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Article

The Impact Mechanism of Urban Green New Quality Productive Forces on the Equity of Energy Transition

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ABSTRACT

Against the backdrop of global sustainable development and energy transition, energy justice has gained increasing prominence. Drawing upon data from 188 cities spanning 2010–2023, this study employs fixed effects regression and double machine learning approaches to examine the impact of green new quality productive forces on just energy transitions. The study constructs a more scientifically rigorous integrated evaluation framework. Fixed effects control for individual variations, while double machine learning addresses endogeneity and high-dimensionality issues in causal inference. This dual approach enhances the robustness of findings. Results indicate that green new quality productive forces significantly advance just energy transitions by increasing renewable energy proportions and narrowing urban-rural energy consumption disparities. Both methodologies reveal stable positive effects, with coefficients of 0.6058 and 0.5569 respectively, significant at the 1% level. Heterogeneity analysis further reveals pronounced regional disparities: coefficients reach 0.6039 and 0.6789 in eastern and developed regions, whereas western and less developed areas register only 0.2139 and 0.1334. Moreover, results remained highly consistent following a series of endogeneity and robustness tests. Based on these findings, this paper proposes accelerating the development of green new quality productive forces, optimizing energy structures, advancing urban-rural energy equity, and implementing differentiated regional policies to provide scientific support for sustainable urban development.

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Research Highlights

- Established a more comprehensive and scientific indicator system
- Effectively combines fixed effects regression with double machine learning
- Green new quality productive forces have a positive effect on just energy transition
- Increasing renewable energy proportion and narrowing urban-rural energy consumption disparities are key pathways
- The role of green new quality productive forces in promoting just energy transition exhibits regional heterogeneity

1. Introduction

Amidst the severe circumstances of accelerating global warming and increasingly frequent extreme weather events, sustainable development has become an urgent imperative, with energy transition emerging as a critical issue requiring urgent resolution by nations worldwide [1,2]. Against this background, energy justice—as a pivotal concept ensuring inclusivity and fairness throughout the transition process—has garnered extensive attention from both the international community and academia. It emphasises safeguarding equitable rights across multiple dimensions—economic, social, and environmental—for diverse groups, regions, and generations throughout the entire energy production, distribution, and consumption chain [3]. This principle has secured a prominent position in global energy governance. For instance, the 13th International Energy Forum adopted the theme “Taking Action for a Just Energy Transition”, urging nations to accelerate renewable energy deployment and commit to building a just and sustainable energy future. As a responsible major power, China has similarly responded proactively. Through a suite of policy instruments—including subsidies, regional coordination, and employment support—it strives to safeguard equity throughout the transition process, fully embodying the practice of energy justice principles [1,4].

The overarching goal of energy justice requires concrete implementation pathways, with the Just Energy Transition (JET) serving as a key vehicle. Energy justice and the Just Energy Transition share the common objective of creating an equitable and sustainable energy future [5]. Fundamentally, however, the Just Energy Transition represents a practical pathway towards broader energy justice [6]. Its core concept entails transitioning from fossil fuel-based energy systems to renewable and sustainable energy sources in an equitable and inclusive manner, while accounting for social, economic, and environmental dimensions [7]. A just energy transition aims to ensure equitable distribution of transition benefits across all societal members and minimise negative impacts by addressing energy poverty, creating green jobs, and promoting community participation [3]. Crucially, it focuses not merely on technological substitution and emissions reduction, but also on addressing the socio-economic challenges that may arise during the transition [8].

Advancing the energy transition relies heavily on technological innovation, which in turn is closely intertwined with green new quality productive forces. Green new quality productive forces represent an advanced form of productivity guided by green development and driven by scientific and technological innovation. Emerging from revolutionary technological breakthroughs, innovative allocation of production factors, and profound industrial transformation and upgrading, they signify the evolution of traditional productive forces towards greater environmental sustainability and enhanced quality. By promoting the deep integration of technological innovation, digital empowerment, and green transformation, green new quality productive forces aim to enhance total factor productivity and strengthen resource and environmental friendliness. This facilitates the coordinated development of economic growth with resource conservation and environmental protection [9,10]. At the urban level, as the primary entities of energy consumption and economic activity, cities increasingly focus on enhancing green new quality productive forces as the key driver for achieving energy transition. The Chinese government has introduced multiple policies to actively promote the development of green new quality productive forces, including establishing a green, low-carbon modern industrial system and accelerating the cultivation of new energy industrial clusters. These measures aim to solidify the industrial and technological foundations for an energy transition that prioritises fairness [11].

In summary, a just energy transition entails two core imperatives: firstly, advancing the energy structure towards greener, sustainable pathways; secondly, ensuring equitable distribution of transition costs and benefits across societal strata and geographical regions. Despite ongoing policy implementation, empirical research remains underdeveloped in unravelling the intrinsic logical connection between green new quality productive forces and just energy transition within urban contexts, particularly its intricate causal mechanisms. Against this backdrop, this paper aims to systematically examine the impact of urban green new quality productive forces on just energy transition. Employing methods such as fixed effects regression and the double machine learning approach (DML), the research seeks to precisely identify causal relationships between variables and dissect their underlying pathways. The findings will provide scientific grounds for formulating targeted and effective energy transition policies within urban green, low-carbon sustainable development pathways, thereby advancing the realisation of energy equity objectives. The general framework of this research is shown in Figure 1.

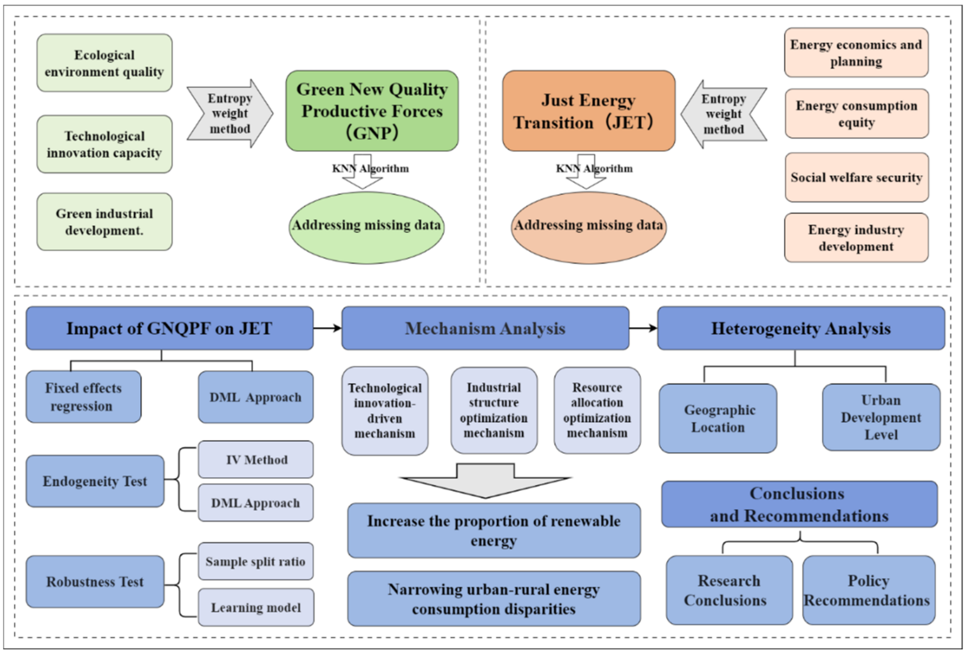

Figure 1. Research framework.

2. Literature Review

2.1. Review on Just Energy Transition

Just Energy Transition (JET) as a pivotal component of energy transformation denotes the process of shifting from fossil fuel dependent energy systems to more sustainable renewable energy systems in an inclusive and socially equitable manner [12–14]. Since the concept was first introduced in the 1997 Kyoto Protocol, JET has been progressively reaffirmed and strengthened in pivotal international climate agreements such as the Cancún Agreements (2010) and the Paris Agreement (2015) [15]. Its core tenets lie in advancing the low-carbon transformation of energy systems while balancing multiple societal values, including equity and justice. This ensures the equitable distribution of energy benefits and responsibilities across different groups, regions, and nations, prevents the emergence of new socio-economic inequalities, and commits to redressing historical imbalances in rights and interests arising from energy development and utilization [16,17].

Existing literature on just energy transitions primarily focuses on two aspects. Firstly, in conceptual development and measurement assessment, scholars endeavour to quantify energy justice through designing comprehensive indicator systems. For instance, ref. [3] analysed data from 30 Chinese provinces, finding that energy justice levels generally show an upward trend, yet eastern regions significantly outperform central and western areas. The most pronounced interaction effect was observed between energy consumption intensity and urbanisation rates. However, ref. [18] survey indicates that overall satisfaction with the just energy transition among vulnerable groups remains below fifty per cent, reflecting persistent gaps in policy implementation. Secondly, concerning driving mechanisms and policy optimisation, ref. [3] identified key factors propelling systemic just transition from provincial-level energy justice assessments in China. Ref. [19] notes that China's Photovoltaic Poverty Alleviation Programme (PAVA) not only positively impacts the clean energy transition but also advances just transition through multiple pathways. Ref. [20] further propose that China's independent research and development contributes to promoting a just transition, whereas technological transformation and collaborative R&D may produce inhibiting effects, with environmental regulations potentially mitigating these negative impacts to some extent. Moreover, structural shifts in labour demand relative to energy demand are also regarded as significant drivers for achieving a just energy transition [21].

2.2. Review on Green New Quality Productive Forces

New quality productive forces constitute a pivotal economic concept proposed by China, denoting a contemporary advanced form of productive capacity catalysed by revolutionary technological breakthroughs, innovative allocation of production factors, and profound industrial transformation and upgrading. It adheres to the intrinsic laws governing productivity enhancement, accurately delineating the defining characteristics of current economic development [9]. While related to concepts like "green innovation" which primarily focuses on environmentally-friendly technological progress, green new quality productive forces encompass a broader systemic transformation. They represent not merely technological upgrades but a fundamental restructuring of production relations and industrial systems, emphasizing the deep integration of technological innovation, digital empowerment, and green transformation [10]. This approach aims to transcend the constraints of traditional growth models, enabling both highly efficient operations and high-quality growth while systematically enhancing resource utilization efficiency and environmental sustainability.

Empirical research confirms that green new quality productive forces significantly promote regional green technological innovation [22], demonstrating particular efficacy in optimising resource utilisation and advancing the greening of production processes. However, their promotional effect exhibits an inverted U-shaped relationship, potentially diminishing beyond a specific threshold. Intellectual property protection (IPP) is therefore required to enhance innovation efficiency. Concurrently, green new quality productive forces contribute to enhancing green total factor energy efficiency [23]. Artificial intelligence (AI) exerts a U-shaped regulatory effect, transitioning from inhibition to promotion upon surpassing a critical threshold, while generating positive spatial spillover effects that drive collaborative transformation in neighbouring regions. Regarding measurement methodologies, existing research primarily falls into two categories: firstly, constructing comprehensive indicator systems at the enterprise or regional level, employing multi-indicator evaluation methods such as entropy weighting for quantification. Secondly, utilising tools like Python to extract keyword frequencies related to “new quality productive forces” from official documents or corporate reports for text analysis. Further analysis reveals pronounced regional heterogeneity in the impact of green new quality productivity. Eastern regions exhibit the highest coupling coordination with carbon-adjusted total factor productivity, while central and western regions lag due to resource constraints and foundational limitations [24]. while the digital economy exhibits stronger driving effects in the Yangtze River Economic Belt than in the Yellow River Basin [25]. These findings suggest implementing differentiated policies, such as enhancing technology diffusion in the east, addressing deficiencies in digital and green infrastructure in the central and western regions, and refining regional coordination mechanisms.

3. Policy Background and Research Hypotheses

3.1. Policy Background

3.1.1. International Policies Guide the Direction of a Just Energy Transition

In the process of global sustainable development, fairness and justice in the energy sector have gradually become the focus of international attention. One of the core goals of the basic framework for global climate change response established by the Paris Agreement is to ensure that all countries follow the principle of fair, common but differentiated responsibilities during the energy transition process. This means that countries at different levels of development should assume responsibilities commensurate with their capabilities in the energy transition, while safeguarding the reasonable rights and interests of developing countries in terms of access to energy, technical support and financial assistance, to prevent the gap between the North and the south from further widening due to transition policies. For instance, in the follow-up to the Paris Agreement, developed countries committed to providing 100 billion US dollars in climate funds to developing countries each year to support their energy transition projects, including the development of renewable energy, the improvement of energy efficiency, and the promotion of fair development in the global energy sector.

A series of reports released by the International Energy Agency (IEA) also emphasized the importance of a just energy transition, proposing to ensure the accessibility, affordability and sustainability of energy during the energy transition process. Among them, accessibility requires ensuring that residents in all regions around the world, especially in remote and poverty-stricken areas, have access to a stable energy supply. Affordability focuses on the impact of energy prices on different income groups, avoiding a significant increase in energy costs due to energy transition and increasing the living burden on low-income groups. Sustainability emphasizes that energy transition should be based on environmental protection and rational utilization of resources to achieve long-term stable energy supply. These concepts provide important references and inspirations for countries to formulate fair policies for energy transition.

3.1.2. China’s Policies Ensure the Fairness and Impartiality of the Energy Transition

China attaches great importance to the issue of fairness and justice in the energy transition and integrates it into the national energy development strategy and relevant policies. Under the guidance of the “dual carbon” goals, China is not only committed to reducing carbon emissions and promoting the transformation of the energy structure towards green and low-carbon, but also pays attention to ensuring social equity during the energy transition process. In terms of policies for the development of renewable energy, the state has built distributed photovoltaic power generation projects in poverty-stricken areas, embodying the concept of sharing the fruits of energy development with all the people. This enables the impoverished population to not only obtain stable power supply through power generation income but also organically combine energy transformation with poverty alleviation, demonstrating the idea that the fruits of energy development should be shared by all the people. This is a significant measure taken by the state to implement the photovoltaic poverty alleviation project.

When formulating energy policies, our country has fully taken into account the resource endowments of various regions as well as the differences in economic development levels. For the western regions rich in energy resources, the state has driven local economic development and promoted employment by building large-scale energy bases and developing new energy industries such as wind and solar energy. At the same time, efforts should be made to strengthen the construction of energy transmission channels, transport clean energy from the western regions to the economically developed eastern regions, achieve the optimal allocation of energy resources, and promote coordinated development among regions. In terms of energy price policies, China has implemented tiered electricity pricing and gas pricing systems to ensure the basic energy needs of low-income groups and prevent excessive impacts on their lives caused by rising energy prices.

3.1.3. Urban Policies Implement the Goal of a Just Energy Transition

As key implementers of energy transition, cities have actively responded to national and international policy requirements and formulated a series of policy measures in line with local realities to achieve a just energy transition. When formulating energy development plans, many cities take ensuring energy equity as an important goal. For instance, some cities have intensified their efforts in energy transformation of old residential areas, promoting energy-saving lamps, smart meters and other devices, thereby reducing residents' energy consumption costs. At the same time, efforts should be made to intensify the construction of public energy infrastructure, enhance the stability and reliability of energy supply, and ensure that every resident enjoys high-quality energy services.

In promoting the development of the new energy industry, cities encourage enterprises to participate in energy transition projects through policy guidance, creating more job opportunities. Some cities have established new energy industrial parks, attracting related enterprises to settle in, providing local residents with job opportunities in multiple links from research and development, production to operation and maintenance, and promoting employment fairness. In addition, cities also attach great importance to widely soliciting public opinions during the process of formulating energy policies, enhancing the transparency of policies and public participation, and ensuring that energy transition policies are in line with the interests of the general public.

3.2. Theoretical Mechanisms and Research Hypotheses

Urban green new quality productive forces exert influence on just energy transitions through multidimensional complex mechanisms, encompassing technological innovation drivers, optimised resource allocation, and industrial structure optimisation. This section will delve into their key pathways of action, thereby establishing the research hypotheses for this paper. A schematic illustration of the theoretical mechanism is shown in Figure 2.

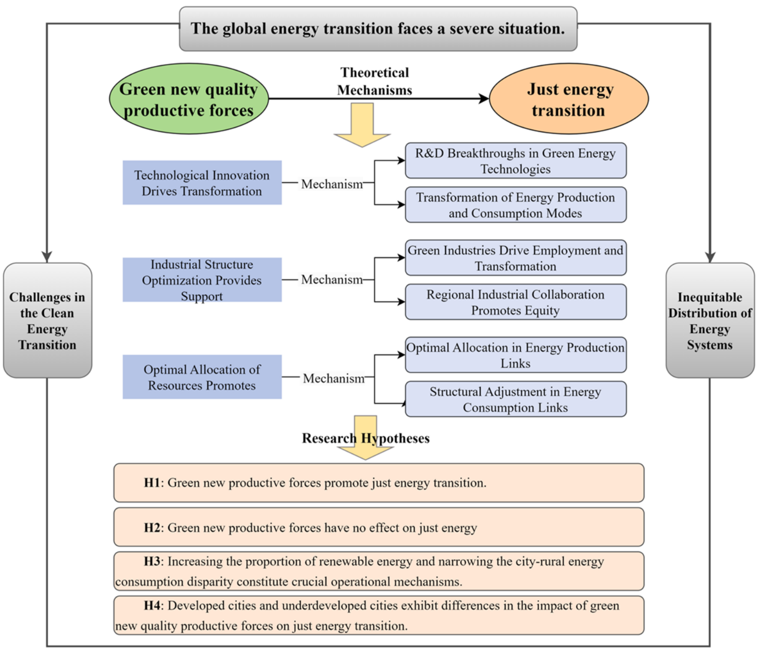

Figure 2. Theoretical mechanism framework.

3.2.1. Technological Innovation-Driven Mechanism

Urban green new quality productive forces, with technological innovation as their core driving force, have spawned a series of green technological innovations in the energy sector, providing crucial technical support for a just energy transition. On the one hand, the concentration of research resources and talent in cities has accelerated the development of key technologies such as photovoltaics and energy storage. This has effectively reduced the cost of clean energy, enhanced the stability and resilience of energy systems, and enabled broader groups to access affordable, reliable clean energy. Concurrently, green technological innovation has catalysed transformations in energy production and consumption patterns. The implementation of smart grid technologies enables precise energy dispatch and efficient distribution, enhancing utilisation efficiency while minimising losses. This facilitates fairer energy allocation across diverse user groups. For instance, technological innovations such as smart grids and intelligent energy management optimise energy allocation and consumption efficiency, further enhancing the justice and sustainability of energy consumption. These technological advances solidify the foundation for a just energy transition from both the perspectives of supply security and consumption equity. Based on this, the following hypotheses are proposed:

Hypothesis 1: *Green new productive forces promote just energy transition.*

Hypothesis 2: *Green new productive forces have no effect on just energy transition.*

3.2.2. Resource Allocation Optimization Mechanism

Urban green new quality productive forces facilitate the optimisation of energy resource allocation, enhance efficiency, and advance the justice of energy transition. Within the energy production sector, cities rationally allocate energy resources through market mechanisms and policy guidance, prioritising the development of renewable and clean energy sources while reducing dependence on fossil fuels. For instance, city governments may formulate energy development plans and implement energy subsidy policies to encourage enterprises to increase investment in renewable energy projects, thereby increasing the proportion of renewables in energy production. Concurrently, strengthening energy infrastructure and improving transmission networks enhances energy delivery efficiency, ensuring resources reach demand areas promptly and effectively.

In the energy consumption phase, the green new productive forces within cities drive the optimisation of energy consumption structures. Measures such as promoting green buildings, developing public transport, and advocating green consumption concepts reduce the energy intensity of households and enterprises while improving energy utilisation efficiency. Furthermore, cities can establish energy demand response mechanisms to guide users in adjusting their energy consumption behaviour rationally. This facilitates the optimal allocation of energy resources, enhancing both the fairness and efficiency of energy utilisation.

3.2.3. Industrial Structure Optimization Mechanism

The development of urban green new quality productive forces has accelerated the greening and upgrading of industrial structures, holding significant implications for a just energy transition. With the rise of green new quality productive forces, green industries such as new energy, energy conservation and environmental protection, and resource recycling have rapidly expanded, emerging as new growth drivers for urban economies. While fostering synergistic development across related industrial chains and generating substantial employment opportunities, these green industries have also catalysed the green transformation and upgrading of traditional high-energy-consuming sectors. Developing green new quality productive forces will spur the rise of green industries like new energy and energy conservation and environmental protection. This will drive the greening of traditional industries, optimise industrial energy consumption structures, create employment opportunities, and enhance the fairness of energy distribution and utilisation at both economic and societal levels. Concurrently, traditional manufacturing sectors are reducing energy consumption and pollutant emissions through measures such as adopting green production processes, decreasing reliance on conventional fossil fuels, strengthening the industrial foundation for equitable energy conversion, enhancing energy efficiency, and achieving green industrial transformation. This approach fosters sustainable development while solidifying the industrial base.

Furthermore, green new quality productive forces emphasise optimal resource allocation. They channel capital and policy support towards renewable energy while optimising terminal energy consumption structures through initiatives such as green buildings and intelligent transport systems. This process directly drives the clean transformation of energy structures and the evolution of energy consumption patterns. Consequently, increasing the proportion of renewable energy or narrowing the urban-rural energy consumption disparity may represent core transmission pathways for achieving these impacts. This paper therefore proposes an intermediary mechanism hypothesis:

Hypothesis 3: *Increasing the proportion of renewable energy and narrowing the urban-rural energy consumption disparity constitute crucial operational mechanisms through which urban green new quality productive forces facilitate just energy transitions.*

The development of green new quality productive forces will spur the rise of green industries such as new energy and energy conservation and environmental protection. This will promote the greening of traditional industries, optimisation of industrial energy consumption structures, creation of employment opportunities, and enhanced fairness in energy distribution and utilisation at both economic and societal levels. However, significant disparities exist among cities in terms of resource endowments, economic foundations, technological capabilities, and industrial structures. This may result in regional heterogeneity regarding the pathways and intensity of impact through which green new quality productive forces influence just energy transitions. Specifically, developed cities, leveraging their abundant research resources, robust financial backing, and strong industrial foundations, can accelerate green and low-carbon transformation under the impetus of green new quality productive forces, thereby exerting a powerful driving force for a just energy transition. In contrast, remote or underdeveloped cities, constrained by limited research investment, talent shortages, and reliance on traditional high-energy-consuming industries, exhibit relatively lagging development of green new quality productive forces and face greater transition challenges. Nevertheless, these cities possess correspondingly larger potential for optimising their energy and industrial structures. Once a green transition is achieved, they may demonstrate more pronounced promotional potential. Consequently, the level of city development may constitute a critical boundary condition influencing the relationship between green new quality productive forces and just energy transitions. Based on the foregoing analysis, the following hypothesis is proposed:

Hypothesis 4: *Developed cities and underdeveloped cities exhibit differences in the impact of green new quality productive forces on just energy transition.*

4. Research Design

4.1. Model Construction

To comprehensively and precisely identify the impact of green new quality productive forces on a just energy transition, this study employs both fixed effects regression and double machine learning (DML) methods, which functionally complement each other. The fixed effects model, by controlling for city and year fixed effects, effectively mitigates omitted variable bias arising from non-time-varying individual heterogeneity and temporal trends, thereby providing a foundational safeguard for causal inference (Figure 3). Building upon this, the dual machine learning approach further addresses the "curse of dimensionality" arising from high-dimensional control variables through its flexible machine learning algorithms and orthogonalisation procedures. It also captures complex nonlinear relationships between variables, enabling more robust and precise estimation of core causal effects. The combination of these two methods significantly enhances the reliability of the research conclusions.

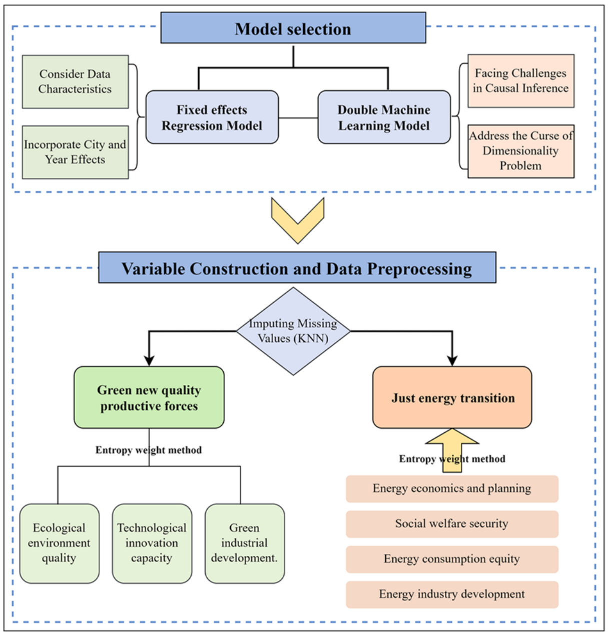

Figure 3. Model setting analysis process.

4.1.1. Construction of a Fixed-Effect Regression Model

When delving into the impact of green new quality productive forces across 188 cities on just energy transitions, it is essential to fully account for the complex characteristics within the data. On the one hand, inherent and acquired disparities exist among cities in terms of resource endowments, industrial foundations, and policy environments, with these differences exerting enduring effects on both green new quality productive forces and just energy transitions. On the other hand, over time, varying macroeconomic conditions, energy technology breakthroughs, and shifts in policy orientation across different years introduce dynamic changes that profoundly shape the relationship between these two phenomena.

To comprehensively and accurately dissect this intricate interplay, a fixed effects regression is employed. This model incorporates city-specific and year-specific effects into the analytical framework, enabling the effective separation of individual city heterogeneity and temporal dynamics from the study outcomes. City effects capture the unique, time-invariant characteristics of each city influencing the just energy transition, while year effects reflect the impact of common macro-level factors on the study variables each year. Based on this, the following mixed-effects regression benchmark equation is constructed:

$$JET_{it} = \alpha_0 + \alpha_1 GNP_{it} + \sum_{j=1}^{i} \varphi_{j+1} Control_{ijt} + \mu_i + \lambda_t + \epsilon_{it} \quad (1)$$

In the above equation: *i* denotes the *i*-th city, *t* denotes the *t*-th year. JET_{it} serves as the dependent variable, measuring the degree of just energy transition in the *i*-th city during the *t*-th year. GNP_{it} serves as the core explanatory variable measuring the level of green new quality productive forces in city *i* during year *t*. $Control_{ijt}$ denotes a set of control variables. μ_i represents the city fixed effect. λ_t denotes the year fixed effect. ϵ_{it} constitutes the random error term.

4.1.2. Construction of the Double Machine Learning Model

When investigating the causal effects of green new quality productive forces on just energy transitions, two key challenges arise: causal inference and the curse of dimensionality. The difficulty in causal inference lies in accurately identifying the causal relationship between green new quality productive forces and just energy transitions amidst numerous complex factors, rather than merely surface-level correlations. In practice, numerous confounding factors exist that are both associated with green new quality productive forces and influence just energy transitions, making causal identification particularly challenging. Concurrently, the curse of dimensionality arises because factors affecting just energy transitions span economic, social, and environmental domains, creating a high-dimensional covariate space. This leads to inaccurate estimates and unstable results when using traditional regression methods in data-sparse scenarios.

To address these challenges, this study employs a double machine learning (DML) approach, which aligns exceptionally well with the dataset's characteristics. The multi-city, long-period panel data utilised encompasses multidimensional control variables, creating a high-dimensional covariate space. DML, by incorporating flexible machine learning algorithms, effectively tackles this high-dimensionality while precisely capturing the latent nonlinear effects of control variables. Concurrently, DML's orthogonalisation procedure facilitates the separation of components within green new quality productive forces (GNP_{it}) associated with various control variables, thereby enabling clearer identification of their causal effects on just energy transition (JET_{it}). Based on this, the dual machine learning partial linear regression benchmark equation is constructed:

$$JET_{it} = \beta_0 + \beta_1 GNP_{it} + m(X_{it}) + \nu_{it} \quad (2)$$

where, JET_{it} and GNP_{it} retain the same meaning as in the fixed effects model; X_{it} denotes the set of all control variables; $m(X_{it})$ represents the unknown nonlinear function describing the influence of control variables on JET_{it}; β_0 is the constant term, and β_1 is the core causal effect coefficient. This framework provides an ideal solution for reliable causal inference within complex data environments.

4.2. Variable Setting and Selection

4.2.1. Explained Variable (Just Energy Transition)

Against the backdrop of global efforts to advance sustainable development and combat climate change, a just energy transition has become a key objective for city development worldwide. This transition not only concerns the efficiency and cleanliness of energy systems but also emphasises the equitable distribution and utilisation of energy across all societal strata, alongside enhancing overall city welfare. This section constructs a comprehensive and scientific evaluation framework for a “just energy transition” based on theories of energy justice, sustainable development, and industrial economics.

Energy justice theory underscores that the allocation of energy resources, provision of energy services, and energy decision-making processes must adhere to principles of fairness and equity. This ensures equitable participation in the energy transition, enabling diverse regions and income groups to benefit. Sustainable development theory focuses on meeting contemporary energy needs without compromising the ability of future generations to meet their own energy requirements, while also considering the long-term environmental and social benefits of energy utilisation. Industrial economics theory examines the structure, behaviour, and performance of the energy sector, positing that rational industrial development can drive efficient energy transition while promoting the upgrading and optimisation of energy systems.

Building upon this theoretical foundation, evaluation criteria for a “just energy transition” are proposed across four dimensions: energy economics and planning, equity in energy consumption, social welfare safeguards, and energy industry development. The specific criteria are outlined in Table 1 below.

Table 1. Just Energy Transition Evaluation System.

First-Level Evaluation Project	Secondary Evaluation Project	Proxy Data	Nature
Just energy transition (JET)	Energy economics and planning	The proportion of energy consumption in GDP	Negative
		The proportion of renewable energy in the total energy consumption	Positive
	Energy consumption equity	The ratio of per capita energy consumption between urban and rural areas	Negative
		The extreme difference in the proportion of per capita energy expenditure to income among different income quartiles	Negative
	Social welfare security	The proportion of energy-specific subsidies in social security expenditures	Positive
		The number of public energy service facilities per 10,000 people	Positive
	Energy industry development	The growth rate of fixed asset investment in the energy industry	Positive
		The average wage growth rate of employees in the energy industry	Positive

4.2.2. Green New Quality Productive Forces (GNP)

In the process of city development, green new quality productive forces have become a key driver of sustainable development, with research into their impact on a just energy transition holding significant importance. To accurately measure green new quality productive forces, this paper constructs a comprehensive and scientific evaluation system based on sustainable development theory, innovation-driven development theory, and industrial ecologisation theory.

Sustainable development theory advocates achieving balanced progress across economic, social, and environmental dimensions, ensuring contemporary needs are adequately met without compromising the ability of future generations to fulfil their own requirements. Innovation-driven development theory emphasises the central role of technological innovation in economic growth and industrial upgrading, positing that innovation enables the reconfiguration of production factors to enhance productivity and economic competitiveness. Industrial ecologisation theory advocates integrating industrial systems with natural ecosystems, aiming for efficient and circular resource utilisation to mitigate the negative environmental impacts of industrial development. Building upon these theoretical foundations, this paper proposes evaluation criteria for green new quality productive forces across three dimensions: ecological environmental quality, technological innovation capacity, and green industrial development. The specific content is presented in Table 2 below.

Table 2. Green New Quality Productivity Evaluation System.

First-Level Evaluation Project	Secondary Evaluation Project	Proxy Data	Nature
Green new quality productive forces (GNP)	Ecological environment quality	The harmless treatment rate of domestic waste	Positive
		The centralized treatment rate of sewage treatment plants	Positive
		Green coverage rate of built-up area	Positive
	Technological innovation capacity	The proportion of research and development (R&D) expenditure in GDP	Positive
		The number of patent authorizations per 10,000 people	Positive
		The number of Internet broadband access users	Positive
	Green industrial development	The proportion of green industry enterprises	Positive
		The proportion of fixed asset investment in green industries to the total investment	Positive
		The proportion of people employed in green industries among the total number of employed people	Positive

4.2.3. Control Variables

To accurately identify the impact of green new quality productive forces on the just energy transition, this study controls for exogenous variables that may interfere with the estimation, including foreign direct investment (*FDI*, measured as the ratio of total *FDI* to GDP), foreign trade level (*TRS*, measured as the ratio of total import and export value to GDP), human capital (*PAT*, measured as the ratio of the number of college students to the resident population), technological level (*TEC*, measured as the ratio of R&D expenditure to GDP), energy price (*PE*, measured using a comprehensive energy consumption price index), and fiscal support intensity (*FIN*, measured as the ratio of fiscal loan balance to total loans). To further mitigate omitted variable bias and capture potential nonlinear effects of the control variables, the study introduces regularization algorithms within the double machine learning framework to handle high-dimensional controls and includes squared terms of these control variables in the model.

4.3. Data Preprocessing and Descriptive Statistics

4.3.1. The Construction of Core Variables

Just energy transition is a complex concept that encompasses an integrated structure of energy structure adjustment, social equity, and environmental sustainability. To precisely quantify this variable, this study selected a series of basic indicators covering the proportion of clean energy production, fair distribution indicators at the energy consumption end, and the degree of improvement in the environmental impact of energy transition, etc., and set them as $x_1, x_2, ..., x_n$. The entropy weight method is adopted to integrate these basic indicators to determine their weights in the measurement of a fair energy transition. The principle of the entropy weight method is to determine the weight by measuring the degree of dispersion of the index data. The greater the degree of dispersion, the stronger the discrimination ability of the index and the higher the weight. The specific measurement process is as follows:

First, calculate the proportion of the sample value of the i under the j indicator p_{ij}:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{3}$$

Second, calculate the entropy value e_j of the j-th indicator:

$$e_j = -k \sum_{i=1}^{m} p_{ij} ln\left(p_{ij}\right) \tag{4}$$

Third, calculate the difference coefficient g_j of the j*-th* indicator:

$$g_j = 1 - e_j \tag{5}$$

Fourth, calculate the weight w_j of the *j*-th indicator:

$$w_j = \frac{g_j}{\sum_{j=1}^{n} g_j} \tag{6}$$

Among them, in Equation (3), m represents the sample size, in Equation (4), $k = \frac{1}{ln(m)}$, and it is necessary to ensure that $0 \leq e_j \leq 1$.

The combined just energy transition indicator is *JET*:

$$JET = \sum_{j=1}^{n} w_j x_j \tag{7}$$

Green new quality productive forces is also a multi-dimensional concept, covering aspects such as green technological innovation, improvement of resource utilization efficiency, and ecological environment protection. This study selected basic indicators such as the number of green patent applications, the improvement rate of energy utilization efficiency, and the reduction rate of carbon emissions per unit of GDP to construct this variable, which was set as $y_1, y_2, \cdots, y_k$. By using the entropy weight method and following the similar steps mentioned above to calculate the weight $v_1, v_2, \cdots, v_k$ of each basic index, the final productive forces index is obtained as *GNP*:

$$GNP = \sum_{i=1}^{k} v_i y_i \tag{8}$$

4.3.2. Data Preprocessing

In data analysis, the existence of missing values is inevitable, and if not dealt with, it will have a serious impact on the accuracy of the analysis results. Therefore, this study adopts the K-Nearest Neighbor (KNN) algorithm to fill in the missing values. The core idea of the KNN algorithm is based on the similarity between samples. It calculates the distance between samples to find the K samples that are most similar to the missing value samples. For numerical data, fill it with the mean of the eigenvalues corresponding to these K samples. For categorical data, the mode is used for padding. Let the eigenvector $x_0 = (x_{01}, x_{02}, ..., x_{0p})$ be and the other samples in the database be $x_i = \left(x_{i1}, x_{i2}, ..., x_{ip}\right), i = 1,2, ..., N$. By calculating the Euclidean distance between x_0 and x_i:

$$d(x_0, x_i) = \sqrt{\sum_{j=1}^{p} (x_{0j} - x_{ij})^2} \tag{9}$$

Select the k nearest samples. If they are numerical data, fill in the average value of the eigenvalues corresponding to these K samples:

$$x_{0j} = \frac{1}{K} \sum_{i=N_k} x_{ij} \quad (10)$$

Among them, N_k is the set of the k nearest samples.

Standardize the data to eliminate the influence of the number sequence and data series of various variables, making the variables comparable. This study adopts the commonly used Z-score standardization method, and the formula is:

$$x'_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j} \quad (11)$$

In the formula, x'_{ij} represents the standardized value, $\bar{x}_j$ is the mean of the j-*th* variable, and s_j is the standard deviation of the j *th* variable. After standardization processing, the mean of the data is 0 and the standard deviation is 1, which helps to improve the convergence speed and robustness of the model.

4.3.3. Data Sources and Descriptive Statistics

The dataset employed in this study encompasses panel data from 188 Chinese cities spanning the period 2010–2023. The data primarily originates from the China City Statistical Yearbook and the EPS Global Data Platform. Through manual collection and systematic collation, we have ensured the data's completeness and consistency. The China City Statistical Yearbook provides authoritative socioeconomic statistics for cities, while the EPS database supplements key energy and environmental indicators. Together, these sources offer comprehensive and reliable data support for the research. All raw data underwent preprocessing, with missing values reasonably imputed. Table 3 presents descriptive statistics for the standardised data.

Table 3. Descriptive Statistical Results.

Variable	Mean	Standard Deviation	Maximum Value	Minimum Value	Observation Value
JET	0.36	0.13	0.76	0.05	2632
GNP	2.15	0.47	3.67	0.53	2632
FDI	0.56	0.29	2.21	0.003	2632
TRS	0.73	0.28	1.43	0.006	2632
PAT	0.62	0.28	0.87	0.02	2632
TEC	0.39	0.28	1.13	0.002	2632
PE	0.50	0.29	0.76	0.00025	2632
FIN	0.49	0.29	0.99	0.0003	2632

5. Empirical Analysis

Before conducting the empirical analysis, correlation analysis and multicollinearity tests were carried out first, and the results revealed the core explanatory variables and the explained variables. The correlation is 0.609169, and the value of the variance inflation factor (VIF) is 12.813427, indicating a correlation. However, the explanatory variable and other control variables show multicollinearity. At the same time, the Hausenman test results are significant at a significance value of 0.05, and fixed-effect regression should be chosen.

5.1. The Impact Effect of GNP on JET

5.1.1. Fixed Effects Regression Results

Column 1 of Table 4 indicates that the coefficient for the core explanatory variable is 0.6058, significant at the 1% level, demonstrating that green new quality productive forces exert a strong positive influence on a just energy transition. At this stage, other variables were not considered, with only time effects and city effects factored in. The core explanatory variable demonstrated moderate explanatory power, yielding an R^2 of 0.36. Upon incorporating the control variable's dummy term into the model, the coefficient for the core explanatory variable shifted to 0.4634, remaining statistically significant at the 10% level, though its positive impact diminished. The R^2 value decreased to 0.31. Column (3), compared to Column (2), only altered the fixed effects configuration (removing the time fixed effect and retaining the city fixed effect). The coefficient for the core explanatory variable became 0.4823, remaining significant, with R^2 at 0.41. Column (4), building upon Column (3) without controlling for the quadratic term of the independent variable, yielded a coefficient of 0.4541 for the core explanatory variable, which was not statistically significant, with R^2 at 0.42. Column (5), controlling for the quadratic term of the variable, yields a coefficient of 0.4734 for the core explanatory variable, which is not significant. The R^2 increases to 0.49, indicating that the inclusion of the quadratic term somewhat enhances the core explanatory variable's promotion of a just energy transition. However, under the influence of high dimensionality and multicollinearity, the equation is not significant. Therefore, a partial linear regression model using dual machine learning is employed.

Table 4. Fixed Effects Regression Results.

Variable	(1)	(2)	(3)	(4)	(5)
GNP	0.6058 ***	0.4634 *	0.4823 *	0.4541	0.4734
Control₁	NO	Yes	Yes	Yes	Yes
Control₂	No	No	No	Yes	Yes
λ_t	Yes	No	Yes	No	Yes
μ_i	Yes	No	Yes	No	Yes
N	2632	2632	2632	2632	2632
R^2	0.36	0.31	0.41	0.42	0.49

Note: ***, * denote 1%, 5%, 10% significance levels respectively; The values in parentheses are SE. The following tables are the same. Here, λ_t represents the fixed effect of the year, μ_i represents the fixed effect of the city, and N represents the sample size.

5.1.2. Double Machine Learning Results

Column (1) of Table 5 shows that the coefficient for the core explanatory variable is 0.5664, significant at the 1% level. After controlling for the first-order term of the control variable, the core explanatory variable exhibits a strong positive influence. Following the inclusion of the second-order term for technological innovation capacity as a control variable, column (3) remains significant even after incorporating time and city fixed effects. The coefficient for the core explanatory variable stands at 0.5569, indicating that the inclusion of fixed effects modulates its influence to some extent, yet its positive impact remains stable. This demonstrates that green new quality productive forces exert a significant positive and catalytic effect on just energy transition (Figure 4).

The findings collectively demonstrate that Hypothesis 1 holds true, namely that green new productive forces promote just energy transition.

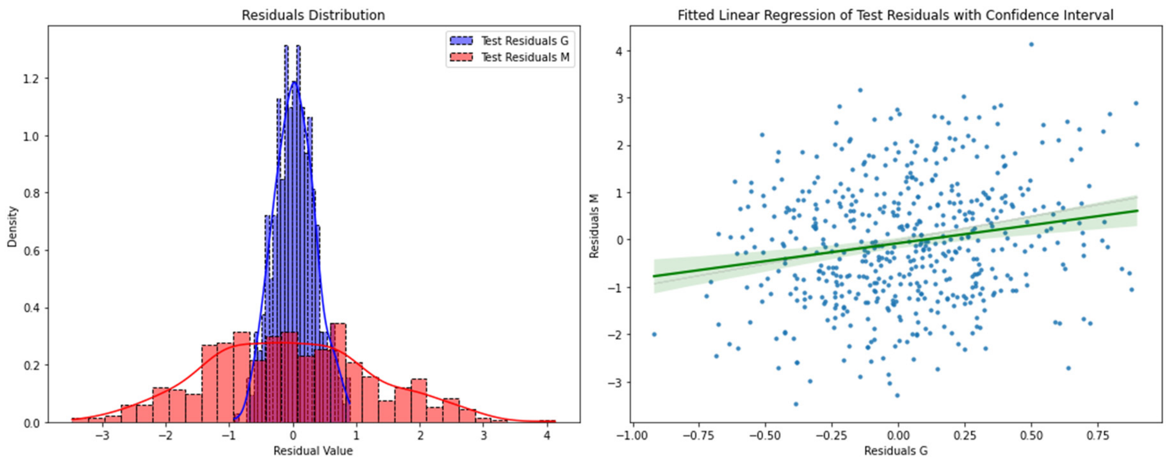

Figure 4. Two-stage residual plot of DML.

Table 5. Double Machine Learning Results.

Variable	(1)	(2)	(3)
GNP	0.5664 ***	0.6306 ***	0.5569 ***
Control₁	Yes	Yes	Yes
Control₂	No	Yes	Yes
λ_t	No	No	Yes
μ_i	No	No	Yes
N	2632	2632	2632

Note: *** denote 1% significance level.

5.2. Endogeneity Test

Endogeneity issues may stem from omitted variables, measurement errors, and bidirectional causality, which interfere with accurately identifying the causal relationship between green new quality productive forces and just energy transitions. To mitigate such biases, this paper employs an IV approach combined with double machine learning for estimation. The selected instrumental variable is the number of fixed telephones per hundred inhabitants in cities in 1984 (*Tele*), with the model specified as follows:

The first-stage regression model is:

$$GNP_{it} = \alpha_0 + \alpha_1 Tele_i + \sum_{j=2}^{m} \alpha_j Controls_{ij} + \epsilon_{it} \quad (12)$$

Among them, GNP_{it} represents the green new quality productive forces of the i-*th* city in period *t*; $Tele_i$ is the number of fixed-line telephones per 100 people in the city in 1984, as an instrumental variable; $Controls_{ij}$ is a series of control variables, including but not limited to the scale of urban economy, industrial structure, etc. These variables may affect the factors of green new quality productive forces. $\alpha_1, \alpha_2, \ldots, \alpha_m$ is the coefficient of the corresponding variable; ϵ_{it} is the error term.

Two-stage regression model is:

$$JET_{it} = \beta_0 + \beta_1 GNP_{it}^{*} + \sum_{k=2}^{m} \beta_k Controls_{ik} + \mu_{it} \quad (13)$$

Among them, JET_{it} represents the fair energy transition degree of the i-th city in period t; GNP_{it}^{*} represents the predicted value of green new quality productive forces obtained in the first stage; $Controls_{ik}$ *i*s also a set of control variables; β_0 is a constant term and $\beta_1, \beta_2, \ldots, \beta_m$ is a coefficient. μ_{it} is the error term.

The instrumental variables method yields statistically significant results at the 1% level, confirming that green new quality productive forces exert a robust positive influence on just energy transitions. However, compared with fixed effects regression and double machine learning approaches, the estimated coefficient for this effect is somewhat diminished. This discrepancy may stem from the instrumental variables method adopting a more conservative adjustment to variable relationships when correcting for endogeneity, thereby moderating the estimated effect.

5.3. Robustness Test

To validate the reliability of the research conclusions, this paper conducted robustness tests. Firstly, the TOPSIS method based on the entropy value approach was employed to construct alternative explanatory variables, thereby reducing data dimensions and enabling re-estimation (Figure 5). As shown in Table 6, although the significance levels of regression coefficients fluctuated under certain control variable settings and differences emerged in the goodness-of-fit, the direction of the coefficient for the core explanatory variable (green new quality productive forces) remained consistent, supporting the fundamental conclusion of hypothesis 1. Further comparison with fixed-effects regression models revealed that the latter maintained stable coefficients across all settings, with positive significance at the 1% level. This further corroborates that the conclusion regarding green new quality productive forces' significant promotion of a just energy transition remains fundamentally unchanged, indicating robust model stability.

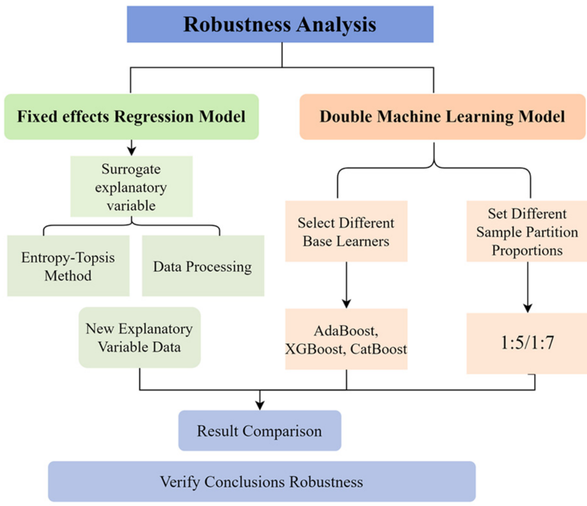

Figure 5. Robustness testing flowchart.

To further validate the reliability of the research conclusions, this paper conducted a second round of robustness testing by re-estimating the results through adjusting the sample splitting ratio and base learners of the double machine learning model. As shown in Table 7, under various settings (sample split ratios of 1:5 or 1:7, with base learners including AdaBoost, XGBoost, or CatBoost), the coefficient of the core explanatory variable (green new quality productive forces) remained positive and statistically significant, ranging from 0.3642 to 0.5639. The results consistently indicate that green new quality productive forces exert a stable, positive influence on a just energy transition. Hypothesis 1 is thus reaffirmed, further enhancing the robustness of the research conclusions.

Table 6. Results of Robustness tests 1.

Variable	(1)	(2)	(3)	(4)	(5)
GNP	0.6058 *	0.4634 *	0.4634 *	0.4541	0.4734
$Control_1$	No	Yes	Yes	Yes	Yes
$Control_2$	No	No	No	Yes	Yes
λ_t	Yes	No	Yes	No	Yes
μ_i	Yes	No	Yes	No	Yes
N	2632	2632	2632	2632	2632
R^2	0.365	0.415	0.416	0.374	0.281

Note: * denotes 10% significance level.

Table 7. Results of Robustness tests 2.

	(1)	(2)	(3)	(4)	(5)	(6)
GNP	0.4455 ***	0.4259 ***	0.4041 ***	0.3642 ***	0.5639 ***	0.5522 ***
Sample separation ratio	1:5	1:5	1:5	1:7	1:7	1:7
Basic learner	AdaBoost	AdaBoost	XGBoost	XGBoost	CatBoost	CatBoost
$Control_1$	Yes	Yes	Yes	Yes	Yes	Yes
$Control_2$	Yes	Yes	Yes	Yes	Yes	Yes
λ_t	Yes	Yes	Yes	Yes	Yes	Yes
μ_i	Yes	Yes	Yes	Yes	Yes	Yes
N	2632	2632	2632	2632	2632	2632

Note: *** denotes 1% significance level.

5.4. Mechanism Analysis

Based on the mechanism analysis results presented in Table 8, green new quality productive forces exert a significant positive influence on the proportion of renewable energy consumption (coefficient 0.3155, significant at the 1% level), whilst exhibiting a significant negative impact on the gap in per capita energy consumption between urban and rural areas (coefficient −0.2091, significant at the 1% level). This indicates that green new quality productive forces can promote a just energy transition by increasing the proportion of renewable energy and narrowing the urban-rural energy consumption gap. The above results validate the validity of hypothesis 3.

Table 8. Mechanism Analysis Results.

Variable	(1) X_1	(2) X_2
GNP	0.3155 ***	−0.2091 ***
$Control_1$	Yes	Yes
$Control_2$	Yes	Yes
λ_t	Yes	Yes
μ_i	Yes	Yes
N	2670	2655

Note: *** denotes 1% significance level. X_1 denotes the proportion of renewable energy within total energy consumption, while X_2 represents the ratio of per capita energy consumption between urban and rural areas.

5.5. Heterogeneity Analysis

According to the heterogeneity analysis results in Table 9, green new quality productive forces exert a significant positive influence on just energy transitions across different regional samples, though the intensity of this impact varies markedly. In eastern regions (Column 1) and developed areas (Column 3), the coefficients for the core explanatory variable stand at 0.6039 and 0.6789 respectively, both significant at the 1% level. This indicates a more pronounced promotional effect of green new quality productive forces on just energy transitions in these areas. By contrast, the coefficients for the western region (Column 2) and less developed regions (Column 4) were 0.2139 and 0.1334 respectively, which, while also significant, exhibited markedly weaker impact intensities. Notably, the promoting effect in developed regions is approximately five times stronger than in underdeveloped areas. This finding supports hypothesis 4, namely that significant differences exist between developed and less developed cities in terms of the influence of green new quality productive forces on just energy transitions.

Table 9. Heterogeneity Analysis results.

Variable	(1)	(2)	(3)	(4)
GNP	0.6039 ***	0.2139 ***	0.6789 ***	0.1334 ***
$Control_1$	Yes	Yes	Yes	Yes
$Control_2$	Yes	Yes	Yes	Yes
λ_t	Yes	Yes	Yes	Yes
μ_i	Yes	Yes	Yes	Yes
(1)	East	West		
(2)			Developed	Underdeveloped
N	1316	1316	658	658

Note: *** denote 1% significance level.

6. Conclusions and Recommendations

6.1. Research Conclusions

This paper first constructs an evaluation framework for green new quality productive forces and just energy transition using the entropy weight method across multiple dimensions. Subsequently, employing fixed effects models and double machine learning models among other empirical approaches, it verifies that green new quality productive forces exert a stable, positive influence on just energy transition. To address potential endogeneity issues, estimation employing instrumental variables combined with dual machine learning yielded statistically significant positive results at the 1% level, further confirming the positive driving effect of green new quality productive forces. To enhance conclusion reliability, systematic robustness tests were conducted, including instrumental variables, explanatory variable substitution, sample partition ratio adjustment, and base learner replacement. All results demonstrated robust core estimates. Mechanism analysis reveals that green new quality productive forces primarily drive equitable energy transition through two pathways: increasing the share of renewable energy consumption and narrowing the urban-rural energy consumption disparity. Heterogeneity analysis indicates that this promotional effect is more pronounced in eastern regions and developed cities, suggesting that regional development levels constitute a key boundary condition moderating its impact. In summary, green new quality productive forces exert a significant and robust catalytic effect in advancing a just energy transition. Their influence mechanisms and regional variation characteristics provide theoretical foundations and empirical references for relevant policy design.

Moreover, the findings of this study not only provide empirical support for energy transition at the urban level in China but also resonate closely with the global Sustainable Development Goals (SDGs). Research indicates that green new quality productive forces advance a just energy transition by increasing the proportion of renewable energy consumption and promoting equitable energy access. This pathway directly contributes to the core tenets of SDG 7 (Affordable and Clean Energy). Concurrently, the green and low-carbon transition driven by green new quality productivity effectively supports carbon emission reduction and climate resilience enhancement, offering a viable city-level solution for achieving global SDG 13 (Climate Action). Consequently, advancing green new quality productive forces is not only pivotal for achieving regional energy justice transitions but also constitutes a crucial practical pathway for synergistically advancing global climate governance and the sustainable development agenda.

6.2. Policy Recommendations

Amidst the pressing global imperative for sustainable development, a just energy transition has emerged as the pivotal pathway towards achieving coordinated socio-economic and ecological progress. This study reveals the significant role of green new quality productive forces in promoting a just energy transition, clarifying its mechanisms and regional heterogeneity. Consequently, formulating scientifically sound and targeted policies is crucial for accelerating the energy transition process and enhancing its fairness. Such policies must focus on fostering the development of green new quality productive forces while establishing a comprehensive, multi-tiered policy framework to effectively advance energy transition objectives. Accordingly, this paper proposes the following policy recommendations:

Firstly, intensify efforts to strengthen the development of green new quality productive forces. Local governments may establish special funds for green technology R&D, creating a mechanism for stable and growing fiscal investment, while guiding universities, research institutions, and enterprises to jointly build innovation platforms. Enterprises achieving substantive green innovation outcomes may be granted appropriate tax incentives and policy subsidies to systematically enhance green technological innovation capabilities, thereby injecting sustained momentum into energy transition. For instance, Shenzhen could establish dedicated funds for new energy battery and smart grid technologies, collaborate with enterprises such as Huawei and BYD to establish joint green technology laboratories, and offer tax incentives including additional deductions for R&D expenditure to relevant enterprises.

Secondly, promote the systematic optimisation of the energy structure. Increase policy support for renewable energy generation, implement differentiated feed-in tariff subsidies, and utilise mechanisms such as carbon markets and carbon taxes to guide the transformation of traditional energy enterprises. Concurrently, strengthen investment in research and development for key technologies like energy storage and smart grids to enhance the stability of the energy system and its capacity to absorb green electricity. For instance, Ningxia could leverage its abundant solar resources by implementing tiered feed-in tariffs for distributed photovoltaic projects, while encouraging coal-fired power enterprises to secure transition funding through participation in carbon market transactions to support energy storage project development.

Thirdly, prioritise equity in urban-rural energy consumption. Increase investment in rural energy infrastructure, focusing on grid upgrades and clean energy access initiatives. Promote distributed photovoltaic and biomass energy adoption in rural areas through equipment subsidies and generation incentives, effectively narrowing the urban-rural energy gap and ensuring shared benefits from the transition. For instance, Zhejiang Province could promote the ‘photovoltaics plus agriculture’ model in mountainous counties, offering farmers up to 50% purchase subsidies for photovoltaic installations. Surplus electricity fed into the grid would benefit from preferential tariffs, complemented by smart grid upgrades in rural areas.

Finally, implement regionally differentiated advancement strategies. Eastern and developed regions may establish green development demonstration zones to attract technology, capital, and talent, serving as pioneers to drive progress. For central, western, and less developed regions, cross-regional industrial collaboration and technical assistance should be strengthened. Combined with transfer payments and policy support, this would enable the development of locally appropriate green industries, gradually enhancing green transition capabilities and achieving coordinated progress. For instance, the Yangtze River Delta region could establish an integrated green demonstration zone focused on new energy equipment manufacturing. Meanwhile, Gansu Province could leverage its wind energy resources to establish industrial collaboration mechanisms with eastern provinces, developing wind power equipment assembly bases while receiving horizontal fiscal transfer payments.

Author Contributions

Y.W.: Conceptualization; Investigation; Visualization; Writing—original draft. Y.S.: Visualization; Writing and editing the paper. X.Z.: Formal analysis; Writing and editing the paper. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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