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Ultra-High-Voltage Construction Projects and Total Factor Energy Efficiency: Empirical Evidence on Cross-Regional Power Dispatch in China

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Abstract: Optimizing cross-regional energy dispatch is crucial for addressing regional energy resource imbalances and significantly enhancing energy utilization efficiency. This study aims to analyze the potential impact of China's ultra-high-voltage (UHV) construction on firms' total factor energy efficiency and provide empirical evidence supporting the role of cross-regional energy dispatch in improving firms' energy efficiency. The construction of UHV infrastructure has become a vital part of China's "New Infrastructure" projects, presenting a "Chinese solution" to the global challenge of regional energy resource mismatches. This study employs an enhanced two-step stochastic frontier method to quantify firms' total factor energy efficiency and utilizes a difference-in-differences model to evaluate the impact of inter-regional electricity dispatch on this efficiency. The empirical analysis results indicate that UHV construction projects increase the total factor energy efficiency of regional firms by an average of 0.45%, which significantly contributes to firms' total factor productivity. This conclusion remains valid after a series of robustness tests. Furthermore, the heterogeneity analysis results indicate that the UHV construction project increases the total factor energy efficiency of non-energy-intensive industries by 0.49%, and significantly enhances the total factor energy efficiency of the manufacturing industry by 0.94%. However, it has no significant effect on energy-intensive industries or non-manufacturing enterprises. Additionally, the mechanism analysis shows that UHV construction projects affect total factor energy efficiency through three pathways: industrial structure adjustment, urban innovation, and clean energy transition. This study offers insights for addressing regional energy spatial mismatches and provides policy recommendations for developing a new energy system aligned with regional needs.

Keywords: cross-regional power dispatch; ultra-high voltage; total factor energy efficiency; new energy system

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Citation: Wang, Y.; Zhen, J.; Pan, H. Ultra-High-Voltage Construction Projects and Total Factor Energy Efficiency: Empirical Evidence on Cross-Regional Power Dispatch in China. *Sustainability* **2024**, *16*, 8083. https://doi.org/10.3390/su16188083

Academic Editor: Enrique Rosales-Asensio

Received: 20 August 2024
Revised: 11 September 2024
Accepted: 11 September 2024
Published: 16 September 2024

1. Introduction

Energy is the cornerstone of advancing modernization with Chinese characteristics, playing a critical role in economic development, national security, and enhancing population well-being. As the world's largest developing country, China's energy demand and supply strategy is pivotal in the global energy landscape. In recent decades, China's rapid economic growth has significantly increased electricity demand. However, the spatial mismatch between the concentrated electricity load in central and eastern regions and the primary energy resources in the western region has led to a persistent supply–demand imbalance [1]. Since 2021, provinces like Guangdong, Jiangsu, and Jilin have implemented measures such as "orderly electricity consumption", temporary power outages, and load shedding. The extreme heat in the summer of 2022 exacerbated electricity shortages in several provinces. Frequent power restrictions disrupt daily life and negatively impact economic and social development [2]. Therefore, scientifically scheduling regional electricity and enhancing grid transmission capacity are essential for advancing a new energy system in China and ensuring regional energy security.

The total factor energy efficiency of firms serves as the micro-foundation for high-quality regional energy development. Since its introduction by Hu and Wang [3], total factor energy efficiency has been widely used in energy research. Unlike traditional single-factor energy efficiency, which measures the ratio of a single energy input to output (e.g., energy consumption per unit of GDP), total factor energy efficiency considers the intrinsic substitution and complementary relationships among multiple inputs, including capital, labor, and energy. Total factor energy efficiency is quantified as the ratio of targeted-to-actual energy input. Enhancing corporate energy efficiency has become a central concern for policymakers and scholars in the pursuit of sustainable development and in response to global climate change [4]. Notably, China's rapid economic growth has significantly increased electricity demand. To meet the growing energy demand and enhance energy efficiency while optimizing the energy mix, China has launched several large-scale energy dispatch projects, including the "West-to-East" electricity transmission initiative. These cross-regional energy dispatch projects are crucial for optimizing the national energy structure, mitigating regional energy imbalances, and promoting clean energy utilization [5]. They also exemplify China's energy policy and management efforts, particularly in improving energy efficiency and advancing a green economic transition.

Unfortunately, few studies have examined the impact of ultra-high-voltage (UHV) construction projects on firms' total factor energy efficiency. Recent research suggests that improving energy efficiency can lower production costs and boost corporate competitiveness [6]. However, the effectiveness of cross-regional electricity dispatch in improving energy efficiency and its underlying mechanisms remain underexplored. UHV strategies affect not only China's power supply structure but also significantly influence energy use and efficiency at the corporate level. This large-scale power dispatch promotes regional energy balance and supply reliability while significantly affecting production operations and energy efficiency in firms [7].

On the energy consumption side, cross-regional electricity dispatch increases regional power supply, enabling companies to expand production and improve efficiency. Additionally, the improved stability of power supply allows businesses to plan long-term production more effectively, reducing energy costs and operational risks [8]. Furthermore, cross-regional electricity dispatch improves the overall energy efficiency of clustered firms [9]. According to the theory of innovation diffusion, advanced energy technologies are promoted among firms, further increasing energy use efficiency [10]. On the energy production side, UHV projects stimulate local energy infrastructure development and advance power transmission and transformation technologies. This improves both the technical standards and conversion efficiency of the local electricity industry while fostering the growth of related industries in resource-rich regions, facilitating the use of local resources [11]. In particular, it promotes the development of new and renewable energy industries. Despite potential higher short-term infrastructure investments, cross-regional electricity dispatch mitigates long-term regional energy imbalances, serving as a foundational project for balanced regional economic development.

While existing studies have mainly focused on the impact of energy policies on macroeconomics and the environment [12], research on specific energy scheduling projects like UHV is relatively scarce. Most current research focuses on overall energy consumption and energy-saving effects [13–15]. However, there is a relative lack of understanding of how energy policies affect energy utilization efficiency across different industries and firms, and the internal mechanisms involved. This research gap may lead to biases in understanding the effects of energy policies.

Furthermore, existing studies often neglect the varied impacts of UHV construction projects on different industries and on both the supply and demand sides of electricity. The impact of energy policies can significantly differ across industries, and how these policies affect electricity production and consumption may also differ [16]. This paper measures firms' total factor energy efficiency using an enhanced two-part stochastic frontier model. It examines how UHV construction projects influence total factor energy efficiency. The study analyzes the mechanisms from three perspectives: industrial structure adjustment, urban innovation development, and clean energy transformation. It also considers the distinct characteristics of electricity production and consumption, providing a detailed analysis of UHV construction projects' impact on firms' total factor energy efficiency.

The marginal contributions of this paper are as follows: First, it extends existing research on energy efficiency and policy impacts, with a specific focus on firm-level total factor energy efficiency. Second, through detailed analysis of UHV transmission projects, it clarifies how these projects impact firm-level total factor energy productivity, providing empirical evidence for evaluating and optimizing cross-regional electricity dispatch strategies. Third, the findings provide valuable insights for policymakers and enterprise managers, helping them understand and respond to energy policy changes.

The remainder of this paper is organized into seven sections. Section 2 provides the policy background and theoretical analysis. Section 3 details the measurement of firms' total factor energy efficiency. Section 4 describes the research design. Section 5 analyzes the empirical results. Section 6 conducts the mechanism analysis. Section 7 presents the conclusion and policy implications.

2. Policy Background and Theoretical Analysis

2.1. Policy Background

2.1.1. Energy Resource Endowment and Cross-Regional Power Dispatch

Cross-regional power dispatch is crucial for transmitting electricity over long distances and enhancing energy efficiency. It addresses the mismatch between the locations of energy resources and the areas where electricity is needed in China. Over 80% of China's energy resources are in the northwest, whereas more than 70% of electricity consumption occurs in the central and eastern regions. These resource-rich areas are approximately 1000 to 4000 km from the main demand centers. This mismatch between electricity demand and energy resources significantly restricts regional economic growth and the utilization of valuable resources. Therefore, China has initiated UHV cross-regional power dispatch projects. In the late 1970s, Central Committee of the Communist Party of China introduced the "West-to-East" electricity transmission strategy with UHV projects, establishing UHV construction as a key component of electrical infrastructure development.

2.1.2. Development Process of China's UHV Project

UHV projects are the main conduits for regional electricity transmission and are crucial for implementing clean energy transformation strategies that prioritize electricity over conventional energy sources. The development of UHV projects in China can be divided into three main stages:

The initial phase (2005–2010): Exploration and Feasibility. In 2005, the National Development and Reform Commission, in collaboration with power grid companies, research institutions, universities, equipment manufacturers, and project design and implementation units, initiated a comprehensive feasibility study for China's first UHV project. By 2009, after overcoming numerous technical challenges, the 1000 kV UHV alternating current (AC) demonstration project from Jindongnan to Nanyang to Jingmen was successfully commissioned. In 2010, the first set of UHV direct current (DC) demonstration projects, including routes from Yunnan to Guangdong and Xiangjiaba to Shanghai at ±800 kV, were progressively completed and became operational, marking the start of China's UHV construction efforts.

The second phase (2011–2014): Refinement and Advancement. Sustained advancements in UHV technology research and engineering have gradually clarified and refined the technical trajectory of UHV project development. At the same time, equipment manufacturing capabilities improved, talent pools expanded, and standardization efforts made significant progress. In May 2014, the National Energy Administration issued a directive to accelerate the construction of 12 key power transmission corridors as part of a broader initiative for air pollution reduction and management. Subsequently, the State Grid established the “Three Vertical and Three Horizontal” UHV backbone networks and completed 13 DC transmission projects, marking a peak in UHV construction efforts.

The third phase (2015-present): Acceleration and Expansion. In September 2018, the National Energy Administration issued a directive to expedite the planning and execution of key power transmission and transformation projects, leading to a new surge in UHV development. During this period, China’s UHV technology advanced significantly, construction methods were refined, and project expertise increased, facilitating rapid progress. By the end of 2022, China had successfully constructed 36 UHV lines, including 16 AC and 20 DC lines. In January 2023, the National Energy Administration released the “Blueprint for the Development of New Power Systems (Draft for Comments)”, designating several UHV projects as key components in developing new power systems.

After over two decades of practical exploration and scientific research, China’s UHV technology has transitioned from being “Made in China” to “Led by China”, and from “Equipping China” to “Equipping the World.” During the 14th Five-Year Plan period (2021–2025), the State Grid of China plans to build 24 AC UHV projects and 14 DC UHV projects, spanning over 30,000 km of lines, with a transformation and conversion capacity of 340 million kVA and a total investment of 380 billion RMB. By 2022, the cumulative power transmission capacity of China’s UHV projects reached approximately 2834.611 billion kWh. Additionally, the annual contract value of UHV DC transmission business is around RMB 1 billion. China’s flexible DC transmission technology is highly regarded internationally; for example, in 2022, China Light and Power Corporation won the bid for the offshore wind power grid connection project in Germany. Cross-regional UHV projects have become crucial for energy transport, aligning with China’s strategic vision of “West-to-East Power Transmission, North-to-South Power Supply, Mutual Support of Hydro and Thermal Power, and Complementary Deployment of Wind and Solar Energy”. These initiatives are strategically significant for reducing regional electricity disparities, advancing energy transformation, and promoting high-quality economic development.

2.2. Theoretical Analysis

Cross-regional power dispatch is crucial for improving energy efficiency and optimizing the power supply framework. By addressing the imbalance between resource availability and energy demand, it improves energy efficiency. Additionally, cross-regional power dispatch promotes balanced economic development across regions and improves the energy consumption matrix. Indirectly, it affects the total factor energy efficiency of enterprises by adjusting industrial frameworks, stimulating regional innovation, and restructuring the energy landscape. Typically, when cross-regional power dispatch policies are implemented, the total factor energy efficiency of enterprises does not directly affect the policy, and there is no clear reverse causal relationship.

China’s UHV project policy strategically involves transferring electricity from resource-rich western regions to energy-scarce eastern regions. Deng et al. [17] emphasized the importance of optimizing energy allocation to reduce wastage and improve efficiency across various consumption sectors. This method improves electricity utilization efficiency, thereby increasing the total factor energy efficiency of enterprises. Cross-regional power dispatch directly increases the electricity resources available to enterprises. Unlike conventional power supply models, which may lead to shortages due to geographic and resource constraints, cross-regional power transmission ensures equitable distribution of electricity resources, providing a stable supply to various regions [15]. A stable power supply is crucial for enterprises, preventing production disruptions from outages and thereby enhancing both production and energy efficiency.

Additionally, inter-regional power dispatch reduces electricity costs for enterprises. By optimizing electricity resource distribution, supply and demand equilibrium is restored, leading to lower electricity prices [18]. This cost reduction directly lowers operational expenses, allowing enterprises to use electricity more cost effectively and efficiently. This is especially important for energy-intensive industries, where energy costs represent a significant portion of total expenses. A reliable and cost-effective electricity supply allows enterprises to plan production schedules better and optimize processes. This leads to increased production efficiency and better energy utilization, reducing waste and improving overall sustainability and overall energy efficiency. Consequently, cross-regional power dispatch creates a favorable environment for business operations, significantly improving overall energy efficiency. This improvement is reflected in reduced production costs, increased production efficiency, and optimized energy utilization. Thus, Hypothesis 1 is proposed as follows:

Hypothesis 1: *Cross-regional power dispatching can improve the total factor energy efficiency of firms.*

Cross-regional power dispatching has transformed the energy supply landscape and directly affected the industrial structure in various regions. Zhang et al. [19] suggest that changes in the energy supply framework can lead to shifts in industrial focus. UHV projects enable interregional energy flow, improving the energy supply in eastern regions and supporting the overall development of industries there. In western regions, known for exporting electricity, there may be a reduced reliance on local energy-intensive sectors, leading to a shift towards developing sectors like services and high-tech industries. These adjustments and optimizations in industrial structure significantly affect firms' energy utilization patterns [20], causing notable variations in energy efficiency across sectors. Typically, non-energy-intensive sectors have lower energy efficiency compared to high-tech and service sectors, which generally show higher efficiency. Consequently, as the industrial structure shifts towards more efficient sectors, overall energy efficiency increases.

In eastern regions, boosted by increased energy supply, enterprises are more likely to develop industries with higher energy efficiency, thereby improving the overall total factor energy efficiency of firms. Acemoglu et al. [21] suggest that industrial upgrading often coincides with technological innovation. In the context of cross-regional power dispatching, as the industrial structure evolves, firms adopt technologies suited to the new landscape, promoting technological innovation and advancement. This technological evolution not only increases production efficiency but also improves energy utilization efficiency.

Additionally, changes in industrial structure are closely linked to regional economic development levels. Gai et al. [22] explain that higher levels of economic development lead to increased energy efficiency. This correlation arises from the need for more efficient energy technologies to support complex, high-value economic activities. Moreover, changes in industrial structure are linked with reforms in environmental policies and market mechanisms. Effective environmental policies and market mechanisms drive the optimization of industrial structure. In the context of cross-regional power dispatching, local governments can implement supportive policies like tax incentives and technical assistance. These measures encourage enterprises to adopt energy-efficient and environmentally sustainable practices, promoting industrial optimization and improving the total factor energy efficiency of firms.

In summary, changes in industrial structure significantly affect how cross-regional power dispatching impacts firms' total factor energy efficiency. Cross-regional power dispatching significantly impacts regional industrial structure, promotes technological innovation in firms, and enhances regional economic development. Additionally, along with environmental policy reforms and market mechanisms, it indirectly improves firms' total factor energy efficiency. Therefore, this study formulates the second hypothesis as follows:

Hypothesis 2: *Cross-regional power dispatching improves the total factor energy efficiency of firms by adjusting the industrial structure.*

Cross-regional power dispatch optimizes resource allocation and supports the innovative development of cities. Electricity, a crucial input in socio-economic activities, significantly affects the stability and efficiency of enterprise operations and technological innovation. For example, a reliable electricity supply reduces uncertainties in business operations, increases efficiency, and supports high-energy-consuming research activities [23]. Thus, cross-regional power dispatch creates favorable conditions for economic development and technological innovation by ensuring a stable electricity supply. Technological advancements and improved management practices are crucial for enhancing the total factor energy efficiency of firms. Technological innovation promotes the development of efficient energy technologies, while management innovation optimizes resource allocation and reduces energy waste [24]. Therefore, fostering innovation in cities indirectly improves the total factor energy efficiency of firms through cross-regional power dispatch. Additionally, it facilitates the exchange of knowledge and technology between regions, accelerating the diffusion and adoption of new energy technologies.

Cities are crucial in influencing the operations and growth of regional firms due to their role as economic hubs. Reliable electricity is essential for cities to attract talent and capital, accelerating technological innovation and knowledge dissemination [25]. A favorable business environment encourages the adoption of efficient production technologies and management practices, improving energy efficiency. This is especially important for the manufacturing sector, where a stable electricity supply and technological innovation are vital for improving energy efficiency. In an innovation-driven urban environment, firms can use technological advancements and improve management practices to optimize energy use and production processes. This approach not only reduces production costs but also lowers environmental pollution, promoting sustainable economic development.

The previous analysis shows that cross-regional power dispatching promotes the innovative development of cities, which in turn indirectly enhances the total factor energy efficiency of firms. This mechanism supports balanced regional economic growth and positively impacts environmental protection and sustainable development. Based on this analysis, this study hypothesizes the following:

Hypothesis 3: *Cross-regional power dispatching will enhance the total factor energy efficiency of firms through the mechanism of urban innovative development.*

Cross-regional power dispatching is a complex process with multiple dimensions, affecting electricity distribution, consumption, regional economic growth, and energy efficiency. A key aspect of this process is energy transformation, which involves shifting from carbon-intensive and non-renewable sources to low-carbon and renewable ones [26]. The main objective of cross-regional power dispatching is to meet diverse regional electricity needs through strategic resource optimization. In high-voltage direct current transmission projects, surplus electricity from resource-rich western regions can be efficiently transferred to demand-heavy eastern regions. This strategic transfer alleviates electricity shortages in the east and improves the utilization of underused resources in the west. This approach refines current electricity resource allocation and consumption while also laying the groundwork for future energy transitions.

Energy transformation is central to this evolution, as cross-regional power dispatching enables the efficient distribution of both traditional and clean energy resources [27]. The western regions, rich in natural resources, are well suited for generating clean energy sources such as hydro and wind power. Cross-regional dispatching allows these resources to be efficiently directed to the east, thereby increasing the share of clean energy in the overall mix and guiding the energy sector towards a greener and more sustainable path.

Total factor energy efficiency is a key metric for evaluating a firm's energy efficiency, including traditional measures and the sustainability and environmental impacts of energy use. By increasing the proportion of clean energy, cross-regional power dispatching can lower energy costs and reduce firms' environmental impact, thereby improving their total factor energy efficiency. In summary, cross-regional power dispatching promotes energy transformation by optimizing electricity resource distribution, increasing the share of clean energy, and significantly improving the total factor energy efficiency of firms. Based on the above analysis, we hypothesize the following:

Hypothesis 4: *Cross-regional power dispatching will improve the total factor energy efficiency of firms by facilitating the transition to clean energy.*

3. Measurement of Total Factor Energy Efficiency

Recent studies have found that technological heterogeneity among industries significantly impacts the total factor energy efficiency of micro-enterprises [22,28]. Therefore, measuring total factor energy efficiency for firms should account for dynamic changes in technological heterogeneity across industries. Consequently, this paper measures the total factor energy efficiency of firms using the two-step stochastic frontier model proposed by Zhang and Zhou [29].

3.1. Model Setting

Referring to the research setting of Zhang and Zhou [29] on the two-step stochastic frontier model, this paper assumes that the input factors of a firm include capital (K), labor (L), and energy (E). The expected output (Y) is total revenue, while non-expected output (B) represents the main pollutant emissions by the company. (The main pollutants emitted by firms include the chemical oxygen demand and ammonia nitrogen emissions in industrial wastewater, as well as sulfur dioxide and nitrogen oxide emissions in industrial exhaust gases. We standardize the four types of pollutant emissions from firms based on the pollution equivalent values determined by the "Management Measures for Pollution Levy Standards".). The production possibility set formed by input–output combinations is denoted as T.

$$T = \{(K, L, E, Y, B) : (K, L, E) \quad \text{can produce} \quad (Y, B)\} \tag{1}$$

Based on the study by Zhou et al. (2012) [30], this study defines the input-oriented Shephard energy distance function as follows:

$$D_E(K, L, E, Y, B) = \sup\{a : K, L, E/a, Y, B\} \tag{2}$$

The reciprocal of the Sheppard distance function can be defined as the energy efficiency within the range economy. Therefore, enterprise total factor energy efficiency (EE) can be represented as the ratio between potential energy input and actual energy input.

$$EE = \frac{E/a}{E} = \frac{1}{a} = \frac{1}{D_E(K, L, E, Y, B)} \tag{3}$$

If EE equals 1, it means that the overall energy use of the enterprise is above the frontier. Otherwise, if EE is less than 1, it indicates that the enterprise's overall energy efficiency is lower. The higher the value of EE, the higher the energy efficiency of the enterprise in terms of all factors.

Due to the ability of transcendental logarithmic production functions to better describe the nature of parameters, this paper chooses a transcendental logarithmic production function to set up an energy distance function. Drawing on the research by Hailu and Veeman [28] and Zhang and Zhou [29], a time trend term is added to the transcendental logarithmic production function in order to capture the dynamic changes in total factor energy efficiency.

$$
\begin{aligned}
\ln D_E(K,L,E,Y,B,t) \quad &= a_0 + \sum_{i=K}^{K,L,E} a_i \times \ln y_i + \sum_{j=Y}^{Y,B} a_j \times \ln y_j \\
&+ \frac{1}{2}\sum_{i=K}^{K,L,E}\sum_{i'=K}^{K,L,E} a_{ii'} \times \ln x_i \times \ln x_{i'} + \frac{1}{2}\sum_{j=Y}^{Y,B}\sum_{j'=Y}^{Y,B} a_{jj'} \times \ln y_j \times \ln y_{j'} \\
&+ \sum_{i=K}^{K,L,E}\sum_{j=Y}^{Y,B} a_{ij} \times \ln x_i \times \ln y_j + a_t \times t + \frac{1}{2}a_{tt} \times t^2 \\
&+ \sum_{i=K}^{K,L,E} a_i \times t \times \ln x_i + \sum_{j=Y}^{Y,B} a_{jt} \times t \times \ln y_j
\end{aligned} \tag{4}
$$

According to the homogeneity of the energy distance function, we can further derive the following model [29,30].

$$
\begin{aligned}
-\ln E \quad &= a_0 + a_K \ln K + a_L \ln L + a_Y \ln Y + a_B \ln B + \tfrac{1}{2}a_{KK} \ln K \times \ln K \\
&+ a_{KL} \ln K \times \ln L + a_{KY} \ln K \times \ln Y + a_{KB} \ln K \times \ln B + \tfrac{1}{2}a_{LL} \ln L \times \ln L \\
&+ a_{LY} \ln L \times \ln Y + a_{LB} \ln L \times \ln B + \tfrac{1}{2}a_{YY} \ln Y \times \ln Y + a_{YB} \ln Y \times \ln B \\
&+ \tfrac{1}{2}a_{BB} \ln B \times \ln B + a_t t + \tfrac{1}{2}a_{tt} \times t^2 + a_{Kt} \times t \times \ln K + a_{Lt} \times t \times \ln L \\
&+ a_{Yt} \times t \times \ln Y + a_{Bt} \times t \times \ln B + \nu - \mu
\end{aligned} \tag{5}
$$

Among them, μ is a non-negative random variable representing the value of energy inefficiency, and $\mu = \ln D_E(K,L,E,Y,B,t)$. v is a random disturbance term following a standard normal distribution.

3.2. Model Solution

The solution of the two-step stochastic frontier model consists of two parts: in the first step, the within-group frontier surface is estimated. Due to differences in production technology between different industries, this paper groups companies based on their industry affiliation and assumes heterogeneous production technologies among different industries. This consideration can reduce estimation bias caused by technological differences between industries.

Therefore, the production technology within the group can be defined as follows:

$$T^g = \{(K,L,E,Y,B) : (K,L,E) \quad \text{can produce} \quad (Y,B), g = 1,2,\cdots,G\} \tag{6}$$

The energy efficiency within the group can be defined as follows:

$$EE^g = \frac{1}{D_E{}^g(K,L,E,Y,B,t)} \tag{7}$$

According to the model set by Equation (5), the estimated value of energy efficiency within the group can be represented as $EE^g = E(\exp(-\mu))$. Furthermore, it is possible to calculate the error $\widetilde{\nu}$ between the estimated and actual values of input.

$$\widetilde{\nu} = \ln EE^g(K,L,E,Y,B,t) - \ln \hat{E}E^g(K,L,E,Y,B,t) \tag{8}$$

The second step is to calculate the energy efficiency of the common frontier. First, build a common frontier production technology:

$$T^m = \left\{T^1 \cup T^2 \cup \cdots \cup T^G\right\} \tag{9}$$

$$T^m = \{(K,L,E,Y,B) : (K,L,E) \quad \text{can produce} \quad (Y,B)\} \tag{10}$$

Furthermore, according to the studies conducted by Zhang and Zhou [29], the calculation of the gap between intra-group frontier and common frontier (*TGD*) is

$$\ln TGD = \ln(\frac{D_E^m}{D_E^g}) \tag{11}$$

At this point, the relationship between the energy efficiency of the common frontier and the energy efficiency within the group can be expressed as

$$EE^m = \frac{1}{D_E^m(K, L, E, Y, B, t)} = \frac{1}{TGD \times D_E^g} = \frac{1}{TGD} \times EE^g \tag{12}$$

Finally, by combining Equations (8) and (11), we obtain the regression equation for the second step:

$$-\ln \hat{EE}^g(K, L, E, Y, B, t) = \ln EE^m(K, L, E, Y, B, t) + \nu^m - \mu^m \tag{13}$$

Among them, $\nu^m = -\widetilde{\nu}$, $\mu^m = \ln TGD$, $TGD = E(\exp(-\mu))$. Define *TGR* as the reciprocal of *TGD*, then the overall energy efficiency at the common frontier is

$$EE^m = TGR \times EE^g \tag{14}$$

4. Research Design

4.1. Model Construction

The construction of China's UHV engineering projects is progressing in phases, creating an ideal setting for applying a difference-in-differences model. To accurately assess the policy effects of cross-regional power dispatching on firms' total factor energy efficiency, this paper uses China's UHV engineering as a quasi-natural experiment and draws on Beck et al.'s [31] research to construct the following econometric model:

$$EE_{it} = \alpha_0 + \alpha_1 did_{it} + \boldsymbol{\beta Z}_{it} + \gamma_i + \tau_t + \varepsilon_{it} \tag{15}$$

Among them, the explained variable EE_{it} represents the total factor energy efficiency of enterprise i in year t. The core explanatory variable did_{it} is defined as $did_{it} = treat_i \times post_t$, representing the double difference estimator. If enterprise i is located in a region where UHV projects are being constructed during year t, then $did_{it} = 1$ for year t and subsequent years; otherwise, it equals 0. If the coefficient α_1 of did_{it} is significantly greater than 0, it indicates that cross-regional power dispatching significantly promotes the improvement of enterprise's total factor energy efficiency. $\boldsymbol{Z}_{it}$ represents a series of control variables; γ_i, τ_t represent firm fixed effects and time fixed effects, respectively; ε_{it} represents the error term.

4.2. Variable Selection and Descriptive Statistics

4.2.1. Dependent Variable

In this study, the total factor energy efficiency of firms, referred to as *EE*, is the dependent variable. Expected output, capital, and labor are measured by total operating revenue, net fixed assets, and number of employees, respectively, of firms listed in the stock exchange database. Energy input is represented by direct energy requirements in the firms' production and operations. This is determined by data on energy consumption from boilers, furnaces, vehicles, and other equipment, as well as energy used in chemical production processes. Unintended output at the enterprise level consists of pollutant emissions. Following Jiang et al. [32], this study considers chemical oxygen demand, ammonia nitrogen emissions in industrial wastewater, and sulfur dioxide and nitrogen oxides emissions in industrial waste gas to define unintended output. These emissions are standardized according to the "Regulations on the Collection Standards of Pollution Fees" to determine the equivalent values of unintended output for the firms.

4.2.2. Core Explanatory Variable

The core explanatory variable in this study is cross-regional power dispatch (*did*), defined as a difference-in-differences variable based on the construction and operation timelines of China's UHV projects. During the sample period, companies within the jurisdictional scope of the UHV projects are set as the treatment group, with $treat_i = 1$; otherwise, they are set as the control group, with $treat_i = 0$. $post_t$ is a time dummy variable for the "West-East Power Transmission" project. When year is greater than the year of operation, $post_t = 1$; otherwise $post_t = 0$. The interaction term between these two variables $did_{it} = treat_i \times post_t$ is the core explanatory variable in this article.

Cross-regional UHV construction projects fall into two main categories: direct current DC UHV and alternating current AC UHV projects. DC UHV projects are primarily point-to-point terminal projects, while AC UHV projects are network-based with multiple flexible landing points. To ensure the scientific validity of the experimental group selection, this study follows Wang et al. [33] and designates the areas under the terminals of both DC UHV and AC UHV projects, as well as the intermediate landing points, as the experimental group.

4.2.3. Control Variables

To ensure comparability between the experimental and control groups, it is essential to control for potential exogenous factors. This study, based on the research of Liu et al. [34] and Shen et al. [35], includes the following control variables: Company Size (*Size*), measured by the logarithm of total assets; Company Age (*Age*), represented by the logarithm of the current year minus the year of establishment plus one; Asset Return (*Dar*), measured by the proportion of earnings before interest and taxes to total assets; State-owned Enterprise (*Sat*), assigned a value of 1 for state-owned firms and 0 otherwise; Industry Concentration (*HHI*), measured using the Herfindahl–Hirschman Index; Solvency (*Cas*), measured by the cash ratio; Return on Assets (*Roa*), measured by the ratio of net profit after tax to total assets.

4.3. Data Description

To thoroughly evaluate the impact of UHV construction projects on firms' total factor energy efficiency, this study limits the sample period to 2007–2021. The experimental group consists of the 22 provinces involved in UHV AC and DC projects: Yunnan, Sichuan, Xinjiang, Ningxia, Gansu, Shanxi, Inner Mongolia, Qinghai, Shaanxi, Guangdong, Shanghai, Jiangsu, Henan, Zhejiang, Hunan, Shandong, Anhui, Guangxi, Hubei, Hebei, Fujian, and Tianjin. The remaining regions constitute the control group.

Data on energy inputs and undesired outputs for total factor energy efficiency are sourced from the Energy, Pollution, and Carbon Emissions Database of listed companies, which is compiled from their annual reports. The timeline for the construction and operation of UHV projects across regions is obtained from the State Grid Corporation of China (www.sgcc.com.cn) and the Southern Power Grid (www.csg.cn). Regional variable data are acquired from the China Economic Database (CEIC), while data on listed companies come from the CSMAR database. Detailed information on specific UHV construction is provided in the Appendix A.

The descriptive statistics of the main variables in this study are shown in Table 1.

Table 1. Descriptive statistics of the main variables.

Variable	Observation	Mean	Std.	Min	Max
EE	26,456	0.2674	0.0583	0.0153	1.0013
did	26,456	0.6097	0.4878	0.0000	1.0000
Size	26,456	21.5713	1.4936	13.4043	28.7183
Age	26,456	2.1772	0.7473	0.6931	3.4657
Dar	26,456	0.4402	0.2170	0.0075	10.0822
Sat	26,456	0.4208	0.4937	0.0000	1.0000
Ass	26,445	0.0628	0.1148	−1.1817	10.6160
HHI	26,361	0.1404	0.1334	0.0324	1.0000
Cas	26,455	0.8030	2.2191	−0.6113	167.5440
Roa	26,456	0.0402	0.1261	−3.1644	10.4009

5. Empirical Results Analysis

5.1. Baseline Estimation Results

Table 2 shows the baseline estimation results for the impact of UHV construction projects on firms' total factor energy efficiency. Columns (3) and (4) provide comprehensive results with additional control variables included. The baseline results show that the coefficient of the policy variable is significantly negative at the 1% level, indicating that UHV construction projects significantly enhance the total factor energy efficiency of firms. The empirical results indicate that the UHV construction project can lead to an average 0.45% increase in the total factor energy efficiency of regional enterprises overall. Therefore, Hypothesis 1 proposed in this paper is supported.

Table 2. Baseline estimated results.

Variables	(1)	(2)	(3)	(4)
	EE	***EE***	***EE***	***EE***
did	0.0050 *** (0.0018)	0.0045 *** (0.0016)	0.0048 *** (0.0017)	0.0045 *** (0.0015)
Size			−0.0050 *** (0.0014)	−0.0046 *** (0.0014)
Age			0.0058 ** (0.0025)	0.0060 ** (0.0025)
Dar			0.0250 *** (0.0059)	0.0233 *** (0.0044)
Sat			−0.0029 (0.0034)	−0.0026 (0.0030)
Ass			0.0151 ** (0.0066)	0.0143 ** (0.0065)
HHI			0.1009 *** (0.0222)	0.1002 *** (0.0223)
Cas			−0.0003 * (0.0002)	−0.0003 * (0.0002)
Roa			−0.0049 (0.0044)	−0.0045 (0.0044)
Constant	0.2644 *** (0.0011)	0.2648 *** (0.0010)	0.3345 *** (0.0267)	0.3273 *** (0.0270)
Enterprise FE	YES	YES	YES	YES
Regional FE	NO	YES	NO	YES
Time FE	YES	YES	YES	YES
Observation	26148	26121	26052	26025
Adjusted R^2	0.394	0.398	0.390	0.394

Note: Robust standard errors at the firm level are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

5.2. Parallel Trend Test

The parallel trends assumption is essential for the difference-in-differences model. In this study, this means that, in the absence of the cross-regional power project, the total factor energy efficiency of firms in both the treatment and control groups would have followed the same trend. This paper tests the parallel trends assumption using the Event Study method, as outlined by Beck et al. [31]. The model construction is as follows:

$$EE_{it} = \psi_0 + \sum_{k=-6}^{6} \psi_k D_{it}^k + \boldsymbol{\beta Z}_{it} + \gamma_i + \tau_t + \varepsilon_{it} \tag{16}$$

Among them, D_{it}^k is a group of dummy variables. If sample i belongs to the jurisdiction area under the UHV project in year t, its value is 1; otherwise, it is 0. The symbols of other variables have the same meanings as those in Equation (1). ψ_k reflects the difference in total factor energy efficiency between the treatment group and the control group enterprises in the k-th year of pilot policy implementation. To avoid multicollinearity, this study takes one year before the implementation of UHV projects as the baseline period. By comparing the magnitude and significance of coefficient ψ_k in Equation (16), we can test for parallel trends in the difference-in-differences model, as shown in Figure 1.

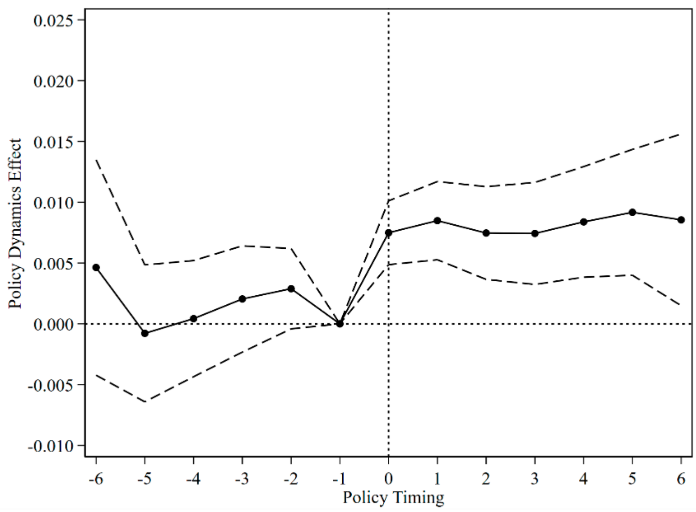

Figure 1. Parallel trend test. Note: Dots in the figure represent estimated coefficients and dotted lines represent 95% confidence intervals.

The parallel trend results shown in Figure 1 indicate that the coefficients of the dummy variables for the years preceding the implementation of the UHV project are small and insignificant. In contrast, coefficients for the years following the project's implementation show a significant increase, with more statistically significant test results. This suggests that the changes in firms' total factor energy efficiency are attributable to the implementation of the UHV project rather than inherent trend variations between the experimental and control groups. These results confirm that the difference-in-differences model used in this paper satisfies the parallel trend assumption.

5.3. Robustness Test

5.3.1. Replace Variables and Adjust Samples

To assess the robustness of the estimated results, this study first performed robustness tests by substituting variables and adjusting samples, as shown in column (1) of Table 3. The dependent variable was calculated using an enhanced two-step stochastic frontier model. Additionally, this paper calculates firms' total factor energy efficiency using the traditional stochastic frontier model, with efficiency from this model used as an alternative variable (*EE_t*) for robustness testing. The results of the robustness test with the replacement variable show that cross-regional electric power scheduling continues to significantly enhance firms' total factor energy efficiency.

Table 3. Robustness test.

Variables	(1)	(2)	(3)	(4)
	Replace Variable	**5% Cut-Off Treatment**	**PSM-DID**	**Standard Error Clustering by City**
	EE_t	***EE***	***EE***	***EE***
did	0.0018 **	0.0017 **	0.0045 ***	0.0045 **
	(0.0008)	(0.0007)	(0.0015)	(0.0022)
Size	−0.0030 ***	0.0008	−0.0045 ***	−0.0046 ***
	(0.0008)	(0.0005)	(0.0014)	(0.0012)
Age	0.0027 ***	0.0022 **	0.0055 **	0.0060 ***
	(0.0010)	(0.0009)	(0.0025)	(0.0020)
Dar	0.0227 ***	0.0095 ***	0.0245 ***	0.0233 ***
	(0.0037)	(0.0021)	(0.0046)	(0.0032)
Sat	0.0022	−0.0009	−0.0030	−0.0026
	(0.0021)	(0.0016)	(0.0030)	(0.0039)
Ass	0.0132 *	0.0113 **	0.0310 ***	0.0143 ***
	(0.0070)	(0.0053)	(0.0083)	(0.0049)
HHI	0.0030	0.0124 ***	0.1004 ***	0.1002 ***
	(0.0033)	(0.0037)	(0.0224)	(0.0305)
Cas	−0.0002	−0.0004 ***	−0.0009 *	−0.0003 **
	(0.0001)	(0.0001)	(0.0005)	(0.0001)
Roa	−0.0020	−0.0024	−0.0073 *	−0.0045
	(0.0042)	(0.0034)	(0.0041)	(0.0037)
Constant	0.3552 ***	0.2340 ***	0.3256 ***	0.3273 ***
	(0.0159)	(0.0108)	(0.0276)	(0.0224)
Enterprise FE	YES	YES	YES	YES
Time FE	YES	YES	YES	YES
Observation	26025	26025	25989	26025
Adjusted R^2	0.140	0.441	0.396	0.393

Note: Robust standard errors at the firm level are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The test results are unaffected by the measurement method of the dependent variable, further confirming the robustness of the baseline regression results. To account for the impact of outliers and anomalies, this study also performed a 5% sample trimming and retested the results. The results in column (2) of Table 3 show that, after removing potential outliers and anomalies, cross-regional electric power scheduling continues to significantly promote firms' total factor energy efficiency.

5.3.2. PSM-DID Model and Replacement of Standard Error Clustering

This article uses the propensity score matching (PSM) method to classify regions established at specific time points during the sample period as the treatment group. By using a 1:1 nearest neighbor matching approach, the PSM-DID model is employed to mitigate endogeneity bias caused by reverse causality and selection bias in the sample. The estimated results of the PSM-DID model are presented in columns (3) and (4) of Table 3. After re-matching the policy variable, the coefficient results for *did* remain significant at the 1% level.

5.3.3. Placebo Test

To address the impact of unobservable omitted variables and specific characteristic factors on the baseline regression results, this study follows the approach of Liu and Lu [36] and Wang et al. [37] by randomly selecting a sample equal in size to the original treatment group from the full sample. A random implementation time for UHV projects is generated, creating a new treatment group with both city and policy timing randomized. This process is repeated 500 times, producing 500 regression results and corresponding *p*-values. The kernel density distributions of the experimental regression coefficients and *p*-values are illustrated in Figure 2.

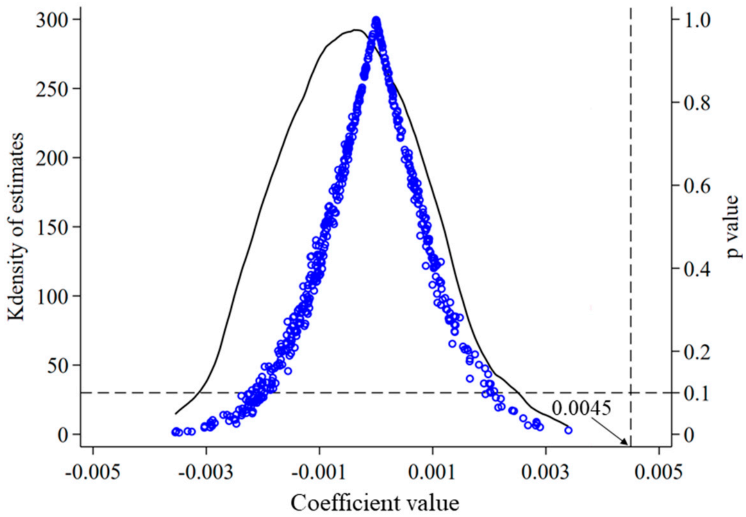

Figure 2. Placebo test.

The estimated results indicate that, after random processing, the regression coefficients are centered around zero and follow a normal distribution. Most of the *p*-values for the regression results are not significant. This suggests that double randomization has significantly reduced both the significance and strength of the policy effects. This finding helps rule out the possibility that unobservable latent factors influenced the baseline estimation results.

5.4. Heterogeneity Analysis

5.4.1. Industry Heterogeneity

To account for the impact of industry heterogeneity on the regression results, Table 4 presents the results for different industries. Columns (1) and (2) of Table 4 show the regression results for energy-intensive versus non-energy-intensive industries. For energy-intensive industries, the policy variable (*did*) is not significant at the 10% level. This lack of significance may be due to these industries having already achieved a high level of energy efficiency, so the policy has minimal impact on their total factor energy efficiency. In contrast, non-energy-intensive industries show significance at the 1% level, indicating a positive response to the UHV policy and highlighting the policy's role in improving their energy efficiency. This may be because these industries have more potential for improving energy utilization or rely more on policy guidance to optimize energy use.

Additionally, columns (3) and (4) of Table 4 present the regression results for manufacturing versus non-manufacturing industries. For manufacturing industries, the policy variable (*did*) is significant at the 5% level, indicating a clear response to policy changes regarding energy efficiency. Given its importance in China's economy, improvements in energy efficiency within the manufacturing sector significantly impact overall economic energy sustainability. In contrast, non-manufacturing industries do not show significance at the 10% level, as improvements in their energy efficiency depend more on factors like technological innovation or management optimization.

Table 4. Industry heterogeneity analysis.

Variables	(1)	(2)	(3)	(4)
	Energy Intensive	Non-Energy Intensive	Manufacturing Industry	Non-Manufacturing Industry
	EE_m	EE_m	EE_m	EE_m
did	0.0031 (0.0029)	0.0049 *** (0.0016)	0.0094 ** (0.0046)	0.0007 (0.0009)
Size	−0.0044 (0.0030)	−0.0041 *** (0.0015)	−0.0013 (0.0031)	−0.0016 * (0.0009)
Age	−0.0019 (0.0043)	0.0047 * (0.0025)	0.0121 (0.0098)	0.0050 *** (0.0013)
Dar	0.0301 *** (0.0064)	0.0249 *** (0.0057)	0.0285 *** (0.0064)	0.0117 *** (0.0039)
Sat	0.0201 *** (0.0076)	−0.0028 (0.0031)	−0.0049 (0.0077)	0.0003 (0.0023)
Ass	−0.0640 (0.0496)	0.0169 ** (0.0066)	0.0017 (0.0292)	0.0131 * (0.0075)
HHI	0.0017 (0.0113)	0.1038 *** (0.0248)	0.1372 *** (0.0470)	0.0116 (0.0095)
Cas	−0.0013 ** (0.0006)	−0.0002 (0.0002)	−0.0038 * (0.0023)	−0.0002 (0.0001)
Roa	0.0984 (0.0602)	−0.0071 * (0.0042)	0.0052 (0.0304)	−0.0029 (0.0030)
Constant	0.3531 *** (0.0652)	0.3166 *** (0.0290)	0.2521 *** (0.0691)	0.2756 *** (0.0191)
Enterprise FE	YES	YES	YES	YES
Time FE	YES	YES	YES	YES
Observation	1861	24155	5546	20443
Adjusted R^2	0.498	0.423	0.602	0.371

Note: Robust standard errors at the firm level are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

5.4.2. Temporal Heterogeneity

In UHV engineering projects, short-term effects may differ significantly from long-term effects. Initially, due to adjustment periods and adaptation processes, the effectiveness of policies may not be immediately apparent or may deviate from expectations. Over time, as firms adjust their strategies and technology advances, the positive impacts of the policy may become more evident. Temporal heterogeneity analysis allows for a more accurate assessment of the policy effects at different stages, providing data support for policy adjustments and future planning. The results are presented in Table 5.

Specifically, setting the time boundary to before 2015 shows that the policy variable has an insignificant impact. This changed notably in 2016, with the policy variable becoming consistently significant from that year onward. These results suggest that the policy's impact may not be immediately apparent in its initial stages. This delay may be due to factors such as the time needed for firms to adapt to the policy or for the policy to impact economic and energy markets. From 2016 onwards, a significant shift occurred. The sustained significance of the policy variable suggests that firms and markets have gradually begun to respond to the policy, with its effects becoming evident.

Table 5. Temporal heterogeneity analysis.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Year < 2013	**Year < 2014**	**Year < 2015**	**Year < 2016**	**Year < 2017**	**Year < 2018**
	EE_m	EE_m	EE_m	EE_m	EE_m	EE_m
did	0.0022	0.0027	0.0037	0.0052 **	0.0040 **	0.0043 **
	(0.0033)	(0.0027)	(0.0025)	(0.0024)	(0.0020)	(0.0017)
Size	−0.0113 ***	−0.0084 **	−0.0063 **	−0.0050 **	−0.0039 *	−0.0038 **
	(0.0035)	(0.0033)	(0.0032)	(0.0026)	(0.0022)	(0.0019)
Age	0.0019	0.0018	0.0039	0.0048	0.0041	0.0057
	(0.0065)	(0.0059)	(0.0053)	(0.0046)	(0.0041)	(0.0037)
Dar	0.0364 ***	0.0339 ***	0.0321 ***	0.0297 ***	0.0278 ***	0.0253 ***
	(0.0111)	(0.0079)	(0.0070)	(0.0062)	(0.0050)	(0.0043)
Sat	−0.0031	−0.0001	0.0031	0.0020	−0.0016	−0.0037
	(0.0080)	(0.0070)	(0.0070)	(0.0059)	(0.0053)	(0.0051)
Ass	0.0827	0.0302 **	0.0199	0.0142	0.0136 **	0.0119 **
	(0.0518)	(0.0146)	(0.0147)	(0.0144)	(0.0056)	(0.0057)
HHI	0.1245 ***	0.1249 ***	0.1213 ***	0.1179 ***	0.1147 ***	0.1124 ***
	(0.0316)	(0.0309)	(0.0304)	(0.0301)	(0.0291)	(0.0276)
Cas	−0.0007	−0.0006	−0.0006	−0.0004	−0.0002	−0.0002
	(0.0007)	(0.0006)	(0.0005)	(0.0003)	(0.0003)	(0.0002)
Roa	−0.0881	−0.0143	−0.0122	−0.0082	−0.0067	−0.0061
	(0.0623)	(0.0130)	(0.0140)	(0.0138)	(0.0042)	(0.0044)
Constant	0.4765 ***	0.4131 ***	0.3623 ***	0.3342 ***	0.3144 ***	0.3115 ***
	(0.0738)	(0.0700)	(0.0652)	(0.0528)	(0.0444)	(0.0385)
Enterprise FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Observation	6628	8371	10108	11755	13592	15664
Adjusted R^2	0.557	0.495	0.466	0.454	0.448	0.441

Note: Robust standard errors at the firm level are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

6. Mechanism Analysis

6.1. Full-Sample Mediation Effect Test

Following the mechanism analysis in the previous section, this paper selects the index of advanced industrial structure [38], the level of urban innovation and development [39], and the share of clean energy as key variables for further analysis. These three variables are referred to as *IS* (industrial restructuring), *UID* (urban innovation and development), and *CET* (clean energy transition).

According to the regression results in Table 6, the policy variable coefficients in columns (1), (3), and (5) are significantly positive at the 1% level. The significance of these coefficients remains unchanged after including all control variables. This finding indicates that the policy impact has intermediary effects on industrial structure adjustment, urban innovation and development, and clean energy transition, thereby validating Hypotheses 2, 3, and 4.

Table 6. Mediation effect test results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	IS	***IS***	***UID***	***UID***	***CET***	***CET***
did	0.0037 *** (0.0010)	0.0037 *** (0.0010)	0.1482 *** (0.0117)	0.1448 *** (0.0117)	0.0120 *** (0.0017)	0.0118 *** (0.0016)
Size		−0.0006 (0.0005)		0.0042 (0.0072)		−0.0006 (0.0010)
Age		−0.0008 (0.0013)		0.0670 *** (0.0158)		0.0044 ** (0.0020)
Dar		0.0040 ** (0.0018)		−0.0027 (0.0198)		0.0060 ** (0.0030)
Sat		−0.0011 (0.0019)		0.0394 (0.0316)		0.0014 (0.0030)
Ass		0.0021 (0.0022)		−0.0006 (0.0311)		0.0004 (0.0048)
HHI		0.0112 *** (0.0038)		0.0418 (0.0438)		0.0170 *** (0.0062)
Cas		0.0003 *** (0.0001)		0.0025 *** (0.0009)		0.0002 (0.0002)
Roa		0.0002 (0.0015)		0.0039 (0.0270)		0.0034 (0.0037)
Constant	2.4463 *** (0.0006)	2.4584 *** (0.0119)	3.7756 *** (0.0071)	3.5150 *** (0.1578)	0.2102 *** (0.0011)	0.2077 *** (0.0205)
Enterprise FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Observation	25998	25907	23429	23343	22034	21960
Adjusted R^2	0.984	0.984	0.992	0.992	0.977	0.977

Note: Robust standard errors at the firm level are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

6.2. Exploratory Analysis: Differences in Electricity Production and Consumption

The results in Table 7 show that the policy variable coefficients in columns (1), (2), and (3) are significantly positive, consistent with the findings from the full sample. This suggests that UHV projects enhance the total factor energy productivity of firms by optimizing the industrial structure in the Middle East, improving urban innovation, and increasing the share of clean energy. In column (4), the regression coefficient is also significantly positive. However, in columns (5) and (6), the regression coefficients indicate that while the project has optimized the industrial structure in the western region, it has suppressed urban innovation and reduced the share of clean energy.

The probable reason for this is as follows: (i) According to the resource curse theory, excessive reliance on a single resource in a region may reduce other innovative activities. After the project was implemented, the expansion of the electricity industry attracted substantial human and capital resources that could have otherwise supported education, scientific research, and innovation. Over time, imbalanced resource allocation may lead to a loss of local talent, hindering urban innovation capabilities in the western region. (ii) The project emphasizes large-scale interregional electricity transmission, which relies heavily on traditional energy sources like coal-fired power. Despite abundant renewable energy resources in the western region, they have not been fully developed due to technological, cost, and infrastructure limitations. Consequently, the UHV project's reliance on traditional energy sources may lead to over-dependence on conventional energies like coal, inhibiting investment in and development of clean energy technologies.

Table 7. Comparative analysis of the production and consumption side of electricity.

Variables	Middle East (Power Consumption Side)			Western Region (Power Production Side)		
	(1)	(2)	(3)	(4)	(5)	(6)
	IS	*UID*	*CET*	*IS*	*UID*	*CET*
did	0.0023 **	0.1834 ***	0.0179 ***	0.0131 ***	−0.0499 **	−0.0083 *
	(0.0011)	(0.0129)	(0.0017)	(0.0025)	(0.0237)	(0.0045)
Size	−0.0007	0.0075	0.0003	0.0002	−0.0016	−0.0030
	(0.0006)	(0.0086)	(0.0011)	(0.0012)	(0.0149)	(0.0024)
Age	−0.0027 **	0.0773 ***	0.0044 **	0.0069	−0.0620	0.0009
	(0.0013)	(0.0171)	(0.0020)	(0.0049)	(0.0384)	(0.0070)
Dar	0.0015	−0.0037	0.0031	0.0061 *	−0.0128	0.0112 ***
	(0.0023)	(0.0298)	(0.0044)	(0.0032)	(0.0237)	(0.0033)
Sat	−0.0028	0.0340	0.0004	0.0068	0.0494	0.0034
	(0.0018)	(0.0350)	(0.0032)	(0.0067)	(0.0647)	(0.0075)
Ass	−0.0033	−0.0312	0.0116	0.0079	0.0043	0.0019
	(0.0069)	(0.0651)	(0.0090)	(0.0064)	(0.0449)	(0.0073)
HHI	0.0105 ***	0.0534	0.0129 **	0.0181	0.0141	0.0190
	(0.0040)	(0.0515)	(0.0061)	(0.0113)	(0.0671)	(0.0166)
Cas	0.0003 **	0.0026 ***	0.0001	0.0003	0.0000	0.0008
	(0.0001)	(0.0010)	(0.0002)	(0.0004)	(0.0043)	(0.0013)
Roa	0.0048	0.0339	−0.0067	−0.0007	−0.0082	0.0033
	(0.0066)	(0.0578)	(0.0066)	(0.0017)	(0.0393)	(0.0032)
Constant	2.4838 ***	3.6703 ***	0.1447 ***	2.3062 ***	2.5928 ***	0.5378 ***
	(0.0130)	(0.1864)	(0.0227)	(0.0302)	(0.3301)	(0.0538)
Enterprise FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Observation	22205	19802	18979	3697	3433	2976
Adjusted R^2	0.987	0.992	0.959	0.881	0.992	0.986

Note: Robust standard errors at the firm level are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

7. Conclusions and Policy Implications

7.1. Conclusions

With China's rising energy demand, the impact of energy policy on corporate operations is becoming increasingly significant. This study examines the impact of UHV projects on total factor energy efficiency within the context of China's economic and energy sector reforms. Using a two-stage stochastic frontier analysis and data from Chinese listed companies across various sectors from 2007 to 2021, we analyze the impact and mechanisms of cross-regional electricity transmission policies on total factor energy efficiency.

Our findings show that cross-regional power dispatch significantly improves total factor energy efficiency. The empirical results indicate that the UHV construction project can lead to an average 0.45% increase in the total factor energy efficiency of regional enterprises overall. This result remains robust even after various methodological refinements, including variable substitution, sample adjustments, the propensity score matching-difference-in-differences model, standard error clustering, and placebo tests. The results of the heterogeneity analysis show that the UHV construction project boosts total factor energy efficiency in non-energy-intensive industries by 0.49% and significantly raises it in the manufacturing industry by 0.94%. However, there is no notable impact on energy-intensive industries or non-manufacturing enterprises. Time-based analysis indicates that the policy's positive effects became evident after 2016. The policy's impact is mediated through industrial restructuring, innovation, and energy transition, although its effects vary by region. In particular, in central and eastern China (consumption hubs), the policy promotes industrial optimization, innovation, and a cleaner energy mix, thereby enhancing total factor energy efficiency. In contrast, in the western region (supply base), the policy appears to dampen local innovation and reduce the adoption of clean energy. This research contributes to the literature on energy policies and their effects on total factor energy efficiency.

7.2. Policy Implications

In the context of global low-carbon development, countries worldwide are increasingly facing the challenge of the geographical mismatch between energy production and consumption. UHV construction can mitigate domestic energy supply and demand issues while fostering international energy cooperation, contributing to the development of a global energy internet and the realization of global energy interconnection. Based on the actual scenario of China's UHV construction, this study provides a practical assessment of the relationship between China's UHV construction and total factor energy efficiency. The findings provide valuable insights for countries worldwide in addressing the spatial mismatch of regional energy resources. Based on these findings, this paper proposes the following policy recommendations:

Firstly, the spatial layout of UHV systems has been optimized, advancing the UHV transmission strategy and enhancing the power transmission capacity of UHV lines. The UHV transmission project has effectively eased regional power and energy supply tensions while improving total factor energy efficiency. However, as of 2021, regional and temporal power supply–demand imbalances still persist in China. Therefore, further optimization of the spatial layout of UHV lines and enhancement of power supply capacity are necessary. Specifically, AC transmission routes with converter stations could be established alongside the UHV project to expand its power supply coverage. Additionally, given the high operational costs of UHV transmission lines, regional governments should coordinate efforts to increase financial input and provide maintenance subsidies for challenging areas, thereby preventing excessively high electricity costs.

Secondly, during the construction of UHV transmission projects, regional governments should promote the projects and develop subsequent industrial plans based on local resources and industrial foundations. The study reveals significant regional heterogeneity in UHV project construction, suggesting that different regions should adopt diversified development strategies. Power-exporting regions with abundant energy resources should actively avoid path dependence resulting from over-reliance on these resources. By leveraging extra-high-voltage transmission and new energy technologies, these regions should upgrade the traditional coal power industry, extend the energy industry chain, and enhance the value-added aspect of key resources and regional industrial competitiveness. For power-importing regions like the southeast coast, the focus should be on high-quality industrial agglomeration and diversified development. These regions should cultivate modern high-end manufacturing clusters and develop supporting service industries such as R&D, management, and marketing, leveraging abundant labor and capital. This approach would enhance productive service inputs and reduce the regional output–energy consumption ratio.

Thirdly, accelerate the development of supporting infrastructure and mechanism planning to ensure that electric power infrastructure plays a leading role in market scale reorganization and energy structure adjustment. The study finds that UHV significantly promotes innovation and optimizes the energy structure. Therefore, we should strategically plan the construction of large-scale integrated energy bases in energy-rich areas, ensuring the coordination of power grid construction and power supply synchronization to achieve seamless integration of power production and grid supply. Additionally, we should actively promote power substitution at load centers and increase the proportion of renewable energy transmitted via extra-high-voltage grids, providing better solutions to multi-energy complementarity issues, such as integrating wind, solar, hydro, and thermal power. Simultaneously, regional governments should intensify R&D investment in UHV transmission technology, develop talent recruitment and training programs for new power systems, and foster deeper integration of industry, academia, and research in the UHV field to enhance transmission efficiency.

Author Contributions: Conceptualization, Y.W.; data curation, Y.W. and J.Z.; formal analysis, Y.W., J.Z., and H.P.; writing—original draft, J.Z.; writing—review and editing, J.Z. and H.P.; supervision, Y.W. funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge financial support from the Key Project of the National Social Science Fund of China [Grant No. 22AJY006] and the Major Project of National Social Science Fund of China [Grant No. 21&ZD133].

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A The Regression Coefficients with All Variables

Table A1. Detailed information on UHV construction in China.

Projects	Input Voltage	Length (km)	Investment (Billions of RMB)	Start Time	Commissioning Time
DC Extra-High-Voltage Project:					
Yunnan–Guangzhou	±800 kV	1438	137	December 2007	June 2009
Xiangjiaba–Shanghai	±800 kV	1907	233	December 2008	July 2010
Jinping–Sunan	±800 kV	2059	220	August 2009	December 2012
Nuozhadu—Guangdong	±800 kV	1413	133	December 2011	June 2015
Hami South–Zhengzhou	±800 kV	2192	234	May 2012	January 2014
Xiluodu–Jinhua	±800 kV	1653	239	July 2012	July 2014
Ningdong–Zhejiang	±800 kV	1720	237	November 2014	September 2016
Jiuquan–Hunan	±800 kV	2383	262	June 2015	June 2017
Jinbei–Nanjing	±800 kV	1119	162	June 2015	June 2017
Ximeng–Taizhou	±800 kV	1641	264	December 2015	October 2017
Shanghaimiao–Shandong	±800 kV	1238	221	December 2015	January 2019
Changji–Guquan	±1100 kV	3324	407	January 2016	January 2019
Northwest Yunnan–Guangdong	±800 kV	1959	222	February 2016	May 2018
Zarut–Qingzhou	±800 kV	1234	221	August 2016	December 2017
Oudong–Guangxi, Guangdong	±800 kV	1452	243	May 2018	December 2020
Qinghai–Henan	±800 kV	1563	226	November 2018	December 2020
Shaanbei–Wuhan	±800 kV	1127	185	February 2020	April 2022
Ya Zhong–Jiangxi	±800 kV	1711	244	September 2019	June 2021
Baihetan–Jiangsu	±800 kV	2080	307	December 2020	July 2022
Baihetan–Zhejiang	±800 kV	2121	299	August 2021	December 2022
AC Extra-High-Voltage Project:					
Jindong–Nanyang–Jingmen	1000 kV	654	57	August 2006	January 2009
Huainan–Anhui–North Zhejiang–Shanghai	1000 kV	649	197	October 2011	September 2013
North Zhejiang–Central Zhejiang–South Zhejiang–Fuzhou	1000 kV	603	200	April 2013	December 2014
Ximeng–Shandong	1000 kV	730	178	November 2014	July 2016
Huainan–Nanjing–Taizhou-Suzhou–Shanghai	1000 kV	780	261	November 2014	December 2016
Mengxi–Jinbei–Beijing West–Tianjin South	1000 kV	608	175	March 2015	November 2016
Yuheng–Jinzhong–Shijiazhuang–Jinan–Weifang	1000 kV	1050	242	May 2015	August 2017
Sutong GIL Integrated Tube Corridor	1000 kV	20	48	August 2016	September 2019
Beijing West–Shijiazhuang	1000 kV	228	35	March 2018	June 2019
Weifang–Linyi–Zaozhuang–Heze–Shijiazhuang	1000 kV	824	146	May 2018	January 2020
Mengxi–Jinzhong	1000 kV	304	50	November 2018	September 2020
Zhangbei–Xiongan	1000 kV	315	60	April 2019	August 2020
Zhumadian–Nanyang	1000 kV	188	22	March 2019	December 2020
Nanchang–Changsha	1000 kV	341	102	February 2021	December 2021
Jingmen–Wuhan	1000 kV	324	65		
Nanyang–Jingmen–Changsha	1000 kV	626	104	June 2021	October 2022

References

1. Jiang, T.; Cao, C.; Lei, L.; Hou, J.; Yu, Y.; Jahanger, A. Temporal and spatial patterns, efficiency losses and impact factors of energy mismatch in China under environmental constraints. *Energy* **2023**, *282*, 128875. [CrossRef]
2. Haupt, W.; Laug, L.; Eckersley, P. Structure, agency and local climate governance: How do individual actors exploit local contexts to shape policymaking in smaller cities and towns? *Reg. Stud.* **2024**, *58*, 1–15. [CrossRef]
3. Hu, J.-L.; Wang, S.-C. Total-factor energy efficiency of regions in China. *Energy Policy* **2006**, *34*, 3206–3217. [CrossRef]
4. Jin, G.; Sun, Y. Too hot for sustainable development: Climate change and energy efficiency. *Clim. Chang. Econ.* **2023**, *14*, 2350014. [CrossRef]
5. Ming, Z.; Lilin, P.; Qiannan, F.; Yingjie, Z. Trans-regional electricity transmission in China: Status, issues and strategies. *Renew. Sustain. Energy Rev.* **2016**, *66*, 572–583. [CrossRef]
6. Filippini, M.; Geissmann, T.; Karplus, V.J.; Zhang, D. The productivity impacts of energy efficiency programs in developing countries: Evidence from iron and steel firms in China. *China Econ. Rev.* **2020**, *59*, 101364. [CrossRef]
7. Sun, C.; Min, J. Dynamic trends and regional differences of economic effects of ultra-high-voltage transmission projects. *Energy Econ.* **2024**, *138*, 107871. [CrossRef]
8. Duscha, V.; Kersting, J.A.N.; Peterson, S.; Schleich, J.; Weitzel, M. Development of low-carbon power technologies and the stability of international climate cooperation. *Clim. Chang. Econ.* **2021**, *12*, 2150013. [CrossRef]
9. Wang, Y.; Yan, W.; Zhuang, S.; Li, J. Does grid-connected clean power promote regional energy efficiency? An empirical analysis based on the upgrading grid infrastructure across China. *J. Clean. Prod.* **2018**, *186*, 736–747. [CrossRef]
10. Sun, H.; Edziah, B.K.; Kporsu, A.K.; Sarkodie, S.A.; Taghizadeh-Hesary, F. Energy efficiency: The role of technological innovation and knowledge spillover. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120659. [CrossRef]
11. Wang, Y.; Xu, C.; Yuan, P. Is there a grid-connected effect of grid infrastructure on renewable energy generation? Evidence from China's upgrading transmission lines. *Energy Environ.* **2021**, *33*, 975–995. [CrossRef]
12. El Bilali, H.; Rokka, S.; Calabrese, G.; Borelli, T.; Grazioli, F.; Tietiambou, S.R.; Nanema, J.; Dan Guimbo, I.; Dambo, L.; Nouhou, B.; et al. Conservation and promotion of neglected and underutilized crop species in west Africa: Policy and governance. *Sustainability* **2024**, *16*, 6194. [CrossRef]
13. He, R.; Wan, P.; Yang, M. The resource curse in energy-rich regions: Evidence from China's ultra-high voltage transmission. *Energy* **2024**, *304*, 132153. [CrossRef]
14. Wang, H.; Zhang, Y.; Lin, W.; Wei, W. Transregional electricity transmission and carbon emissions: Evidence from ultra-high voltage transmission projects in China. *Energy Econ.* **2023**, *123*, 106751. [CrossRef]
15. Yang, H.; Shi, C.; Li, J.; Liu, T.; Li, Y.; Wang, Y.; Yang, Y. Has the inter-regional power transmission promoted economic development? A quantitative assessment in China. *Sustainability* **2022**, *14*, 13402. [CrossRef]
16. Patchell, J.; Tsai, K.S.; Wang, H.; Cheung, B. Competition and coordination: Regional dynamics in the rise of China's new energy vehicle industry. *Sustainability* **2024**, *16*, 1907. [CrossRef]
17. Deng, X.; Lv, T.; Xu, J.; Hou, X.; Liu, F. Assessing the integration effect of inter-regional transmission on variable power generation under renewable energy consumption policy in China. *Energy Policy* **2022**, *170*, 113219. [CrossRef]
18. Tan, X.U.; Lin, S.; Xie, B.-C. The distributional effect of inter-regional transmission grid expansion on China's power industry. *Clim. Chang. Econ.* **2022**, *13*, 2240005. [CrossRef]
19. Zhang, G.; Zhang, N.; Liao, W. How do population and land urbanization affect CO2 emissions under gravity center change? A spatial econometric analysis. *J. Clean. Prod.* **2018**, *202*, 510–523. [CrossRef]
20. Zhang, X.; Wu, L.; Zhang, Z. Does air quality ecological compensation improve total factor energy efficiency?—A quasi-natural experiment from 282 cities in China. *Sustainability* **2024**, *16*, 6067. [CrossRef]
21. Acemoglu, D.; Gancia, G.; Zilibotti, F. Competing engines of growth: Innovation and standardization. *J. Econ. Theory* **2012**, *147*, 570–601.e573. [CrossRef]
22. Gai, Z.; Guo, Y.; Hao, Y. Can internet development help break the resource curse? Evidence from China. *Resour. Policy* **2022**, *75*, 102519. [CrossRef]
23. Li, M.-J.; Tao, W.-Q. Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry. *Appl. Energy* **2017**, *187*, 203–215. [CrossRef]
24. Lv, C.; Shao, C.; Lee, C.-C. Green technology innovation and financial development: Do environmental regulation and innovation output matter? *Energy Econ.* **2021**, *98*, 105237. [CrossRef]
25. Bridge, G.; Bouzarovski, S.; Bradshaw, M.; Eyre, N. Geographies of energy transition: Space, place and the low-carbon economy. *Energy Policy* **2013**, *53*, 331–340. [CrossRef]
26. Pingkuo, L.; Huan, P. What drives the green and low-carbon energy transition in China?: An empirical analysis based on a novel framework. *Energy* **2022**, *239*, 122450. [CrossRef]
27. Nie, Y.; Zhang, G.; Duan, H. An interconnected panorama of future cross-regional power grid: A complex network approach. *Resour. Policy* **2020**, *67*, 101692. [CrossRef]
28. Hailu, A.; Veeman, T.S. Environmentally sensitive productivity analysis of the Canadian pulp and paper industry, 1959-1994: An input distance function approach. *J. Environ. Econ. Manag.* **2000**, *40*, 251–274. [CrossRef]
29. Zhang, N.; Zhou, M. The inequality of city-level energy efficiency for China. *J. Environ. Manag.* **2020**, *255*, 109843. [CrossRef]

30. Zhou, P.; Ang, B.W.; Zhou, D.Q. Measuring economy-wide energy efficiency performance: A parametric frontier approach. *Appl. Energy* **2012**, *90*, 196–200. [CrossRef]
31. Beck, T.; Levine, R.; Levkov, A. Big Bad Banks? The Winners and Losers from Bank Deregulation in the United States. *J. Financ.* **2010**, *65*, 1637–1667. [CrossRef]
32. Jiang, Y.; Guo, Y.; Bashir, M.F.; Shahbaz, M. Do renewable energy, environmental regulations and green innovation matter for China's zero carbon transition: Evidence from green total factor productivity. *J. Environ. Manag.* **2024**, *352*, 120030. [CrossRef] [PubMed]
33. Wang, Y.; Li, M.; Wang, L.; Wang, H.; Zeng, M.; Zeng, B.; Qiu, F.; Sun, C. Can remotely delivered electricity really alleviate smog? An assessment of China's use of ultra-high voltage transmission for air pollution prevention and control. *J. Clean. Prod.* **2020**, *242*, 118430. [CrossRef]
34. Liu, K.; Liu, X.; Long, H.; Wang, D.; Zhang, G. Spatial agglomeration and energy efficiency: Evidence from China's manufacturing enterprises. *J. Clean. Prod.* **2022**, *380*, 135109. [CrossRef]
35. Shen, T.; Chen, H.H.; Zhao, D.H.; Qiao, S. Examining the impact of environment regulatory and resource endowment on technology innovation efficiency: From the microdata of Chinese renewable energy enterprises. *Energy Rep.* **2022**, *8*, 3919–3929. [CrossRef]
36. Liu, Q.; Lu, Y. Firm investment and exporting: Evidence from China's value-added tax reform. *J. Int. Econ.* **2015**, *97*, 392–403. [CrossRef]
37. Wang, Y.; Hou, L.; Hu, L.; Cai, W.; Xiao, D.; Chen, J.; Wang, C. Do areas with a higher proportion of single-person households save more on electricity consumption? Evidence from the difference-in-differences model. *Energy Sustain. Dev.* **2023**, *77*, 101350. [CrossRef]
38. Zhu, X. Have carbon emissions been reduced due to the upgrading of industrial structure? Analysis of the mediating effect based on technological innovation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 54890–54901. [CrossRef]
39. Luo, S.; Yimamu, N.; Li, Y.; Wu, H.; Irfan, M.; Hao, Y. Digitalization and sustainable development: How could digital economy development improve green innovation in China? *Bus. Strategy Environ.* **2023**, *32*, 1847–1871. [CrossRef]