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Impact of Energy Transition on Regional Carbon Emissions: Evidence from China

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Abstract

Against the backdrop of global climate change and China's commitment to carbon reduction, energy transition has become an important pathway toward low-carbon development. Using panel data from 26 Chinese provinces between 2013 and 2022, this study investigates how regional energy transition affects carbon emissions. An evaluation framework covering three dimensions—cleanliness, security, and efficiency—is constructed, with indicator weights determined through the entropy method. The development levels of the three subsystems are measured and further integrated through a coupling coordination model to assess the overall progress of energy transition and its evolution over time. Regression analysis is then employed to examine the relationship between energy transition and carbon dioxide emissions. The results suggest that China's energy transition has generally advanced during the study period, although the development of different subsystems remains uneven. The relationship between energy transition and carbon emissions follows an inverted U-shaped pattern. At relatively low levels of transition, carbon emissions continue to increase, whereas the emission-reduction effect becomes more evident as the transition deepens, eventually contributing to a decline in emissions. The impacts are not uniform across regions and differ according to urbanization level, economic development, and coastal–inland location. By examining both the evolution of energy transition and its environmental consequences, this study offers additional evidence on the role of energy transition in reducing carbon emissions and provides implications for region-specific low-carbon development under China's dual-carbon strategy.

Keywords

energy transition, carbon emissions, coupling coordination

1. Introduction

Global climate change has become one of the most pressing challenges facing contemporary society. In response, countries around the world have strengthened efforts to reduce greenhouse gas emissions following the adoption of the Paris Agreement in 2015. As the largest developing economy, China has incorporated carbon peaking and carbon neutrality into its long-term development agenda and has attached increasing importance to balancing economic growth with environmental sustainability. Against this background, reducing carbon emissions through adjustments in the energy system has become an important policy objective.

A large body of research has examined the determinants of carbon emissions from institutional, corporate, and regional perspectives. Existing studies suggest that institutional development, enterprise strategies, and regional innovation capacity can influence carbon emissions by improving resource allocation, encouraging technological progress, and facilitating low-carbon transformation [1–3]. While these studies provide valuable insights into the drivers of carbon emissions, less attention has been paid to the role of energy transition itself. In particular, the relationship between energy transition and carbon emissions may be more complex than a simple linear association. The expansion of clean energy can help reduce emissions, yet the benefits of transition may be offset when energy demand grows more rapidly than the pace of structural adjustment.

To explore this issue, provincial-level data for China from 2013 to 2022 are used to construct a multidimensional indicator system of energy transition. The analysis focuses on how different stages of energy transition are associated with changes in carbon emissions and whether this relationship varies across regions. Several findings emerge from the empirical analysis. First, energy transition in China has gradually moved beyond improvements in individual dimensions toward more coordinated development across the clean, secure, and efficient subsystems. Nevertheless, the overall level of coordination remains relatively limited. Second, energy transition exhibits a significant inverted U-shaped relationship with carbon emissions. Carbon emissions tend to increase during the initial stage of transition, whereas deeper transition is associated with stronger emission-reduction effects. Third, considerable regional variation exists, with the relationship differing across areas characterized by different levels of urbanization, economic development, and geographic location.

This study contributes to the literature in three respects. It develops a multidimensional framework for evaluating energy transition at the provincial level and provides a systematic assessment of its evolution. It further shows that the effect of energy transition on carbon emissions is nonlinear rather than uniformly negative, highlighting the importance of considering different stages of transition. Finally, the heterogeneity analysis reveals substantial regional differences in the environmental consequences of energy transition, offering additional evidence for the design of differentiated low-carbon development policies.

2. Literature Review

2.1 Research on Energy Transition

Although scholars differ somewhat in how they define energy transition, there is broad agreement that it involves a far-reaching transformation of both energy systems and the wider socio-economic structures associated with them. A commonly cited definition is provided by Kabeyi and Olanrewaju [4], who describe energy transition as a long-term structural process driven by technological progress, economic change, and social development. At its core, the transition aims to improve sustainability by reshaping multiple social and economic subsystems and gradually reducing dependence on fossil-fuel-based energy.

In recent decades, energy transition has attracted increasing attention across countries facing the dual pressures of energy demand and climate change. The process is closely related to a range of issues, including changes in energy structure, shifts in end-use energy consumption, greenhouse gas mitigation, air quality improvement, and public health outcomes. The transition is not without costs. Slameršak et al. [5], for example, note that the early stages of low-carbon transition may reduce the amount of net energy available to society and may still involve considerable carbon emissions. Nevertheless, the potential environmental and social benefits are generally regarded as substantial.

A recurring theme in the literature is the role of energy transition in promoting cleaner and less carbon-intensive energy systems. Hou Meifang [6] argues that a key feature of the transition is the gradual replacement of fossil fuels by renewable energy sources, ultimately leading to an energy system in which renewables play a dominant role. Consistent with this view, Zhang and Chen [7] suggest that carbon neutrality goals are likely to accelerate the expansion of renewable energy in both energy consumption and electricity generation, while also increasing the degree of end-use electrification.

Another strand of research focuses on the environmental consequences of energy transition. By reducing reliance on fossil fuels, the transition is expected to contribute to lower greenhouse gas emissions [4]. Its benefits may also extend beyond climate mitigation. Qin et al. [8] find that low-carbon energy transition under

China’s carbon neutrality agenda can help alleviate air pollution and reduce the associated health burdens. These findings suggest that the implications of energy transition reach well beyond the energy sector itself and may generate broader environmental and social gains.

2.2 Research on Carbon Emissions

A substantial body of research has explored the determinants of carbon emissions, reflecting growing concern over climate change and emission reduction strategies. Existing studies generally emphasize the roles of energy use, socio-economic development, and policy interventions, although the relative importance of these factors may vary across countries and regions.

Among these determinants, the energy dimension has received particular attention. A broad consensus exists that dependence on fossil fuels remains one of the major sources of carbon emissions. Evidence from both developing and developed economies supports this view. Using long-term data from Morocco, Bouyghrissi et al. [9] show that heavy reliance on fossil fuels contributes to environmental degradation. Similar conclusions are reported by Perone et al. [10], whose analysis of OECD countries identifies fossil energy consumption as a key driver of carbon dioxide emissions. By contrast, a transition toward cleaner energy sources is generally associated with lower emissions. Lau et al. [11] find that improvements in the greenness of energy consumption structures can help mitigate CO_2 emissions among OECD countries. Existing research also suggests that factors such as globalization and institutional quality may shape the environmental outcomes of energy use.

Beyond the energy system itself, socio-economic development is closely linked to changes in carbon emissions. Urbanization, economic growth, and energy demand often evolve simultaneously, making their environmental effects difficult to separate. Drawing on cross-country evidence, Wang et al. [12] identify strong associations among urbanization, economic expansion, energy consumption, and CO_2 emissions. Lin et al. [13] further argue that these relationships are particularly pronounced in non-high-income economies, where rapid urbanization and industrialization continue to reshape patterns of energy use and environmental pressure.

Policy and institutional arrangements constitute another important strand of the literature. As governments increasingly rely on market-based and regulatory instruments to address climate challenges, attention has turned to their effectiveness in reducing emissions. Wang and Zhang [14] find that the environmental consequences of trade openness differ substantially across countries, suggesting that institutional and developmental contexts matter. Focusing on China, Jiang and Sun [15] provide evidence that carbon emission trading schemes can significantly reduce regional carbon emissions, highlighting the role of policy interventions in promoting low-carbon development.

3. Theoretical Foundation

Sustainable development theory stresses the need to balance economic growth, resource utilization, and environmental protection while maintaining coordination among development momentum, quality, and social equity [16]. From this perspective, the traditional energy development model, characterized by high resource consumption and high emissions, has increasingly exposed problems such as resource constraints, environmental degradation, and rising carbon emissions. These challenges have made the transition toward a more sustainable energy system an important policy objective.

Within this framework, energy transition can be understood as a process of shifting from a fossil-fuel-based, high-carbon energy system toward one that is cleaner, safer, and more efficient. Such a transition involves not only adjustments in energy structure but also technological progress and improvements in energy utilization. Through these changes, the relationship between economic development, resource consumption, and environmental protection is gradually reshaped.

The environmental implications of energy transition are particularly important. As the share of high-carbon energy sources declines and energy efficiency improves, carbon emissions generated in production and consumption activities are expected to decrease. In this sense, energy transition contributes not only to emission reduction but also to the broader transformation toward greener patterns of development. Its significance therefore extends beyond the energy sector and is closely linked to the long-term objectives of sustainable development.

From the perspective of emission reduction mechanisms, energy transition affects carbon emissions through several channels. The substitution of fossil fuels by cleaner energy sources reduces the carbon intensity of the energy mix, thereby lowering emissions at the source. Meanwhile, technological upgrading and improvements in energy efficiency help reduce the amount of carbon emitted per unit of economic output.

Nevertheless, the relationship between energy transition and carbon emissions may not be linear. During the transition process, China continues to face substantial pressure from growing energy demand. Expanding energy consumption tends to increase carbon emissions and may offset part of the environmental benefits generated by structural adjustment. In the early stage of energy transition, although clean energy substitution and efficiency improvements begin to emerge, their effects remain relatively limited. When energy demand expands more rapidly than the pace of transition, the emission-reduction benefits are insufficient to compensate for the additional emissions associated with growing energy consumption. Under such circumstances, total carbon emissions may continue to rise.

As energy transition deepens, however, the contribution of structural optimization gradually becomes more pronounced. Once the pace of transition approaches that of energy expansion, the upward pressure generated by increasing energy demand begins to weaken, and carbon emission growth slows. This stage corresponds to the approach of carbon peaking. At more advanced stages of transition, the cumulative effects of clean energy substitution, structural adjustment, and efficiency improvement become increasingly evident. When these effects outweigh the emissions associated with energy expansion, carbon emissions begin to decline.

Based on the above discussion, the following hypothesis is proposed:

H1: Regional energy transition and carbon emissions exhibit an inverted U-shaped relationship.

4. Construction and Measurement of Energy Transition Indicators Based on the Coupling Coordination Model

4.1 Data Sources and Indicator Description

Drawing on the indicator framework proposed in the Blue Book of Modern Energy System Index 2024, the level of energy transition is evaluated from three dimensions: cleanliness, efficiency, and security. A total of eight indicators covering 26 Chinese provinces during 2013–2022 are selected, and detailed descriptions are reported in Table 1. The data are obtained from the National Bureau of Statistics of China, provincial statistical yearbooks and statistical bureaus, as well as the China Carbon Accounting Database.

Table 1: Indicator System for Measuring Energy Transition Levels

Dimension	Indicator Name	Unit	Indicator Direction
Cleanliness	NO_x emissions per unit of GDP	tons of NO_x /100 million yuan	-
	SO_2 emissions per unit of GDP	tons of SO_2 /100 million yuan	-
	Particulate matter emissions per unit of GDP	tons /100 million yuan	-
Security	Ratio of natural gas production to consumption	/	+
	Ratio of electricity production to consumption	/	Interval
	Length of natural gas supply pipelines per unit area	km / km²	+
Efficiency	Energy consumption per unit of GDP	tons of standard coal / 10,000 yuan	-
	Energy consumption elasticity coefficient	/	-

4.2 Model Construction

To capture the degree of interaction and coordinated development among multiple subsystems, a coupling coordination model is employed. The original indicators are first standardized. Among them, the ratio of electricity production to electricity consumption is treated as an interval indicator, with the optimal value set at 1.05. Indicator weights for the clean, secure, and efficient subsystems are then determined using the entropy weight method. Based on the standardized indicators and corresponding weights, the development levels of the three subsystems are calculated through linear aggregation $U_i = \sum_{j=1}^{n} w_j^1 x_{ij}$. Finally, a ternary coupling coordination model is used to assess the degree of coordinated development among the clean, secure, and efficient dimensions.

The ternary coupling coordination model is expressed as follows:

$$C=\left[\frac{U_1U_2U_3}{\left(\frac{U_1+U_2+U_3}{3}\right)^3}\right]^{1/3} \tag{1}$$

$$T=\frac{1}{3}(U_1+U_2+U_3) \tag{2}$$

$$D=\sqrt{C\times T} \tag{3}$$

where U1, U2, and U3 denote the development levels of the clean, secure, and efficient subsystems, respectively. C represents the coupling degree and reflects the strength of interaction among the three subsystems. T refers to the coordination degree and measures the extent to which the three subsystems develop in a balanced manner. D denotes the coupling coordination degree, which is used to evaluate their overall level of coordinated evolution. Larger values indicate stronger interactions, better developmental balance, and a higher degree of overall synergy.

4.3 Analysis of Measurement Results

Energy transition is decomposed into the clean, secure, and efficient subsystems, and their development levels are estimated using the coupling coordination model. The following discussion examines their evolution over time and across regions.

4.3.1 Temporal Characteristics of the Clean Subsystem

Figure 1: Temporal Differences in the Development Level of the Clean Subsystem

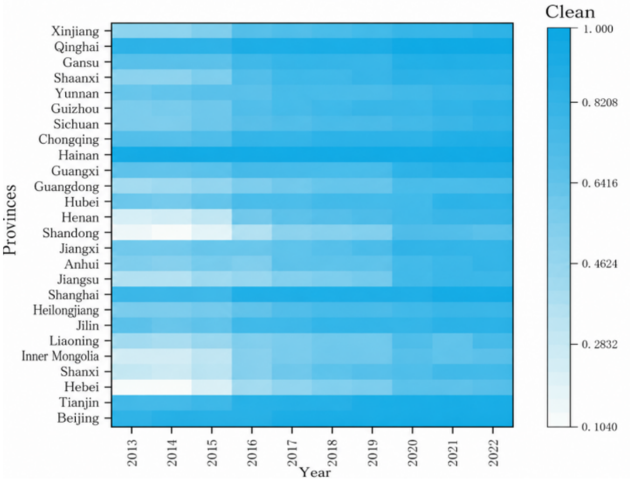
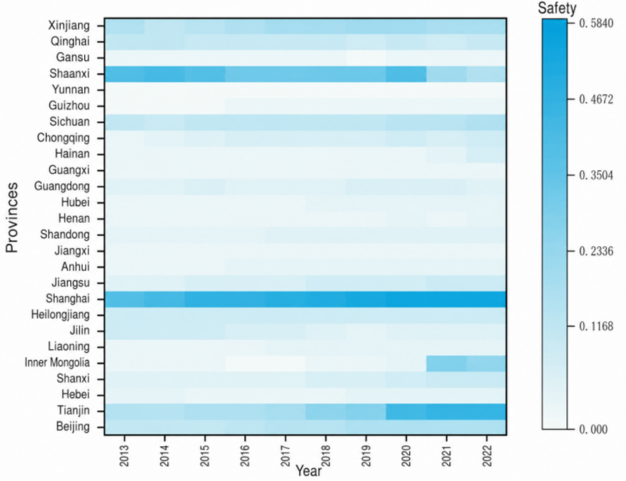


Figure 1 shows that the clean subsystem generally improved throughout the sample period. Beijing, Tianjin, Shanghai, Hainan, Qinghai, and Chongqing remained at relatively high levels with only limited fluctuations, indicating comparatively stable performance. Several provinces in central and western China, as well as parts of central-eastern China, started from lower levels but experienced a steady rise over time, suggesting a gradual narrowing of regional gaps. Differences across provinces appear to be associated with variations in clean energy development conditions, existing energy structures, and the capacity to invest in pollution control. Taken together, the evolution of the clean subsystem reflects a pattern in which leading regions maintained their advantages while lower-level regions gradually caught up.

4.3.2 Temporal Characteristics of the Secure Subsystem

As illustrated in Figure 2, improvement in the secure subsystem was relatively slow during 2013–2022, and regional disparities remained evident. Compared with the clean dimension, progress in energy security was much less pronounced. Shanghai and Shaanxi consistently recorded relatively high values, while Tianjin experienced noticeable improvement in the later years of the sample period. Most provinces remained in the middle or lower range for a prolonged period and exhibited only modest fluctuations. These patterns suggest that the security dimension is influenced more heavily by factors such as resource endowments, the spatial distribution of energy bases, interregional transmission capacity, and reserve systems. As a result, progress tends to be gradual and constrained by long-term structural conditions. Throughout the sample period, high-value regions remained relatively concentrated, whereas improvements in lower-level regions proceeded at a slower pace.

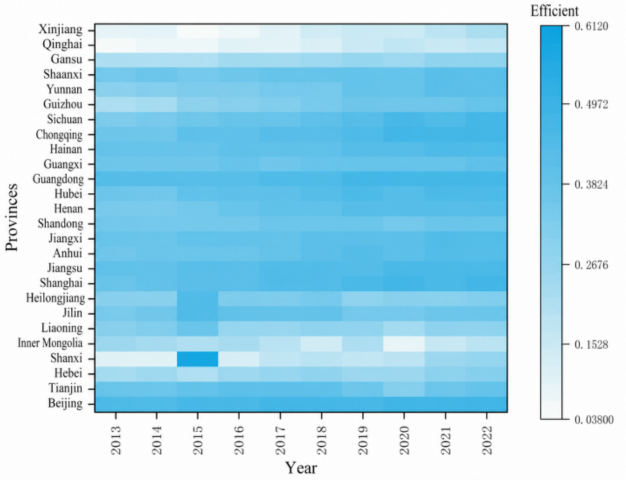
Figure 2: Temporal Differences in the Development Level of the Secure Subsystem



4.3.3 Temporal Characteristics of the Efficient Subsystem

Figure 3 indicates that the efficient subsystem generally remained at a medium-to-high level between 2013 and 2022, although substantial differences persisted across provinces. Beijing, Shanghai, Jiangsu, and Guangdong consistently ranked among the leading regions. Shaanxi, Sichuan, Chongqing, and Hubei also maintained relatively favorable development trajectories. In contrast, provinces such as Xinjiang, Qinghai, Inner Mongolia, and Hebei experienced only limited improvement despite some upward movement over time. Tianjin followed a different pattern, with an initial increase followed by a subsequent decline. The observed differences appear closely related to industrial upgrading, technological progress, and changes in energy utilization efficiency. Overall, the efficient subsystem maintained a comparatively strong performance and continued to improve over the study period.

Figure 3: Temporal Differences in the Development Level of the Efficient Subsystem



In general, the clean, secure, and efficient subsystems followed different development trajectories. The coupling degree, coordination degree, and coupling coordination degree respectively capture the strength of inter-system linkages, the degree of developmental matching, and the overall level of synergy among the three dimensions. The coupling degree remained relatively high throughout the sample period, indicating that the three subsystems were closely connected. By contrast, the coordination degree stayed at a comparatively low level, suggesting that balanced development among the subsystems had not yet been achieved in most regions. The coupling coordination degree also remained relatively low, implying that comprehensive synergy across the clean, secure, and efficient dimensions was still limited.

Overall, the results suggest that China's energy transition has gradually evolved from improvements in individual dimensions toward stronger systemic linkages. However, a high level of interaction has not yet translated into a similarly high level of coordination. Achieving more balanced and synergistic development across the three dimensions remains an important challenge for the next stage of energy transition.

5. The Impact of Energy Transition on Carbon Emissions

5.1 Data, Model, and Variable Measurement

The analysis is based on panel data for 26 Chinese provinces covering the period from 2013 to 2022. Data are collected from the China Statistical Yearbook, China Energy Statistical Yearbook, the China Carbon Accounting Database (CEADs), and other official statistical sources.

After measuring the level of energy transition, its relationship with regional carbon emissions is further examined using a two-way fixed effects model. Given the possibility that the effect of energy transition on carbon emissions may vary across different stages of transition, a quadratic term of the energy transition index is included to capture potential nonlinearity. The model is specified as follows:

$$\mathrm{ZCO_2Emissions_{ik}}=\beta_0+\beta_1\mathrm{ZEnergytran_{ik}}+\beta_2\mathrm{ZEnergytran^2_{ik}}+\beta_3\mathrm{controls_{ik}}+\delta_{\mathrm{Year}}+\eta_{\mathrm{Province}}+\varepsilon_{\mathrm{ik}} \tag{4}$$

where *i* and *t* denote province and year, respectively. $ZCO_2Emissions_{ik}$ represents standardized carbon emissions, while $ZEnergytran_{ik}$ denotes the standardized energy transition index. $ZEnergytran^2_{ik}$ is the squared term of the energy transition index. The vector (*controls*) includes a set of control variables. δ_{Year} and $\eta_{Province}$ represent year fixed effects and individual fixed effects, respectively, and ε_{ik} is the random error term.

In the equation, $ZCO_2Emissions_{ik}$ is the core explained variable, representing regional carbon emissions. $ZEnergytran_{ik}$ and $ZEnergytran^2_{ik}$ are the core explanatory variables, measured using the energy transition index constructed earlier. Control variables include per capita GDP (lngdp), industrial structure upgrading (ind), urbanization rate (urban), population density (lnedu), human capital (human), degree of openness (open), and government intervention (gov).

Descriptive statistics for all variables are reported in Table 2. The sample contains 260 observations. Carbon emissions ($ZCO_2Emissions$), the energy transition index ($ZEnergytran$), and its squared term ($ZEnergytran^2$) have all been standardized prior to estimation. As a result, these variables have a mean value of 0 and a standard deviation of 1, reducing the influence of differences in measurement scales across variables.

Table 2: Descriptive Statistics

Variable	N	Mean	SD	Min	p50	Max
ZCOEmissions	260	0	1	-1.338	-0.340	2.462
ZEnergy tr~s	260	0	1	-2.139	-0.168	2.752
ZEnergy tr~2	260	0	1	-1.647	-0.252	3.213
lngdp	260	10.92	0.437	10.00	10.86	12.15
ind	260	1.471	0.799	0.665	1.285	5.244
urban	260	0.612	0.119	0.379	0.593	0.896
lnedu	260	4.715	1.503	0.742	5.243	6.559
human	260	0.0143	0.00760	0.00210	0.0131	0.0345
open	260	0.190	0.285	0.00930	0.104	1.619
gov	260	0.324	0.265	0.0942	0.233	1.289

5.2 Benchmark Regression Analysis

The benchmark regression results are reported in Table 3. Column (1) presents the baseline specification including only the key explanatory variable and carbon emissions, while Column (2) further incorporates the full set of control variables. The estimated coefficients remain statistically significant at the 1% level after the inclusion of controls. The coefficient on the linear term of energy transition is positive (0.6402), whereas the coefficient on the squared term is negative (-0.5586), and both are statistically significant. This pattern suggests a non-linear relationship between energy transition and carbon emissions and is consistent with an inverted U-shaped trajectory.

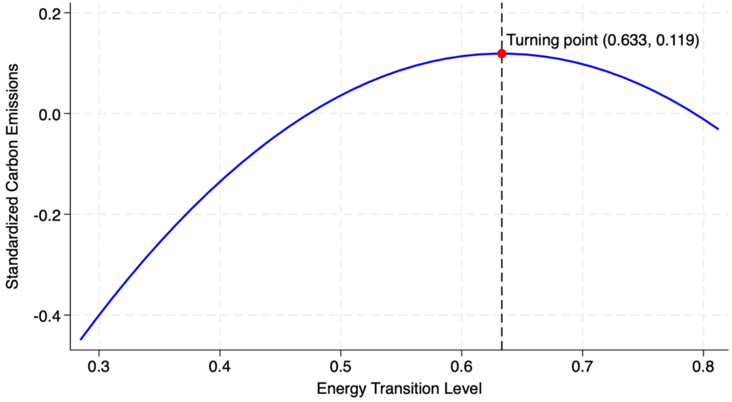
Figure 4 provides a visual illustration of this relationship. When the energy transition index remains below approximately 0.633, carbon emissions tend to increase as the transition progresses. Beyond this threshold, the relationship reverses, and further improvements in energy transition are associated with declining carbon emissions. These results are consistent with the theoretical expectation proposed in Hypothesis H1.

Table 3: Benchmark Regression Results

	(1)	(2)
VARIABLES	ZCOEmissions	ZCOEmissions
ZEnergytran	0.6973***	0.6402***
	(5.9649)	(4.5970)
ZEnergytran^2	-0.5806***	-0.5586***
	(-4.4256)	(-3.5872)
ind		-0.3706***
		(-5.8065)
urban		-1.5532**
		(-2.1396)
lngdp		-0.0896
		(-0.4860)
lnedu		0.0211
		(1.1633)
human		-0.0162
		(-0.0126)
open		-0.0845**
		(-2.0398)
gov		0.0609
		(0.7188)
Constant	-0.0000	2.3720
	(-0.0000)	(1.1991)
Pro_FE Year_FE	YES YES	YES YES
N	260	260
R2	0.987	0.989

*Note: ***, *, and * indicate significance at the 1%, 5%, and 10% levels, respectively. t-statistics are in parentheses.*

Figure 4: Inverted U-shaped Relationship Between Energy Transition and Carbon Emissions



5.3 Robustness Tests

Several additional tests are conducted to assess the stability of the benchmark results, including the exclusion of special years, the use of robust standard errors, and winsorization treatment. The corresponding results are reported in Table 4.

First, following Lyu Bingyang et al. [17], observations from 2020 and 2021 are excluded to reduce the potential influence of the COVID-19 pandemic. As reported in Column (1), the estimated coefficients remain statistically significant and continue to support the inverted U-shaped relationship between energy transition and carbon emissions.

Second, heteroskedasticity-robust standard errors are adopted to address potential clustering and variance-related concerns [18]. The results presented in Column (2) are largely unchanged, and the inverted U-shaped relationship remains statistically significant.

Third, following Han et al. [19], all control variables are winsorized at the 1% and 99% levels to mitigate the influence of extreme observations. Column (3) reports results that are highly consistent with the benchmark regression.

Taken together, the findings remain stable across different specifications, suggesting that the main conclusions are not sensitive to alternative treatments of the sample or estimation procedure.

Table 4: Robustness Test Results

	(1)	(2)	(3)
	Excluding Special Years	Robust SE	Winsorization
VARIABLES	ZCOEmissions	ZCOEmissions	ZCOEmissions
ZEnergytran	0.5794***	0.6402**	0.6331***
	(3.7580)	(2.2883)	(4.5378)
ZEnergytran2	-0.4881***	-0.5586*	-0.5518***
	(-2.7573)	(-1.7612)	(-3.5353)
lngdp	0.0723	-0.0896	-0.0325
	(0.3668)	(-0.2771)	(-0.1735)
ind	-0.3821***	-0.3706**	-0.3626***
	(-5.3829)	(-2.3001)	(-5.6482)
urban	-1.8002**	-1.5532	-1.5278**
	(-2.2100)	(-0.9509)	(-2.0740)
lnedu	0.0220	0.0211*	0.0225
	(0.9443)	(1.9269)	(1.2324)
human	0.4918	-0.0162	-0.0772
	(0.3682)	(-0.0105)	(-0.0595)
open	-0.0801**	-0.0845**	-0.0870**
	(-2.0340)	(-2.5696)	(-2.0820)
gov	-0.0021	0.0609	0.0666
	(-0.0180)	(1.4083)	(0.7752)
Constant	0.7352	2.3720	1.7144
	(0.3491)	(0.6641)	(0.8489)
Pro_FE Year_FE	YES YES	YES YES	YES YES
N	208	260	260
R2	0.990	0.989	0.989

Note: ***, *, and * indicate significance at the 1%, 5%, and 10% levels, respectively. t-statistics are in parentheses.

5.4 Heterogeneity Analysis

To explore whether the impact of energy transition differs across regions, further analyses are conducted by grouping provinces according to geographic location, urbanization level, and economic development level.

(1) Coastal vs. Inland Regions

Considerable differences exist between coastal and inland provinces in terms of industrial structure, energy use patterns, and economic development. The results reported in Columns (1) and (2) of Table 5 indicate that the inverted U-shaped relationship is statistically significant in coastal provinces, whereas no comparable relationship is observed in inland areas. One possible explanation is that energy transition has generally progressed further in coastal regions, where cleaner energy adoption and structural adjustment have advanced more rapidly. As a result, some coastal provinces may have already entered the stage in which the emission-reduction effects of energy transition become more evident.

(2) Urbanization Level

Provinces are divided into high- and low-urbanization groups based on the sample median of the urbanization rate. The results in Columns (5) and (6) show that the inverted U-shaped relationship is significant in highly urbanized regions but insignificant in regions with lower levels of urbanization. This pattern may be related to differences in environmental governance, infrastructure conditions, and the adoption of cleaner energy technologies. Compared with less urbanized areas, highly urbanized regions often face stronger environmental pressures and may therefore have greater incentives to promote low-carbon transformation.

(3) Economic Development Level

To further examine regional heterogeneity, provinces are grouped according to the sample median of GDP. The results indicate that the inverted U-shaped relationship is significant among provinces with relatively high levels of economic development, whereas the relationship is not statistically significant among less developed provinces. A possible reason is that economically developed regions generally possess stronger financial resources and technological capabilities, which facilitate the adjustment of energy structures and the diffusion of cleaner technologies. Consequently, energy transition in these regions may progress more rapidly relative to the growth of energy demand, making its emission-reduction effects more apparent.

Table 5: Heterogeneity Analysis Results

	(1)	(2)	(3)	(4)	(5)	(6)
	Coastal	Inland	High Urbanization	Low Urbanization	High GDP	Low GDP
VARIABLES	ZCO～ns	ZCO～ns	ZCO～ns	ZCO～ns	ZCO～ns	ZCO～ns
ZEnergyt～s	0.6561**	0.4028*	1.1113***	-0.0456	1.0801***	0.2145
	(2.3934)	(1.9447)	(5.4527)	(-0.2183)	(5.4810)	(0.6728)
ZEnerg～s2	-0.6012**	-0.2823	-1.0484***	0.1287	-1.0592***	-0.1892
	(-2.1812)	(-1.1857)	(-5.0359)	(0.4982)	(-5.1124)	(-0.4603)
lngdp	0.5010	-0.1130	0.4123	-0.9606***	-0.3949	-0.2945
	(1.3152)	(-0.4499)	(1.3344)	(-2.9546)	(-1.0383)	(-0.9082)
ind	-0.3568***	-0.4146***	-0.3522***	-0.6398***	-0.3437***	-0.1334
	(-3.8846)	(-4.7447)	(-3.7980)	(-4.4247)	(-3.7922)	(-1.1355)
urban	-0.0204	-1.8703*	-0.9898	-0.4595	-0.6856	2.1104
	(-0.0131)	(-1.9030)	(-0.8303)	(-0.2384)	(-0.5856)	(1.3328)
lnedu	0.0489	0.0148	0.0427*	0.0012	0.0047	0.0342
	(1.3790)	(0.6373)	(1.7842)	(0.0386)	(0.2385)	(1.2287)
human	0.2570	-0.6156	-2.5853	2.6877	-0.1940	1.0173
	(0.1465)	(-0.3505)	(-1.4778)	(1.4978)	(-0.1169)	(0.6423)
open	0.0078	-0.1006*	-0.1727*	-0.0861*	0.0992	-0.0690*
	(0.0998)	(-1.8708)	(-1.7059)	(-1.7716)	(0.7138)	(-1.7325)
gov	0.2459	-0.0011	0.1552	-0.3116**	-0.0225	0.2008*
	(1.5158)	(-0.0101)	(1.3979)	(-1.9995)	(-0.2330)	(1.7166)
Constant	-4.8629	2.6270	-3.4045	11.2108***	5.6330	1.7671
	(-1.2849)	(0.9655)	(-0.9534)	(3.3720)	(1.2589)	(0.5666)
Pro_FE	YES	YES	YES	YES	YES	YES
Year_FE	YES	YES	YES	YES	YES	YES
N	90	170	129	130	130	129
R2	0.997	0.974	0.989	0.994	0.992	0.995

*Note: ***, *, and * indicate significance at the 1%, 5%, and 10% levels, respectively. t-statistics are in parentheses. After grouping, fixed effects absorb single-region samples, resulting in one fewer observation in some groups.*

6. Research Conclusions and Policy Implications

Using panel data from 26 Chinese provinces between 2013 and 2022, this study examines the relationship between energy transition and carbon emissions from the perspectives of cleanliness, security, and efficiency. By constructing a multidimensional evaluation framework and measuring the degree of coordination among these dimensions, the analysis provides a broader view of how energy transition evolves and how it is associated with changes in regional carbon emissions.

Several observations emerge from the empirical results.

To begin with, energy transition does not proceed uniformly across different dimensions. Improvements in cleanliness and efficiency have generally been more visible over the sample period, while progress in the security dimension appears to have been slower in a number of provinces. Although the degree of coordination among the three subsystems has increased over time, regional differences remain noticeable and show no clear tendency toward convergence. Taken as a whole, however, the development of the three dimensions and their level of coordination both exhibit a gradual upward trend.

Another finding concerns the relationship between energy transition and carbon emissions. The results indicate an inverted U-shaped pattern rather than a simple linear relationship. In the earlier stages of transition, the expansion of energy demand may offset part of the environmental gains generated by structural adjustment, meaning that carbon emissions can continue to rise. As the transition deepens and cleaner energy sources account for a larger share of the energy mix, the emission-reduction effects become increasingly apparent, eventually contributing to a decline in emissions.

The analysis also points to substantial regional variation. The inverted U-shaped relationship is more evident in provinces with higher levels of economic development and urbanization, as well as in coastal regions. By contrast, similar effects are not observed in many less-developed or inland provinces. This suggests that the environmental benefits associated with energy transition may depend not only on the transition process itself but also on local economic conditions, infrastructure, and institutional capacity.

Several policy implications follow from these findings.

Rather than focusing solely on emission reduction targets, greater attention may need to be paid to the pace and quality of energy transition itself. Continued efforts to expand clean energy use, improve energy efficiency, and optimize energy structures remain important if the long-term emission-reduction benefits of transition are to be realized.

The results also highlight the importance of regional differentiation. Provinces that have already made substantial progress in energy transition may place greater emphasis on improving transition quality and strengthening technological innovation. In regions where transition remains at an earlier stage, more attention could be directed toward infrastructure construction, energy storage capacity, grid modernization, and the removal of institutional barriers that constrain structural adjustment.

Finally, the findings suggest that carbon reduction policies and energy transition policies are unlikely to be fully effective if pursued in isolation. The coordination among the clean, secure, and efficient dimensions of the energy system appears to matter as much as progress in any single dimension. Strengthening policy linkages between carbon neutrality goals, modern energy system development, and regional development strategies may therefore contribute to a more balanced and sustainable transition process.

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Conflicts of Interest

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