneity. Subsequent sub-regional heterogeneity analyses will further explore the differentiated mechanisms through which these factors operate across different regions.

5.3. Robustness Tests

To ensure the reliability of the baseline regression conclusions, this paper conducts robustness tests from three dimensions: First, provincial cluster-based robust standard errors are used to replace ordinary standard errors, to correct for potential within-group correlation and heteroscedasticity issues; Second, outliers at the 1% percentile of each variable were excluded to reduce the interference of outliers on the estimation results; third, the dependent variable was replaced with a composite score directly weighted using the entropy method to test whether differences in measurement methods affect the consistency of the conclusions. Table 6 reports the estimation results of the above three robustness tests.

Table 6. Results of robustness tests.

Variable	Cluster Robustness	Exclusion of Outliers	Replacement of the Dependent Variable
$\ln$ (GDP per capita)	−0.2765 ** (0.0894)	−0.3021 *** (0.0891)	−1.0035 *** (0.2804)
$\ln$ (per capita fiscal revenue)	0.1909 * (0.0862)	0.2289 * (0.0922)	0.5237 * (0.2698)
$\ln$ (total population)	0.1420 (0.2586)	0.2714 (0.2589)	−0.6278 (0.7844)
Coal Dependency Intensity	0.0015 (0.0054)	0.0022 (0.0054)	0.0293 (0.0222)
Water resource pressure (Per capita water use/Total water resources)	−0.0004 (0.0013)	0.0001 (0.0013)	−0.0010 (0.0016)
Province fixed effects	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Control variable	Yes	Yes	Yes
Observation	434	406	434
R^2	0.1225	0.1310	0.0890

Note: Significance levels: *** $p < 0.001$, ** $p < 0.05$, * $p < 0.1$; no symbol indicates no significance.

The results of the robustness tests generally support the core conclusions of the baseline regression, as evidenced by the following three aspects:

(1) The direction and significance of the coefficients for the core explanatory variables remain stable. Across the three test scenarios, the coefficient for $\ln$ (per capita GDP) remains negative and is significant at the 5% or 1% level; the coefficient for $\ln$ (per capita fiscal revenue) remains positive and passes the 10% significance test at a minimum. This indicates that the negative impact of economic development and the positive effect of fiscal capacity are not attributable to standard error settings, outlier samples, or measurement methods, but rather demonstrate good stability. Notably, after replacing the dependent variable, the absolute values of the coefficients for the two core variables increased significantly (the coefficient for per capita GDP increased from −0.2765 to −1.0035, and the coefficient for per capita fiscal revenue increased from 0.1909 to 0.5237). This may be due to differences in dimension handling between direct weighting in the entropy method and the TOPSIS proximity

measure; however, the direction and significance of the coefficients remain consistent, and this does not affect the qualitative assessment.

(2) The lack of significance of the control variables remains consistent in the robustness tests. Across the three testing scenarios, ln (total population), coal dependency intensity, and water resource pressure all failed the significance test, which is fully consistent with the conclusions of the baseline regression. This indicates that the impact of population size and resource endowment variables on the just energy transition is indeed unstable; their effects may be absorbed by regional heterogeneity and temporal trends, further highlighting the necessity of conducting subsequent sub-regional heterogeneity analyses.

(3) After removing outliers, the model fit improved. Comparing the R^2 values across the three testing approaches shows that R^2 increased from 0.1225 to 0.1310 following the removal of outliers. This indicates that outliers interfere with model estimates to some extent, and the model's explanatory power was slightly enhanced after their removal; After replacing the dependent variable, R^2 decreased to 0.0890. This is related to differences in how various measurement methods extract variance information; however, the core conclusions remain fundamentally unchanged, and the findings of this study are reliable.

5.4. Heterogeneity Analysis

In this study, the baseline heterogeneity analysis uses the traditional eastern, central, and western geographic divisions. This division can intuitively reflect differences in resource endowments, policy timing, and economic foundations. At the same time, it should be noted that if we further group by whether a region is resource-based or a high-carbon province, some subgroups would have too few samples, and the panel regression would lack degrees of freedom, making the stability of the estimation results hard to guarantee. Therefore, this study primarily uses the main geographic regions for heterogeneity testing, which can be considered as a direction for future research.

Estimates grouped by eastern, central, and western regions reveal the regional heterogeneity mechanisms of each influencing factor (see Table 7):

Table 7. Results of heterogeneity analysis.

Explanatory Variable	Eastern	Central	West
ln (GDP per capita)	0.1468	−0.4975 *	−0.3272 **
ln (per capita fiscal revenue)	0.0449	0.0364	0.3062 **
ln (total population)	0.2914	1.3912	−0.5840
Coal Dependency Intensity	−0.0153	0.0065	−0.0001
Water Resource Pressure (Per capita water use/Total water resources)	−0.0038	−0.0543	−0.0001

Note: Significance levels: ** $p < 0.05$, * $p < 0.1$; no symbol indicates no significance. All groups control for fixed effects of province and year, and use provincial cluster-robust standard errors.

(1) The impact of economic development level shows significant regional divergence. The coefficients for ln (per capita GDP) in the central and western regions are −0.4975 and −0.3272, respectively, and are negative at the 10% and 5% significance levels, consistent with the direction of the national baseline regression. This reflects that provinces in the central and western regions are still in a "transition period," Economic growth is closely tied to traditional energy consumption and is unlikely to translate into accelerated transition progress in the short term. The corresponding coefficient for the eastern region is 0.1468; although it did not pass the significance test, the direction of the effect is positive, preliminarily indicating that economic growth in the east has a "green effect," though it has not yet established a stable positive driving effect. This disparity suggests that the role of economic development in energy transition exhibits stage-specific characteristics, making a one-size-fits-all policy approach inappropriate.

(2) The positive effect of fiscal capacity is most pronounced in the western region. The coefficient of ln (per capita fiscal revenue) in the western region is 0.3062, which is significantly positive at the 5% level. In contrast, the coefficients in the eastern and central regions are merely 0.0449 and 0.0364 respectively, and they are not significant. This indicates that in the western provinces with better resource conditions but lagging economic development, fiscal investment plays an important role in facilitating the just transition of energy. Adequate financial resources can effectively guarantee the development of clean energy, environmental governance, and supporting infrastructure for the transition. However, in the eastern and central regions, fiscal expenditures are more directed towards general construction investments, and the targeted support for the energy transition has not been fully exerted. These results provide empirical references for formulating differentiated regional fiscal support policies and optimizing expenditure structures.

(3) The population size and resource endowment variables were not significant in all regions. The variables ln (total population), coal dependence intensity, and water resource pressure failed to pass the significance test in the three regression groups for the east, middle, and west regions. After controlling for individual and time fixed effects, the static differences in provincial population size have been fully accounted for, and their net effects at the regional level cannot be identified. The coefficients corresponding to the coal dependence intensity and water resource pressure in the central region were 0.0065 and −0.0543 respectively. However, the trend can still be observed to some extent. This result once again verifies the judgment made in the full sample regression, that is, the heterogeneity at the provincial level can easily mask the effects produced by resource endowment variables. To accurately obtain its net effect, more precise indicators or a longer observation period may be needed.

(4) The central region is under the dual pressures of economic development and water resource constraints. From the perspective of the absolute value of the coefficient, the negative coefficient of ln (per capita GDP) in the central region is the largest, with a value of −0.4975. The coefficient of water resource pressure is −0.0543. Although it does not reach the significance level, the negative development trend is more prominent. This indicates that when the central provinces are experiencing “transition pain”, they are also subject to the rigid constraints of water resource carrying capacity. As traditional energy-producing areas and regions with heavy industries, the central region does not have the resources that the west has, nor does it have the technological and capital advantages that the east has. The foundation for the transition is relatively weak overall, becoming a weak point in the energy fair transition. This conclusion can be mutually confirmed with the result from the DEA efficiency calculation that “the transformation efficiency of the central region is the lowest and the improvement pressure is the greatest”, meaning that policy formulation should give more attention and preferential support to the central region.

6. Research Conclusions and Policy Recommendations

6.1. Key Research Findings

This study takes 31 provinces in China from 2010 to 2023 as the sample, and constructs an energy justice transition evaluation system covering the effectiveness and fairness dimensions. The entropy method, DEA model, and TOPSIS method are used for comprehensive measurement. The panel regression model, heterogeneity analysis, and robustness test are employed to examine the influencing factors. The main conclusions are as follows:

From the overall trend, the level of energy justice transition across the country shows a steady upward trend. During the sample period, the TOPSIS comprehensive score continued to increase and reached the peak of the research period in 2023, indicating that the transition process has been continuously advancing and the overall effectiveness has gradually improved. At the same time, the mean DEA transition efficiency gradually declined and stabilized, reflecting that the overall transition efficiency of the country has continuously improved and the improvement space of output has continuously narrowed.

At the regional level, there is a significant spatial differentiation in energy justice transition, roughly forming a pattern where the comprehensive score of the western region leads, the transformation efficiency of the eastern region is dominant, and the development pressure of the central region is under pressure. The TOPSIS comprehensive score ranking is that the western region is greater than the central region and greater than the eastern region. The western region ranks first due to its resource endowment advantage, while the eastern region has a low score but a clear catching-up trend. The regional gap tends to converge. The DEA transition efficiency shows that the eastern region has the highest efficiency, the western region is second, and the central region has the lowest efficiency. The eastern region has the optimal output efficiency under the given input, while the central region has a low efficiency and a prominent improvement pressure, constituting the weak link of the transition.

At the national level, economic development level and fiscal capacity are the key factors affecting energy justice transition. Per capita GDP has a significant negative impact on the comprehensive score of transition, which may be related to the fact that economically developed regions are mostly in the period of industrial adjustment and transition pain, and their comprehensive scores are not dominant in the short term. Per capita fiscal revenue shows a significant positive effect. The stronger the local fiscal strength, the more capable it is of providing financial support for environmental governance and clean energy construction, thereby effectively promoting justice transition. Variables such as population size, coal dependence intensity, and water resource pressure did not show significant effects in the entire sample, and their effects may have been absorbed by regional heterogeneity and fixed effects.

The regional heterogeneity analysis shows that there are significant differences in the influencing mechanisms of the eastern, central, and western regions. The positive effect of economic development in the eastern region has initially emerged, but it has not yet formed a stable driving force; the economic development in the central region also has a negative impact, and water resource pressure constitutes an important constraint on the transition; the economic development in the western region is also a negative impact, while the positive promoting effect of fiscal capacity is the most prominent, and the transition process is highly dependent on resource endowment and fiscal investment.

This study uses clustering robust standard errors, eliminating extreme values, and replacing the dependent variables, etc. to conduct robustness tests. The coefficient direction and significance of the core variables remain stable, indicating that the research conclusion has good reliability.

6.2. Policy Recommendations

Based on the above research conclusions, in light of the regional development disparities in China and the actual demands of energy transition, the following policy suggestions are proposed.

First, implement differentiated regional energy fair transition policies. The eastern region should focus on consolidating its efficiency advantage in the transition process, through technological innovation and upgrading of high-energy-consuming industries, to continuously stimulate the driving effect of economic development on green transition. The central region needs to focus on solving the problem of water resource constraints and improving the efficiency of transition, providing reasonable fiscal compensation during the transition period, with the core being to ensure employment stability and ensure energy fairness. The western region should be cautious of the “false high” scores caused by resource endowments, accelerate the improvement of energy inclusiveness and public participation procedures, and effectively transform its resource advantages into high-quality transition outcomes.

Second, fiscal expenditure structures must be optimized to enhance the efficiency of fund utilization. Merely expanding the scale of fiscal revenue has no significant independent effect on promoting a just transition. Therefore, the primary focus of policy should shift from aggregate expansion to optimizing expenditure structures. Targeted efforts should be made to increase investment intensity in clean energy infrastructure, subsidies for energy-poor groups, and green technology innovation. At the same time, oversight and performance evaluation of environmental governance investment projects must be strengthened to ensure that fiscal funds serve the just energy transition more precisely and efficiently.

Third, water resource co-management should be incorporated into the policy framework for a just energy transition. Water-related indicators carry the greatest weight in the evaluation system and impose significant constraints on the transition in the central region. It is necessary to consider energy transition and water resource carrying capacity in a coordinated manner, using water resource conditions as key indicators for the layout of energy projects and transition planning. A mechanism for the coordinated governance of energy and water resources should be established to prevent further exacerbation of regional water scarcity during the transition period.

Fourth, establish a provincial-level dynamic monitoring and evaluation system for just energy transition. Focusing on four dimensions—achievements of the transition, distributive justice, procedural justice, and sustainability—develop a routine monitoring indicator system tailored to the provincial level. Additionally, incorporate the level of just energy transition into the performance evaluation of local governments. Establish a closed-loop policy framework featuring regular monitoring, dynamic evaluation, and timely adjustments to help ensure that the energy transition continuously achieves a balance between fairness and efficiency.

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Data Availability Statement

The raw data used in this study can be obtained from the official public statistical database.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used AI language tool to polish sentences. After using this service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

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