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Can Green Finance Policies Promote the Transformation of Urban Energy Consumption Structure? Causal Inference Based on a Double Machine Learning Model

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Abstract

This study constructs an urban energy consumption structure transformation (UECST) index and utilizes a double machine learning model to investigate the impact and underlying mechanisms of green finance policies on this transformation. Based on panel data from 281 prefecture-level cities in China from 2010 to 2022, we find that green finance policies significantly promote the UECST. This finding holds after a series of robustness checks and endogeneity tests. Furthermore, our analysis reveals that these policies facilitate the transition not only through direct financial support but also indirectly by driving green technological innovation, enhancing green economic efficiency, and promoting industrial upgrading. The positive impact is more substantial in central cities, transportation hubs, non-resource-based cities, non-old industrial bases, and key environmental protection cities. By providing empirical evidence and policy insights, this study contributes to optimizing green finance policy design and addressing specific bottlenecks in energy transition, thereby supporting the achievement of the "Beautiful China" development goal.

Keywords: green finance reform and innovation; quasi-natural experiment; double machine learning; energy consumption structure transition

1. Introduction

Global climate change, as a systemic crisis, stands as an inescapable core challenge for humanity. Thus, the international community has reached a consensus on transitioning energy systems towards green and low-carbon pathways (Lee et al., 2022) [1], even as the Russia–Ukraine conflict intensified global fossil fuel supply–demand tensions and triggered a temporary resurgence in European coal demand, leading to a record-high global coal consumption that year, as reported by the International Energy Agency (IEA). However, nations' commitment to clean energy development remains unwavering. Notably, the United States has enacted the Inflation Reduction Act to accelerate domestic clean energy development, and emerging economies such as India and Brazil have successively rolled out renewable energy development plans. Globally, 67 countries have launched over 1600 financial support measures for clean energy, with investments totaling more than USD 1.215 trillion. In this wave of global collaborative transformation, energy restructuring is not only an inevitable choice for addressing the climate crisis but also a critical pathway to ensure national energy security.

China's energy transition has profound implications for global climate governance. Despite a clear national emphasis on transforming the energy consumption structure,

Check for updates

Academic Editor: Andrew John Chapman

Received: 5 December 2025
Revised: 11 January 2026
Accepted: 26 January 2026
Published: 1 February 2026

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China's long-standing dependence on coal and other high-carbon pathways has sustained a high carbon emission intensity. The resulting high-carbon lock-in effect of the energy system has become a major constraint. Robust policy instruments are urgently needed to enable a fundamental shift from fossil fuel dependence to a clean, low-carbon energy system. In this context, green finance, as an innovative mechanism to connect environmental protection and financial resource allocation, through its market-oriented incentive and risk-pricing functions, has been widely recognized as a critical tool for overcoming transformation financing constraints and redirecting capital and other production factors toward green industries.

Against this background, China's Green Finance Reform and Innovation Pilot Zones (hereinafter referred to as the "Pilot Zones"), launched in successive stages since 2017, have created additional avenues for adjusting urban energy consumption patterns. Accordingly, this study focuses on three key questions: Do the Pilot Zone policies facilitate changes in urban energy consumption patterns? If so, through which channels are such changes realized? In addition, do the promotional effects of the innovative pilot zone policy exhibit heterogeneity? Addressing these issues is of both theoretical and practical importance for China, as it can help accelerate the transformation of energy consumption patterns by enhancing the effectiveness of green finance policies.

To address these issues, this study employs municipal-level panel data and constructs an indicator capturing changes in urban energy consumption patterns, measured by the share of electricity, natural gas, and liquefied petroleum gas in total energy use. Prior to calculation, the consumption of these energy sources is converted into standard coal equivalents using their respective conversion coefficients. Methodologically, a causal-inference-based double machine learning approach is adopted to account for selection bias and nonlinear relationships while mitigating the "curse of dimensionality" associated with high-dimensional control variables (Zhao et al., 2024) [2]. In the mechanism analysis, green technological innovation, green economic efficiency, and industrial structure upgrading are incorporated as three key channels to examine how green finance policies affect changes in urban energy consumption patterns. Finally, heterogeneity in the promotional effects of the Pilot Zone policy on urban energy consumption patterns is analyzed from three perspectives.

Relative to existing studies, this paper offers three main contributions. First, rather than relying on provincial-level data, we employ municipal-level panel data to examine how green finance policies influence changes in urban energy consumption patterns and to explore the associated transmission mechanisms. Using city-level data provides two key advantages. On the one hand, it more closely corresponds to the actual implementation scale of green finance pilot programs, as pilot cities often differ substantially from the provinces to which they belong, making provincial-level data an imperfect representation. On the other hand, it increases the number of observations, thereby improving the accuracy and robustness of the empirical analysis.

Second, we develop an integrated theoretical and empirical framework to analyze how green finance policies facilitate changes in urban energy consumption patterns. Specifically, the direct effects of green finance policies are examined from the perspectives of financial supply-side reform and industrial structure evolution. Building on the established literature on green technological innovation, we further incorporate green economic efficiency and industrial upgrading to systematically assess the transmission mechanisms through which green finance policies affect changes in urban energy consumption patterns. In addition, urban heterogeneity is explored from multiple dimensions, including infrastructure conditions, ecological endowments, and the stringency of environmental regulation.

Third, from a methodological standpoint, this paper adopts the double machine learning (DML) framework for causal inference in the empirical analysis. Relative to conventional difference-in-differences approaches, this method combines nonparametric predictive techniques with the capacity to accommodate high-dimensional information, enabling a more flexible evaluation of how green finance policies affect changes in urban energy consumption patterns. By doing so, the DML framework helps alleviate several limitations inherent in standard DID models, such as biases related to control variable selection, nonlinear relationships, and challenges posed by high-dimensional settings, thereby enhancing the credibility and accuracy of the empirical results.

2. Literature Review

Academic research on pilot zone policies has expanded rapidly in recent years. Existing studies primarily rely on the difference-in-differences (DID) framework to examine the policy impacts from both macro- and micro-level perspectives.

From a macro perspective, scholars have investigated the impact of pilot zone policies on urban environmental outcomes, specifically pollution and carbon emission reduction, and carbon intensity. Evidence suggests these policies have facilitated urban pollution and carbon reduction, particularly in resource-based cities and northwestern China, while also enhancing energy utilization efficiency. This has been associated with a substantial decline in carbon emission intensity at the prefecture level (Ma et al., 2021) [3]. Mechanism studies consistently identify green technological innovation and reduced energy intensity as pivotal mediating factors in achieving these environmental objectives (Chen et al., 2025; Zhang et al., 2023) [4,5].

From a micro perspective, research explores how pilot zone policies influence corporate green innovation and green transformation. These policies tend to advance green innovation among local enterprises without necessarily exerting their influence on heavily polluting enterprises compared to cleaner ones (Ge et al., 2023; Liu and Xiong, 2022; Liu and Wang, 2023) [6–8]. Furthermore, pilot zone policies primarily drive corporate green transformation by alleviating financing constraints (Li et al., 2024; Shi et al., 2022; Zhang et al., 2023) [9–11].

Nevertheless, studies that directly explore the relationship between green finance policies and shifts in energy consumption structures remain relatively limited. Green finance policies involve multiple policy instruments, such as policy-based incentives, green bonds, and green credit. Caragnano et al. (2020) [12] emphasize the role of green credit as a key mechanism for improving energy structures in their assessment of pilot zone policy outcomes.

While prior research offers valuable insights, much of this work tends to emphasize "outcome-oriented" indicators like carbon emissions and pollution control. A direct and systematic examination of energy consumption structure transformation often appears less prominent. Furthermore, many existing studies primarily utilize provincial-level data, perhaps reflecting challenges in obtaining granular micro-level data pertaining to urban energy consumption structure transformation. This may contribute to a relative scarcity of research analyzing the impact of pilot zone policies on energy transformation at the prefecture level (Chen et al., 2025) [4].

Chen et al. (2025) [4], drawing on the work of Shen et al. (2023) [13], constructed a municipal-level low-carbon energy transition index. Their work then employed a multi-period DID model to analyze the impact of pilot zone policies on prefecture-level low-carbon energy transition. However, while composite index systems can offer a multi-dimensional characterization of urban energy consumption structure transformation, they may also present challenges such as indicator redundancy and subjective biases in indi-

cator selection. These factors can potentially complicate the accurate measurement of the transformation degree. Furthermore, traditional DID methods might encounter difficulties in adequately addressing selection bias and nonlinear relationships, which could, in turn, affect the precision of causal inference. The inclusion of high-dimensional control variables can also introduce a 'curse of dimensionality' problem.

3. Policy Background and Research Hypotheses

3.1. Policy Background

The pilot zones established in China represent a key institutional advance aligning with the national ecological civilization strategy and the Beautiful China initiative. The pilot zones pursue regional experiments to address financing bottlenecks in green transformation and to identify replicable market-oriented mechanisms. Their development unfolds in distinct phases with notable policy implications. The initial batch, launched in June 2017, encompasses eight cities across Zhejiang and Jiangxi, prioritizing foundational institutional arrangements such as green credit and environmental rights trading. In 2019 and 2022, Lanzhou, Chongqing, and Xining were added, shifting the focus to frontier topics like climate finance and transition finance and emphasizing regional coordination within economic belts, including the Yangtze River Economic Belt and the Yellow River Basin. By 2025, the zones are expected to span major economic belts and ecological functional zones nationwide, with policy instruments expanding from credit support to a diversified suite of tools, including green bonds, green funds, green insurance, and carbon finance (Shao and Huang, 2023) [14].

The pilot zone policy pursues two primary objectives. First, it aims at environmental improvement by constraining high-carbon activities through financial levers, for example, by tightening financing for heavily polluting firms to reduce emissions (Chai et al., 2022) [15], promoting the adoption of clean technologies, and strengthening coal-chain resilience via environmental regulations and incentives. Second, it seeks economic transformation by redirecting resources from traditional high-carbon sectors to greener industries, thereby reshaping regional growth drivers.

As regards specific policy instruments, pilot zones have established a multidimensional framework encompassing mandatory, incentive-oriented, and market-oriented tools. Specifically, mandatory tools include environmental information disclosure requirements and green credit standards (Su et al., 2022) [16], which raise financing costs for high-carbon projects; the incentive-oriented tools comprise green bond subsidies and risk compensation funds, which mitigate investment risks in green technologies; the market-oriented tools include carbon emission trading and energy consumption right trading (Guo et al., 2025) [17].

However, policy implementation still faces challenges. First, resource-based cities are hindered in their transformation due to the "resource curse," leading to a "dual-objective conflict" between environmental goals and growth targets (Zhou et al., 2024) [18]. Second, the micro-level transmission of policies is impeded. It shows that policy incentives for heavily polluting enterprises to pursue green transformation are insufficient, thereby exacerbating their financing difficulties (Lin and Pan, 2023) [19]. Third, policy coordination mechanisms are inadequate, as green finance policies in some cities fail to synergize with the carbon market, digital economy, and other relevant policies (Wang et al., 2025) [20]. Such challenges highlight the urgency and practical value of studying the effects of pilot zone policies on the transformation of the energy consumption structure (Shi and Yang, 2024) [21].

3.2. Research Hypotheses

3.2.1. Direct Effect

The pilot zones reshape the intrinsic operational logic of urban energy consumption structures through institutionalized financial supply-side reforms. Their core driving force lies in constructing targeted support mechanisms for low-carbon industries via green capital. On one hand, pilot zone policies have established targeted green credit allocation mechanisms, priority issuance channels for green bonds, and environmental rights' collateral financing tools, which significantly reduce financing costs for clean-energy projects (Zhang, 2023) [9]. According to the financial market risk pricing theory, the policy's specialized discount compensation mechanism for environmental risks makes financial institutions more inclined to allocate capital to sectors such as photovoltaics and wind power, creating a structural tilt in capital supply. On the other hand, the policy compels high-carbon industries to undergo technological upgrading or capacity withdrawal through industrial access lists and credit negative lists. This expansion of demand for low-carbon industries and contraction of demand for high-carbon industries fundamentally alter the supply–demand pattern of urban energy consumption.

Furthermore, the environmental risk pricing mechanisms implemented in pilot zones—such as green credit performance assessments and higher risk weights assigned to brown assets—compel urban commercial banks to adjust capital allocation. As a result, credit provision to conventional energy infrastructure, including coal and thermal power, is curtailed, while financial support for renewable energy projects, notably solar and wind power, is expanded (Zhou and Li, 2022) [22]. In practice, green credit channels preferential financing toward the service sector and high-tech manufacturing, whereas energy-intensive industries face mounting financing costs that force either market exit or technological upgrading (Sun and Chen, 2022) [23], thereby reducing energy intensity at the macro level. Evidence from the Yangtze River Economic Belt indicates that this mechanism raises the proportion of the tertiary sector in pilot cities and weakens urban economic reliance on fossil fuels. In addition, green consumer finance products stimulate low-carbon demand (Hu et al., 2023) [24], extending the energy transition from the production side to household consumption and fostering a more integrated transformation pathway. Accordingly, this study proposes Hypothesis H1:

H1. *Pilot zone policies directly promote the transformation of urban energy consumption structures.*

3.2.2. Indirect Effect

The green finance reform and innovation pilot zone policies drive urban energy transition through three synergistic transmission pathways: fostering green technological innovation, enhancing green economic efficiency, and accelerating industrial structure upgrading. These mechanisms do not operate in isolation but form a dynamic feedback loop that reshapes the urban energy landscape.

As regards the mechanism of green technological innovation, a pilot zone stimulates green technological innovation by facilitating the conversion of technology into collateralizable capital and leveraging its positive externalities. Innovation in clean technology is characterized by high risks, long cycles, and significant positive externalities, often leading to market failure and underinvestment. Pilot zone policies address this by transforming R&D sunk costs into tradable financial assets through instruments like green patent pledge financing, thereby incentivizing enterprises to invest in frontier clean technologies (Huo et al., 2022) [25]. Furthermore, the establishment of green industry funds expands public investment, effectively sharing the risk of R&D (Liu and Wang, 2023) [8]. Beyond direct funding, the policy fosters an "industry-academia-research-finance" ecosystem, accelerat-

ing the commercialization of breakthroughs in areas such as photovoltaic efficiency and hydrogen storage (Xu et al., 2022) [26]. Mandatory disclosure requirements for carbon reduction roadmaps further facilitate knowledge spillovers, accelerating the diffusion of generic green technologies across industrial clusters (Lin and Zhang, 2013; Wurlod and Noailly, 2018) [27,28].

As regards the mechanism of green economic efficiency, a pilot zone improves green economic efficiency through optimizing resource allocation. According to the theory of allocative efficiency, green finance policies act as a filter, channeling factors of production toward high-productivity sectors. The policy forces the market exit or transformation of high-energy-consuming enterprises. This process releases productive factors such as land and labor, facilitating their reallocation toward high-value-added green industries. (Huang et al., 2025) [29]. Consequently, this optimization of capital stock significantly elevates the green total factor energy efficiency of pilot cities (Liu et al., 2024) [30]. Additionally, the policy promotes industrial agglomeration and the development of circular economy parks, where industrial symbiosis enables cascading energy utilization (Wang et al., 2021) [31]. The integration of digital technology further empowers real-time optimization of energy dispatching, reducing transmission losses and redundant consumption.

Considering the mechanism of industrial structure upgrading, the policy drives industrial structure upgrading, aligning with the Environmental Kuznets Curve (EKC) and the Porter Hypothesis. By restricting capital flows to traditional high-carbon sectors and offering preferential support to low-carbon industries, the policy steers the urban economy turn to innovation-driven. This financial guidance propels the industrial structure toward technology- and knowledge-intensive sectors (Chen and Xie, 2025) [32]. Consistent with the Porter Hypothesis, appropriate environmental regulation via green finance not only expands the tertiary sector and servitization of manufacturing but also stimulates technological progress. This structural shift reshapes energy consumption preferences, reducing the economy's reliance on fossil fuels through demand-side structural changes.

In summary, technological innovation lowers the adoption threshold for clean energy; allocative efficiency enhances the competitiveness of the green economy; and industrial upgrading reshapes energy demand. Based on the above analysis, this paper proposes Hypothesis H2:

H2. *Green finance reform and innovation pilot zone policies promote the transformation of urban energy consumption structures through channels including green technological innovation, green economic efficiency, and industrial upgrading.*

3.2.3. Heterogeneous Mechanisms

The effectiveness of pilot zone policies in the transition of the urban energy consumption structure depends on cities' own characteristics: geographic and economic foundations, natural ecological endowments, and environmental institutions.

Cities endowed with robust geographic and economic foundations exhibit a more accelerated energy transition. Favorable geographic conditions foster efficient transportation, logistics, and talent mobility, creating a flexible labor market attractive to specialized technical professionals. Crucially, advanced infrastructure, such as integrated power grids and pipelines, facilitates the cost-effective delivery of clean energy. Economically strong cities also possess greater fiscal capacity, enabling effective capital mobilization. Developed financial infrastructure attracts green capital, directing more funds towards green industries and technologies (Yuan and Zhang, 2019) [33]. Abundant local fiscal resources further support the issuance of green special bonds, leveraging private capital for municipal energy transition projects. Conversely, smaller cities often depend on regional collaboration and policy spillover effects to secure necessary technological advancements.

Resource-based cities confront significant transition hurdles, including potential unemployment and diminished fiscal revenue, as fossil fuel industries frequently constitute over one-third of their total revenue. This creates strong path dependence and resistance to structural adjustment. In contrast, non-resource-based cities, with their more diversified industrial structures, can adjust their energy systems with greater agility (Wang et al., 2023) [34]. A particular challenge for old industrial bases stems from the substantial sunk costs embedded in their existing high-carbon equipment.

The pre-existing strength of environmental institutions influences the marginal impact of pilot zone policies. In cities with high regulatory intensity, enterprises have typically already invested in carbon reduction technologies and data management capabilities. Here, green finance policies can integrate seamlessly, generating an institutional synergy multiplier effect that reinforces corporate compliance through both "financial pricing" and "regulatory penalties." Conversely, in environments with low regulatory intensity, the absence of comprehensive environmental information and weak enforcement capacity leads to information asymmetry, hindering financial institutions' ability to accurately assess green credit risks. This often results in perfunctory policy implementation and allows enterprises to evade green financing requirements. Furthermore, coal-dependent regions may experience a green paradox, where local governments tacitly support high-carbon projects to maintain economic growth, despite long-term environmental goals. Based on the foregoing analyses, this paper proposes Hypothesis H3:

H3. *Policies implemented under the green finance reform pilot zone framework generate stronger positive impacts on the upgrading of energy consumption structures in central cities, transportation hubs, non-resource-dependent cities, cities outside old industrial bases, and key environmental protection cities.*

4. Research Design

4.1. Model Selection and Construction

This study uses a double machine learning (DML) framework to examine how pilot zones influence the transformation of urban energy consumption structures. Existing studies indicate that green finance is positively associated with firms' total factor productivity (Zou and Wang, 2024) [35] and exhibits nonlinear characteristics, including a U-shaped relationship, while an inverted U-shaped effect has been identified for green technology transfer (Fang et al., 2023) [36]. These findings imply that the policy effects of pilot zones may not conform to a purely linear trajectory, underscoring the need for a more flexible analytical approach.

Traditional linear econometric models face notable limitations in this setting. On the one hand, multicollinearity and omitted variable bias may lead to endogeneity problems and unreliable parameter estimates. On the other hand, accurately capturing the complex transmission mechanisms of green finance policies requires a high-dimensional set of control variables, which often results in the "curse of dimensionality" and reduced estimation efficiency.

The double machine learning approach addresses these challenges by combining machine learning techniques with a partially linear causal inference framework. Specifically, DML first applies machine learning algorithms to flexibly model the potentially nonlinear relationships between covariates and both the outcome variable and the policy variable. It then removes the influence of high-dimensional controls through orthogonalization, allowing the policy effect to be consistently estimated in the second stage. This design enables robust inference while mitigating bias arising from nonlinearity, multicollinearity,

and overfitting. Accordingly, this study constructs the following partially linear double machine learning model:

$$DECS_{it} = \theta_0 Policy_{it} + g(X_{it}) + U_{it}, E(U_{it}|Policy_{it}, X_{it}) = 0 \quad (1)$$

Here, i denotes city and t denotes year; $DECS_{it}$ is the dependent variable, specifically representing the urban energy consumption structure transformation index of city i in year t; $Policy_{it}$ is the core explanatory variable, denoted as a proxy variable for the pilot zone policy implemented in city i during year t. The core focus of this study is to estimate the coefficient θ_0, which quantifies the strength of the causal effect of the policy variable $Policy_{it}$ on $DECS_{it}$. In the model specification, the error term U_{it} satisfies the zero conditional mean assumption. The control variable set X_{it} includes the original variables and their potential high-dimensional combinations. The specific form of $g(X_{it})$ is estimated nonparametrically using machine learning algorithms. Based on Equation (1), the coefficient estimator is obtained as follows:

$$\hat{\theta}_0 = \left(\frac{1}{n}\sum_{i\in I, i\in T} Policy_{it}^2\right)^{-1} \frac{1}{n}\sum_{i\in I, i\in T} Policy_{it}(DECS_{it} - \hat{g}(X_{it})) \quad (2)$$

To ensure that the coefficient estimator remains free from bias in small samples, an auxiliary regression is specified as follows:

$$Policy_{it} = m(X_{it}) + V_{it}, E(V_{it} \mid X_{it}) = 0 \quad (3)$$

Here, $m(X_{it})$ refers to the regression relationship between the core explanatory variable and the high-dimensional set of control variables, and its functional form is approximated using machine learning algorithms. V_{it} denotes the disturbance term, which has a zero conditional expectation. The estimation proceeds as follows: first, Equation (3) is estimated to recover the residual $V_{it} = Policy_{it} - m(X_{it})$; subsequently, V_{it} is employed as an instrument for $Policy_{it}$ to yield unbiased coefficient estimates:

$$\hat{\theta}_0 = \left(\frac{1}{n}\sum_{i\in I, t\in T} \hat{V}_{it} Policy_{it}\right)^{-1} \frac{1}{n}\sum_{i\in I, t\in T} \hat{V}_{it}(DECS_{it} - \hat{g}(X_{it})) \quad (4)$$

4.2. Variable Selection and Data Sources

4.2.1. Dependent Variable

The transformation of the urban energy consumption structure (UECST) is commonly measured using three approaches. The first constructs a dual substitution index, either by calculating the geometric mean of the "oil–gas substituting coal" index and the "non-fossil energy substituting fossil fuels" index (Li et al., 2020) [37], or by adopting a top–down estimation method (Shan et al., 2018) [38]. The second approach uses the share of clean energy in total energy consumption as a proxy (Wang et al., 2018; Mao et al., 2024) [39,40]. The third approach builds a comprehensive indicator system to reflect changes in the energy consumption structure.

Following the third approach, this study focuses on electricity, natural gas, and liquefied petroleum gas (LPG) as key energy carriers in the transformation process. Although electricity generation in China is still dominated by thermal power, electricity itself is an end-use energy form with relatively high efficiency and lower direct emissions at the consumption stage. More importantly, the increasing penetration of renewable energy into the power generation mix implies that a higher share of electricity consumption reflects a transition toward cleaner and more efficient energy use on the demand side. Therefore,

expanding the share of electricity, natural gas, and LPG in total energy use represents a central pathway for advancing the low-carbon transition of urban energy systems.

Accordingly, UECST is proxied by the share of electricity, natural gas, and LPG consumption (all converted into standard coal equivalents using their respective conversion coefficients) in aggregate energy use. Electricity use, natural gas use, and LPG consumption are captured by total social electricity consumption, city-level natural gas consumption, and total LPG supply volume, respectively.

Due to the lack of direct city-level energy consumption data, this study follows the work of Shi and Li (2020) [41] and decomposes provincial total energy consumption to the city level using night-time light data as a weighting indicator. The rationale is that higher night-time light intensity is generally associated with greater economic activity and, correspondingly, higher energy consumption. This approach has been applied in related studies and provides a reasonable approximation of city-level energy use.

4.2.2. Core Explanatory Variable

The policy variable ($Policy_{it}$), constructed based on green finance reform and innovation pilot zones, functions as the core explanatory variable in this study. It specifically represents the product of the city dummy variable ($Treat_i$) and the time dummy variable ($Post_{it}$). For the city dummy variable ($Treat_i$), the eight cities that simultaneously implemented the green finance reform and innovation pilot zone policy are designated as the experimental group, where $Treat_i = 1$ and the remaining 273 cities form the control group, where $Treat_i = 0$. For the time dummy variable ($Post_{it}$), a value of 1 is assigned to the sample in the first year when the pilot zone policy is implemented and in all subsequent years; otherwise, the value is 0.

The policy indicator ($Policy_{it}$), derived from the green finance reform and innovation pilot zones, serves as the key explanatory variable in this study. It is defined as the interaction between a city-level dummy ($Treat_i$) and a time dummy ($Post_{it}$). With respect to the city dummy, the eight cities that jointly implemented the green finance reform and innovation pilot policy are classified as the treatment group ($Treat_i = 1$), while the remaining 273 cities constitute the control group ($Treat_i = 0.$). Regarding the time dummy, ($Post_{it}$) takes a value of 1 for the initial year of policy implementation and all subsequent years, and 0 otherwise.

4.2.3. Mechanism Variable

The low-carbon green technology innovation index (GTI) functions as a direct impetus for changes in the structure of urban energy consumption. By means of financial support and risk-sharing arrangements, green finance policies reduce firms' R&D expenditures, thereby promoting progress in clean technologies, including renewable energy systems and energy-efficiency-enhancing processes. The volume of green patent applications constitutes an observable measure reflecting both the scale and the quality of technological innovation. More specifically, it captures not only the intensity of green research and development activities but also the prospects for technological commercialization. Accordingly, this paper measures the level of green technological innovation at the city level using the natural logarithm of the annual number of green patent applications.

Green economic efficiency (GEE) enables systematic identification of the dynamic impact pathways through which green finance policies shape the evolution of the energy consumption structure, viewed from two complementary perspectives: resource allocation efficiency and total factor productivity improvement, under environmental constraints. This study adopts the methodological framework proposed by Guo et al. (2019) [42] and Jiao et al. (2023) [43], employing the Global Malmquist–Luenberger (GML) index

to measure urban green economic efficiency. Input indicators primarily include labor input, capital input, and energy input; output indicators encompass both desired outputs (economic outputs) and undesired outputs (pollutant emissions).

Industrial structure upgrading (ISU) functions as a core indicator of the economic transformation and upgrading process. Thus, this study employs the ratio of tertiary industry value-added to secondary industry value-added as a measurement metric, which reflects the key characteristics of the economic structure's transition from industrialization to post-industrialization. A continuous rise in this ratio indicates that the service economy is gradually emerging as the dominant driver of development, which, in turn, reflects a shift in industrial focus from material production to knowledge-intensive services and high-end manufacturing.

To improve the precision of estimating policy impacts, this study additionally accounts for a set of variables that could affect the evolution of the energy consumption structure. The control variables include the following: (1) energy consumption efficiency (ECE), measured as the ratio of total energy consumption to local real GDP; (2) economic development level (ED), measured as the natural logarithm of regional per capita GDP; (3) financial development (FD), defined as the ratio of the year-end balance of deposits and loans of local financial institutions to regional GDP; (4) human capital level (HC), measured as the ratio of full-time students enrolled in regular institutions of higher education to the year-end total population; and (5) urbanization level (LU), captured by the proportion of urban permanent residents in the total permanent population (commonly referred to as the urbanization rate).

4.2.4. Data Selection and Sources

This study compiles a panel dataset covering 281 Chinese cities for the years 2010–2022. The sample includes cities located across eastern, central, western, and northeastern China, thereby capturing considerable variation in economic development levels, industrial structure, and resource endowments. Prefecture-level cities are selected because they constitute the principal administrative units for policy execution and statistical reporting, enabling a precise assessment of the local impacts of the pilot zone policy. Owing to data limitations, the analysis excludes the Tibet Autonomous Region, Hong Kong, Macao, and Taiwan, along with cities exhibiting substantial missing data, such as Bijie, Tongren, and Suihua.

The study period extends from 2010 to 2022, a timeframe chosen to balance data consistency with credible policy evaluation. The base year of 2010 corresponds to the point at which city-level data on energy use, financial conditions, and socioeconomic characteristics become relatively standardized and continuously accessible nationwide. More importantly, it allows for a sufficiently long pre-policy window prior to the introduction of the pilot zone policy in 2017. The sample concludes in 2022, the most recent year with complete and reliable city-level information available at the time of analysis, ensuring an adequate post-policy span for examining dynamic and medium-term effects. Information on pilot cities is obtained from official releases issued by relevant ministries and commissions, while the data are sourced from municipal statistical yearbooks, the China Urban Statistical Yearbook, and the China Stock Market and Accounting Research (CSMAR) Database. Missing observations are supplemented using interpolation methods.

5. Empirical Results and Analysis

5.1. Analysis of Benchmark Regression Results

This research integrates the transformation of urban energy use patterns as the outcome variable within a double machine learning framework to identify the causal impact of the pilot zone policies. The estimation findings are presented in Table 1.

Table 1. Baseline regression results.

Category	(1)	(2)	(3)	(4)
Variable	UECST	UECST	UECST	UECST
Policy	0.037 **	0.041 *	0.034 **	0.040 *
	−0.015	−0.022	−0.016	−0.023
Number of folds	3	3	5	5
City, time effect	Yes	Yes	Yes	Yes
Control variable single term	Yes	Yes	Yes	Yes
Control variable quadratic term	No	Yes	No	Yes
Observations	3653	3653	3653	3653

Note: **, and * indicate significance at the 5%, and 10% levels, respectively.

Across alternative model specifications, the pilot zone policy consistently exerts a positive and statistically significant impact on the adjustment in urban energy consumption structures. As shown in Column (1), which adopts a sample split ratio of 1:2 and controls for city-level fixed effects, and time effects, together with first-order control variables, the estimated coefficient equals 0.037, implying that the introduction of the pilot zone policy corresponds to a higher share of cleaner energy within urban energy use. Column (2) further incorporates second-order terms for the control variables, and the estimated effect remains statistically significant. Columns (3) and (4) report the results based on an alternative sample split ratio of 1:4, with Column (3) including first-order terms only and Column (4) incorporating both first-order and second-order terms. In both cases, the corresponding coefficients remain positive and statistically significant, indicating that the core conclusions are robust across alternative sample splits as well as variations in model specification.

From a policy perspective, these findings imply that green finance reform and innovation pilot zones play a substantive role in guiding urban energy consumption toward cleaner energy carriers. By facilitating green credit allocation, encouraging environmentally oriented investment, and improving financing conditions for low-carbon projects, pilot zone policies contribute to the adjustment of urban energy consumption structures.

Overall, the empirical evidence provides consistent support for Hypothesis H1, confirming that the pilot zone policy effectively promotes the transformation of urban energy consumption structures.

5.2. Robustness and Endogeneity Tests

To ensure the accuracy and robustness of the findings, this section reports robustness and endogeneity checks on the baseline regression, with the results shown in Table 2.

Table 2. Robustness and endogeneity test results.

Category	(1) Low-Carbon City	(2) Exclude	(3) Change the Research Period	(4) 01:08	(5) Instrumental Variables	(6) Sample Selection Bias
Variable	UECST	UECST	UECST	UECST	UECST	UECST
Policy	0.032 *	0.035 **	0.035 **	0.045 ***	0.073 ***	1.975 *
	−0.017	−0.016	−0.016	−0.019	−0.021	−1.133
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Control primary	Yes	Yes	Yes	Yes	Yes	Yes
Control the quadratic term	Yes	Yes	Yes	Yes	Yes	Yes

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

5.2.1. Controlling for Concurrent Policy Interference

To account for policy interference in the period, we include the dummy for the "Low-Carbon City Pilot" launched in 2010. As shown in Column (1) of Table 2, after controlling for concurrent policies, the pilot zones continue to positively affect urban energy consumption structure transformation, confirming the robustness of the main results.

5.2.2. Adjusting the Research Sample

First, we exclude autonomous regions and municipalities directly under central government oversight and re-estimate after removing those cities. Second, we shift the sample to 2012–2020 and re-estimate. The results are reported in Columns (2) and (3) of Table 2, and they again indicate a significant positive effect of pilot zones on the transformation, consistent with the benchmark findings.

5.2.3. Adjusting the Ratio of the Sample Split

Although a 3-fold cross-over is deemed optimal, we also estimate with a 1:8 split to test for potential sensitivity. Column (4) of Table 2 presents these results, which show a significant positive impact of the pilot zone policy on urban energy consumption structure transformation, with only a minor deviation in the coefficient from the benchmark, underscoring robustness.

5.2.4. Endogeneity Issues

(1) Reverse causality may arise if cities with more advanced financial systems are more prone to being chosen as policy pilot areas, thereby generating endogeneity concerns. To mitigate this issue, we construct an instrumental variable based on the logarithm of the total number of bank branches at the prefecture-level city level. A higher concentration of bank branches indicates a greater degree of local financial development and, accordingly, a higher likelihood of designation as a pilot zone, satisfying the relevance condition. Meanwhile, green finance policies do not exert a direct influence on the number of bank branches, thereby fulfilling the exogeneity assumption. The estimation results presented in Column (5) of the partial linear instrumental variable model estimated via double machine learning reveal a significantly positive coefficient, confirming that the baseline findings remain robust after controlling for potential endogeneity.

(2) Non-randomness in sample selection: The selection of cities for green finance reform and innovation pilots is not random and is often correlated with inherent urban characteristics, such as geographical location and environmental regulatory conditions. This non-random selection may induce sample selection bias, as persistent differences in these relatively stable attributes could influence the transformation of urban energy consumption structures. To mitigate this concern, we follow the work of Lu et al. (2017) [44] and introduce interaction terms between time trends and city-specific characteristics into the benchmark regression. Specifically, environmental regulation intensity and a dummy variable indicating whether a city is designated as a key area for atmospheric pollution control are employed to capture inherent inter-city differences. The results in Column (6) show that, after controlling for these factors, green finance pilot zone policies continue to exert a significant positive effect on the transformation of urban energy consumption structures.

5.3. Mechanism Examination and Results' Analysis

The theoretical analysis suggests that the pilot zone policies promote urban energy consumption structure transformation through three interrelated channels: green technological innovation, green economic efficiency, and industrial structure upgrading. This

section empirically examines whether these channels constitute statistically significant indirect transmission paths, rather than reiterating the theoretical mechanisms.

5.3.1. Green Technology Innovation Mechanism

Column (1) of Table 3 presents the estimated indirect effect routed through green technological innovation. The coefficient is positive and statistically significant (0.393), showing that pilot zone policies facilitate energy consumption structure transformation by boosting green technological innovation.

Table 3. Mechanism test results.

Category	(1)	(2)	(3)
Variable	GTI	GEE	UIS
Policy	0.393 ***	0.070 ***	0.219 ***
	−0.144	−0.025	−0.069
Time FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Control primary	Yes	Yes	Yes
Control the quadratic term	Yes	Yes	Yes

Note: *** indicates significance at the 1% levels, respectively.

This outcome reflects green finance's role in easing R&D funding constraints, improving the allocation of innovative resources, and strengthening market incentives for the deployment of clean technologies. As green innovation capacity expands, the costs and adoption barriers of low-carbon energy technologies fall, reducing reliance on high-carbon energy and supporting structural adjustment in urban energy use.

5.3.2. Green Economic Efficiency Mechanism

Column (2) of Table 3 shows that green economic efficiency serves as a significant transmission channel, with an estimated coefficient of 0.070. This suggests that pilot zone policies influence energy consumption structure transformation by improving the efficiency of factor allocation under environmental constraints.

By strengthening environmental information disclosure and adjusting credit allocation, green finance policies redirect capital from energy-intensive sectors toward low-carbon and energy-efficient activities. The resulting improvement in green total factor productivity narrows the cost gap between clean and conventional energy sources, inducing market-driven adjustments in energy use patterns.

5.3.3. Industrial Structure Upgrading

Column (3) of Table 3 presents evidence that industrial structure upgrading constitutes another significant indirect channel, with a coefficient of 0.219. This indicates that pilot zone policies promote urban energy transition by guiding production factors toward technology-intensive and low-carbon industries.

As traditional high-energy-consuming sectors contract and green manufacturing and modern services expand, energy demand shifts toward higher-quality and cleaner energy carriers. This structural reallocation directly reduces energy intensity and accelerates the substitution of fossil fuels with cleaner energy sources.

Overall, the results confirm that green technological innovation provides the technological foundation, green economic efficiency creates market-based incentives, and industrial structure upgrading reshapes energy demand. These channels jointly form an indirect transmission mechanism through which the pilot zone policies promote the transformation of urban energy consumption structures, providing empirical support for Hypothesis H2.

5.4. Heterogeneity Analysis

This study examines the heterogeneous effects of the Pilot Zone policies on urban energy consumption structure transformation from urban, ecological, and environmental regulation perspectives. These dimensions capture differences in cities' regional economic positioning and outward influence, resource endowments and development paths, and the intensity of environmental institutions. The empirical results are consistent with Hypothesis H3.

5.4.1. Urban Heterogeneity

A city's strategic position within the regional economic system and its external influence capacity play an important role in shaping policy effectiveness. Following the work of Zhao et al. (2020) [45], central cities include provincial capitals, sub-provincial cities, and China's four municipalities. Based on the Medium- and Long-Term Railway Network Plan (2016) [46], cities are further divided into transportation hub cities and non-hub cities.

As reported in Table 4, the pilot zone policy exerts significantly stronger effects on energy consumption structure transformation in central cities and transportation hub cities. These cities function as core nodes of regional development and key channels for factor flows, enabling them to more effectively leverage green finance policies.

Table 4. Results of urban heterogeneity analysis.

	Urban Heterogeneity			
	(1)	**(2)**	**(3)**	**(4)**
Variable	Central city	Non-central city	Transportation hub city	Non-transportation hub city
	UECST	UECST	UECST	UECST
Policy	0.038 *	−0.015	0.040 *	0.012
	−0.021	−0.04	−0.023	−0.013
Time FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Control primary	Yes	Yes	Yes	Yes
Control the quadratic term	Yes	Yes	Yes	Yes

Note: * indicates significance at the 1% levels, respectively.

This advantage mainly stems from stronger factor aggregation and allocation capacity, larger market scale and demand for clean energy, and higher policy implementation capability. Dense concentrations of financial institutions, research resources, and skilled labor facilitate access to diversified green financial instruments and support green technology development. Meanwhile, a larger market size improves the expected returns of green projects, reducing investment risk and attracting social capital. More robust governance systems further ensure effective policy execution and prevent greenwashing.

5.4.2. Ecological Heterogeneity

Zhang et al. (2024) [47] contend that resource-based cities encounter considerable barriers to transformation as a result of the "resource curse" or the "green paradox." Accordingly, resource endowments and path-dependent development patterns may condition the effectiveness of policy measures. Following the National Sustainable Development Plan for Resource-Based Cities (2013–2020) [48], cities are distinguished between resource-based and non-resource-based categories. In addition, pursuant to the National Adjustment and Transformation Plan for Old Industrial Bases (2013–2022) [49], cities are further divided into old industrial base cities and those without such a designation.

Columns (2) and (4) in Table 5 show that the pilot zone policy exerts a statistically significant effect in promoting the transformation of the energy consumption structure in non-resource-based cities and non-old industrial base cities. In contrast, Columns (1) and (3) suggest that the estimated policy impacts are statistically insignificant for resource-based cities and old industrial base cities.

Table 5. Results of ecological basis heterogeneity analysis.

	Ecological Heterogeneity			
	(1)	**(2)**	**(3)**	**(4)**
Variable	Resource-based city	Non-resource-based city	Old industrial base cities	Non-old industrial base cities
	UECST	UECST	UECST	UECST
Policy	−0.033	0.042 **	−0.020	0.045 ***
	(0.044)	(0.017)	(0.103)	(0.015)
Time FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Control primary	Yes	Yes	Yes	Yes
Control the quadratic term	Yes	Yes	Yes	Yes

Note: ***, ** indicate significance at the 1%, 5% levels, respectively.

This disparity mainly reflects strong path dependence and high transformation costs in traditional energy-dependent regions. Their industrial structures, fiscal revenues, and employment are deeply tied to fossil energy industries, making short-term structural adjustment difficult. In addition, large sunk costs, social adjustment pressures, limited human capital, and weaker fiscal and financial systems constrain the effective use of green finance, thereby weakening policy outcomes.

5.4.3. Heterogeneity in Environmental Regulation Intensity

Environmental regulation intensity represents a key external institutional condition influencing green finance effectiveness. Based on the State Council's National Environmental Protection Plan for the 11th Five-Year Plan Period (2007) [50], cities are categorized into core environmental protection cities and non-core cities.

As shown in Table 6, the policy effect is significantly stronger in core environmental protection cities. Stricter regulatory requirements and stronger enforcement increase the cost of high-pollution activities and enhance enterprises' incentives for green transformation. Green finance policies, in turn, provide financial support and cost advantages, generating a complementary policy synergy.

Moreover, stronger environmental institutions are typically associated with better-developed environmental monitoring and information disclosure systems, reducing information asymmetry faced by financial institutions. In contrast, looser regulation and weaker enforcement in non-core cities limit both policy implementation incentives and enterprises' motivation for energy transition, resulting in weaker policy effects.

Table 6. Results of analysis on heterogeneity in environmental regulation intensity.

	Heterogeneity in Environmental Regulation Intensity	
	(1)	**(2)**
Variable	Key cities for environmental protection	Non-environmental protection key city
	UECST	UECST
Policy	0.033 *	0.018
	(0.020)	(0.028)
Time FE	Yes	Yes
City FE	Yes	Yes
Control primary	Yes	Yes
Control the quadratic term	Yes	Yes

Note: * indicates significance at the 10% levels, respectively.

5.5. Discussion

The empirical analysis provides consistent evidence that the pilot zone policies significantly promote the transformation of urban energy consumption structures. The benchmark results confirm a stable and robust average treatment effect, while robustness and endogeneity tests further support the causal interpretation of the findings. These results indicate that green finance policies play a substantive role in guiding capital allocation and energy use toward cleaner energy carriers.

The mechanism analysis clarifies that the policy effect operates through indirect transmission channels rather than direct administrative intervention. Specifically, green technological innovation, green economic efficiency improvement, and industrial structure upgrading jointly constitute the transmission mechanism. Each channel captures a distinct dimension of how green finance influences energy transition, and together they explain how financial instruments are translated into structural changes in energy consumption.

The heterogeneity analysis further reveals that policy effectiveness is conditional on urban characteristics, resource endowments, and the intensity of environmental regulation. The stronger effects observed in central cities, transportation hubs, non-resource-based cities, non-old industrial base cities, and core environmental protection cities indicate that green finance policies tend to perform better in settings where factor markets are more mature, adjustment costs are lower, and institutional constraints are tighter. This finding highlights the need to align green finance reforms with local economic conditions and regulatory frameworks.

Overall, the empirical results demonstrate that green finance pilot policies influence urban energy consumption structures through an indirect, market-oriented, and context-dependent process, providing systematic empirical support for Hypotheses H1–H3.

6. Conclusions and Policy Implications

6.1. Conclusions

This paper employs panel data covering 281 prefecture-level cities over the 2010–2022 period. An index capturing the transformation of the urban energy consumption structure is constructed based on the share of electricity, natural gas, and liquefied petroleum gas in total energy consumption. All energy types are converted into standard coal equivalents using the corresponding conversion coefficients. Within a double machine learning framework, this paper investigates the role played by pilot zone policies in driving changes in urban energy consumption structures. The principal findings are summarized as follows: (1) Pilot zone policies generate a positive and statistically significant impact on the transformation of urban energy consumption structures, and this result remains robust across multiple robustness checks and endogeneity treatments. (2) Pilot zone policies promote

the transformation of urban energy consumption structures through three main mechanisms: fostering green technological innovation, enhancing green economic efficiency, and accelerating industrial structure upgrading. (3) The effects of pilot zone policies on the transformation of urban energy consumption structures differ across cities depending on baseline characteristics, resource endowments, and the intensity of environmental regulation. In particular, central cities, transportation hubs, non-resource-based cities, non-old industrial base cities, and core environmental protection cities exhibit stronger capacities to harness green finance policies in support of the energy transition.

6.2. Policy Implications

In light of the empirical evidence, the following policy implications are advanced.

First, green finance supply-side reforms should be further deepened by establishing a multi-tiered and sustainable policy support system to strengthen the foundation of transition finance. Given the significant positive effect of pilot zone policies on urban energy consumption structure transformation, policy efforts should gradually extend from pilot zones to a broader regional and national scope. Local governments should serve as coordinators by clarifying policy standards, improving information disclosure, and strengthening performance evaluation mechanisms. Financial institutions should expand green credit, green bonds, and risk-sharing instruments, while enterprises should be guided to align investment decisions with green finance eligibility criteria. A transparent monitoring and feedback system is essential to ensure effective policy transmission and prevent greenwashing.

Second, policy design should prioritize green technological innovation, green economic efficiency improvement, and industrial structure upgrading to form an integrated and self-reinforcing transformation mechanism. Consistent with the identified transmission channels, financial support should be more precisely directed toward green technology enterprises facing high uncertainty and financing constraints. This can be achieved by combining credit support, equity financing, and guarantee mechanisms. At the same time, policies should promote the assessment of and improvement in green economic efficiency by guiding firms to optimize factor allocation and by attracting innovative capital and talent into pilot zones. By strengthening the linkage between financial capital, knowledge capital, and industrial capital, green technological innovation, efficiency gains, and industrial upgrading can jointly generate sustained momentum for urban energy consumption structure transformation.

Third, a regionally differentiated and coordinated advancement strategy should be adopted to address heterogeneity constraints. The heterogeneity results indicate that policy effectiveness varies systematically across urban hierarchy, resource endowment, and environmental regulation intensity. Central cities and transportation hubs should further leverage their factor aggregation and diffusion functions to amplify policy spillovers. For resource-based cities and old industrial bases, transition finance should play a stronger supportive and inclusive role by alleviating adjustment costs and easing financing constraints during structural transformation. In cities with stringent environmental regulation, green finance policies should be further integrated with regulatory enforcement, while in cities with weaker regulation, institutional capacity building should be prioritized to enhance policy effectiveness.

6.3. Limitations and Future Research

Notwithstanding the robustness of the empirical findings, this paper is subject to several limitations. First, the analysis is conducted at the prefecture-level city scale, which may obscure within-city heterogeneity in energy consumption behaviors and the imple-

mentation of green finance. Future studies may incorporate micro-level data, such as firm- or household-level energy usage, to offer more detailed and fine-grained evidence.

Second, although this study examines multiple transmission channels, the mechanisms are captured through indirect effects and may not fully reflect dynamic interactions among green finance, technological innovation, and industrial restructuring. Future studies could adopt dynamic models or long-term panel data to investigate the persistence and evolution of policy effects.

Third, policy evaluation is conducted within the institutional context of China's green finance pilot zones. Differences in financial systems, regulatory frameworks, and energy markets may limit the external validity of the conclusions. Future research could conduct comparative analyses across countries or regions to assess the generalizability of the findings.

Addressing these limitations would help deepen the understanding of how green finance policies influence energy transitions under different economic and institutional conditions.

Author Contributions: F.P.: Conceptualization, Methodology, Supervision, Funding acquisition, Project administration, Writing—review & editing. Z.T.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Validation, Visualization, Writing—original draft, Writing—review & editing. Y.L.: Investigation, Resources, Data curation, Writing—review & editing. X.Q.: Resources, Project administration, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research on the generation mechanism and implementation path of new productive forces driven by innovation in leading technology enterprises in Heilongjiang Province (25GLI005) Heilongjiang Province Social Science Fund Project.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in this article. Further inquiries can be directed to the corresponding author.

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

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