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Quantifying the energy trilemma in China and assessing its nexus with smart transportation

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Abstract

Purpose – Mitigating the energy trilemma (ET) is of great importance for dealing with climate change and realizing carbon neutrality. To this end, effectively assessing the level of the ET is essential. The purpose of this study is to evaluate the current situation and the spatio-temporal changes of the ET in the whole of China.

Design/methodology/approach – Moreover, based on provincial-level data in China for the period 2002–2017, and by using the dynamic estimation model, we aim to determine the specific marginal impacts of smart transportation (ST) on the ET, and the possible channels through which ST works on the ET.

Findings – We thus present the following findings: (1) The performance of both ET and its three pillars is gradually improving in China. Moreover, the situation tends to vary dramatically among various regions and provinces, and the gap between the best performers and the worst is large. (2) ST plays a significant role in inhibiting the ET, a finding that remains robust after a series of tests. And (3) the ET eradication effect of ST is caused mainly by improved innovation, advanced technical efficiency, and the increasing energy scale.

Originality/value – Accordingly, we put forward some policy recommendations to help tackle ET and accelerate ST in China.

Keywords China, Internal mechanisms, Energy trilemma, Smart transportation, Spatial-temporal analysis

Paper type Research paper

JEL classification – C33, O32, P28, Q43, R41

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Highlights

- Energy trilemma (ET) is assessed by balancing security, equity, and sustainability.
- We evaluate the spatiotemporal characteristics of the ET in Chinese provinces.
- We investigate the impact of smart transportation (ST) on the ET.
- ST significantly helps mitigate the ET.
- The indirect impact mechanisms are innovation, efficiency, and energy scale.

1. Introduction

Recently, concerns about climate change and energy decarbonization have become increasingly obvious in academic and political circles (Iacobuţ ă *et al.*, 2022; Luo *et al.*, 2021). To realize the goal of keeping temperature rises below 2°C, which was set at the Paris Agreement, a sustainable, sound, and affordable energy system is indispensable (Razmjoo *et al.*, 2022). The concept of energy trilemma (ET), first proposed by the World Energy Council (WEC), refers to the capacity to equilibrate the trade-offs among energy security, energy equity, and energy sustainability (World Energy Council, 2022). Despite the fact that China is listed among the top 10 improvers in terms of the ET, the situation of China's ET is not a cause for optimism. In 2022, China ranks 51st among 101 countries around the world, according to the WEC. On the other hand, China has declared that global efforts should be directed at realizing carbon emission peak before 2030 and carbon neutrality before 2060 (Xu *et al.*, 2022). To achieve this ambitious zero carbon goal, improving energy efficiency and decarbonization is necessary. At the same time, energy security and energy equity should be accelerated urgently (Šprajc *et al.*, 2019). Put differently, the three pillars of the ET are crucial for our future energy and low-carbon economy development (Fu *et al.*, 2021; Shah *et al.*, 2021; Valdes, 2021). To this end, a detailed analysis and assessment of the ET are paramount. Although numerous scholars and researchers in China have aimed to promote energy security and solve energy inequity (Alola, 2022; Heffron *et al.*, 2022; Tu *et al.*, 2021; Warren and Jack, 2018), studies on ways to reduce the ET from the perspective of smart transportation (ST) are still insufficient.

Supported by the application and implementation of advanced devices and technologies such as the Internet of Things, cloud computing, artificial intelligence, and 5 G, ST has been vigorously developed, and such development can be measured by a summary of performances across the core dimensions of transportation supply, consumption, service affordability, infrastructure, efficiency, and technology (Hsu *et al.*, 2015; Wang *et al.*, 2021; Zhang *et al.*, 2020; Zhao *et al.*, 2022). Due to the spillover effect of innovation and technology, these technologies may also help to promote the development of energy storage systems and improve the resilience of the energy system, which will then contribute to the mitigation of the ET (Peng *et al.*, 2019; Razmjoo *et al.*, 2022; Zhu *et al.*, 2022). On the other hand, the development of ST may be the key for dealing with the ET in that ST makes travel more convenient for people and shortens their commute time and costs. Moreover, ST offers a measure of optimism because it makes energy more accessible to people in remote areas. In this regard, the popularization of ST helps people in both urban and rural areas have better access to energy (Buys and Miller, 2011; Saleemi *et al.*, 2021). Therefore, ST is not only essential for reducing the cost of acquiring energy, but also enhancing its accessibility. Hence, ST plays a vital role in improving energy security and simultaneously reducing energy inequity.

In this context, how to effectively measure China's ET has become the top priority in this study. Some important questions have motivated our research:

RQ1. What is the current level of the ET in China?

RQ2. Have there been some spatial-temporal changes of the ET in the past decades?

RQ3. How can the three trilemma dimensions be balanced via ST? In other words, how does ST help tackle ET? and

RQ4. What are the possible internal impact channels in the ST-ET nexus?

To this end, based on a balanced panel dataset from 2002 to 2017 in China, this study first constructs a composite indicator system to evaluate the current level of the ET in the country. Then we analyze the temporal and spatial characteristics of China's ET in detail. Based on the characteristics, we further investigate the static and dynamic nexus between the ET and ST in Chinese provinces. In addition, we find three internal influence mechanisms between the above two crucial factors. Accordingly, the research framework is presented in Figure 1.

In this regard, this study contributes to the existing literature on the ST-ET nexus from the following three aspects. First, we are one of the first studies to quantify the level of the ET and its three pillars in China, and analyze the spatial and temporal characteristics of this index. Second, we detect the quantified impact of ST on the ET, which can inspire policymakers to promote the coordinated development of the transportation and energy system. Third, this study creatively checks three effective transmission mechanisms through which ST helps eradicate the ET, namely technological innovation, carbon efficiency, and total energy consumption. This can provide policymakers with the perspectives of innovation and efficiency when they consider measures to solve ET problems.

This paper is organized as follows: In Section 2 we review the relevant literature; in Section 3 we assess ET performance and its spatial-temporal changes; Section 4 introduces the methodology and data; and Section 5 presents the estimation results, detailed analysis, and robustness checks; we further discuss the mediation effects in Section 6, and conclude the paper in Section 7.

2. Literature review and research gap

2.1 Overview of definitions and measurements of the energy trilemma

Since the recent establishment of the Sustainable Development Goals (SDGs), increasing attention has been paid to the sustainable development of energy, and the definition and measurement of the ET. According to a report released by the WEC (World Energy Council, 2022), which has studied the ET since 2010 and published annual reports, three pillars constitute the ET index: energy security, energy equity, and environmental sustainability. Among them, energy security refers to the ability to meet current and future energy needs, withstand shock changes, and be able to recover quickly. This dimension covers the effectiveness of energy management and the reliability and flexibility of energy infrastructure (Al Asbahi *et al.*, 2019; Song *et al.*, 2017). The second dimension, energy equity, examines the ability to provide domestic residents and commercial operations abundant energy that is universally available and reasonably priced (McCauley, 2017). The WEC maintains that energy equity includes the basic use of electricity, clean cooking fuel, and advanced technology to harness and use energy. Energy equity also considers the affordability

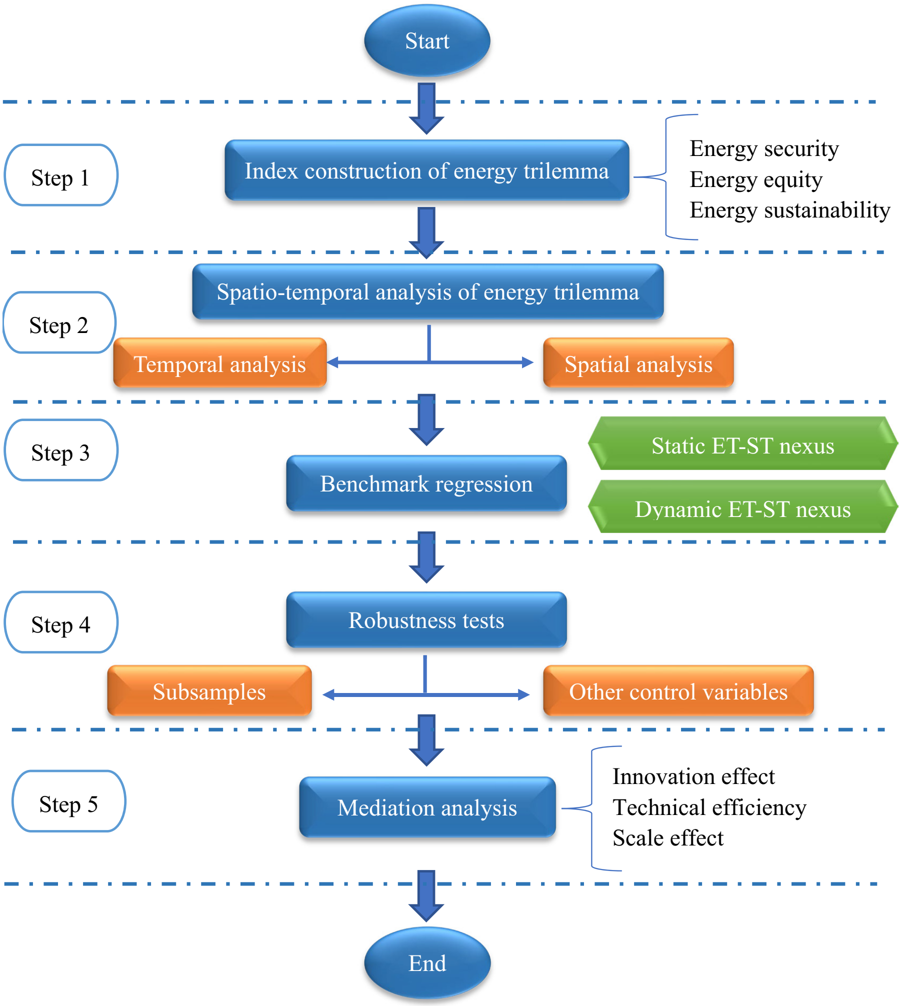


Figure 1.
Research framework

of electricity, natural gas, and fuel. The third dimension, environmental sustainability, represents the transformation of the energy system to mitigate potential environmental hazards and the impact of climate change (Wu and Sansavini, 2021). This third pillar stresses the efficiency and decarbonization of energy. Many scholars have adopted the evaluation system of the WEC on ET (Quitoras *et al.*, 2020; Weiss *et al.*, 2021; Zafeiratou and Spataru, 2018).

In addition to the ET index constructed by the WEC, many other scholars have proposed various measurements to assess the ET. For example, Kosai and Tan (2017) proposed that energy security, environment, and economy are three important dimensions when considering the ET. Their proposal has been supported by the studies of Xia *et al.* (2020). Heffron *et al.* (2015) viewed economics, energy law and policy politics, and the environment as indispensable factors to be considered in evaluating the ET. In contrast, Jing *et al.*'s (2021) study takes account of the role of cost, emissions, and resilience. Other studies shed light on the significance of mitigating climate change and energy poverty (Stempien and Chan, 2017).

2.2 Overview of the energy trilemma and socio-economic factors

A growing body of studies has pointed to the linkage between the ET and other socioeconomic factors. Specifically, Heffron *et al.* (2015) and Heffron *et al.* (2018) linked the ET to energy justice and believed that energy justice plays a significant role in balancing the three intertwined goals of the ET in five developed countries. Moreover, Kosai and Tan (2017) believed zero-energy buildings were in line with the concept of the ET, and had the potential to tackle this dilemma. So, they proposed specific measurements that were linked to the ET to assess zero-energy buildings' performance. Khan *et al.* (2021) detected both the short- and long-term effects of the ET on economic development using dynamic models, and demonstrated that the ET has a positive impact on energy growth only in the long run. Their results were consistent with Khan *et al.* (2022) and Marti and Puertas (2022). In addition, Gunningham (2013) took Indonesia as a case study and showed that the ET can be a crucial factor accounting for Indonesia's imperfect energy policy. Weiss *et al.* (2021) focused on the power markets and electricity markets in sample countries and found that policies aimed at solving the ET were also beneficial for the decarbonization of the Swiss energy market. Similar findings were made by La Viña *et al.* (2018), who studied the role of the ET in energy transition.

2.3 Overview of the energy-smart transportation nexus

Recently, many scholars have focused on the nexus between the ET and energy. For instance, Xie *et al.* (2020) presented a novel optimal intelligent transportation framework that included not only transportation, but also energy utilization and an urban distribution network that contributes to energy saving and is also essential for reducing energy loss by approximately 5.6%. Aujla *et al.* (2018) investigated an innovative charging station (CS) that can advance the ST system by improving travel conditions of electric vehicles (EVs) and thus help to improve energy efficiency. According to Chen *et al.* (2017), the increasing investment in the ST system is associated with increasing energy efficiency and decreasing carbon emissions. Peng *et al.* (2019) also suggested that the development of the ST system is beneficial for energy conservation. Their results reveal that the application of the newly designed ST networks is efficient for restraining energy demand and consumption. Hsu *et al.* (2015) emphasized the cloud-based service system and eco-driving, and mentioned that these advancements in the ST system play a significant role in reducing traditional fuel consumption. These advancements are also conducive to energy sustainability. These viewpoints have been confirmed by Saleemi *et al.* (2021). In addition, the findings from Ghaffarpasand *et al.* (2022), Qiu *et al.* (2022), Yang *et al.* (2020), and Zhao *et al.* (2022) have confirmed that ST is beneficial for the sustainable development of both the transportation and energy systems.

2.4 Literature gaps

Through the literature review of the above three Sections (i.e. Section 2.1–2.3), the definition and measurement of the ET given by the WEC are viewed as the benchmark. However, some other studies focusing on specific developing countries have argued that the standard and criteria of WEC are imperfect. Put differently, to date there has been no unified consensus on the measurement of the ET. In addition, to the best of our knowledge, although some researches have shed light on developing countries or taken a specific country as a case study, China has received scant attention to date. Few studies have explored the situation on China's ET, and it would be very significant to cover this gap. Moreover, in spite of some studies on the topic of the ET, energy transformation and economic development, there is still a lack of research on how to alleviate ET from the perspective of ST.

3. Quantifying the energy trilemma in China

In this section, we first proposed criteria for assessing the current situation of the ET in China (see Section 3.1); afterwards, based on the calculation of the ET, we analyzed the spatial and temporal situation of the ET for the period 2000–2019 in various Chinese provinces and regions (see Section 3.2).

3.1 Indicator system of the energy trilemma

We evaluate China's ET with regard to its ability to be diversified, accessible, affordable, and sustainable. To this end, we classified three dimensions of the ET as well as its specific indicators and measurements as follows:

(1) Energy security. The energy security dimension assesses energy supply security, which can be seen as the ability to provide energy consumption security; in other words, the ability to cater for residents' energy needs, and ensure the security and resilience of the energy system (Ahmadi *et al.*, 2021; Hasselqvist *et al.*, 2022; Zhang *et al.*, 2022). Among these three specific indicators, energy supply security is measured by natural gas supply and liquefied petroleum gas supply, which are two commonly used energies. Energy consumption includes people's demand for gasoline, kerosene, diesel oil, fuel oil, and electricity. To measure energy security, we consider the supply and consumption of various energy sources which can reflect the diversification of the energy system (De Rosa *et al.*, 2022; Gozgor and Paramati, 2022; Islam *et al.*, 2022). If a region relies only on traditional oil resources, once the oil market fluctuates, the national energy system will be dramatically shocked, which is not conducive to the stability of the energy system (Bao *et al.*, 2021; Heffron *et al.*, 2022; Hung and Vo, 2021). As for the third indicator, we consider not only the end consumers, but also the decentralized energy system. Accordingly, energy system security covers investments in energy fixed assets and the energy industry.

(2) Energy equity. Energy equity highlights rural energy investment and management, modernization of the energy consumption structure, and household energy facilities. The above three indicators reflect energy affordability, cleanness, and accessibility, respectively. Among them, rural energy investment and management are calculated through energy investment and energy management agencies for rural residents. In this specific indicator, we emphasize the role of rural energy development, which is an indispensable part of national energy strategies in many current studies (Han *et al.*, 2022; Wu and Han, 2022). A vital aspect of rural energy modernization is introducing household solar water heaters and household biogas digesters (Garcia *et al.*, 2019; Nuru *et al.*, 2022; Pizarro-Loaiza *et al.*, 2021). Rural energy issues deserve much attention because we need to ensure people in remote areas have reliable access to energy and that they can afford it. The energy price is reasonable, and energy management covers poor areas (Abbas *et al.*, 2022; Lan *et al.*, 2022; Sy and Mokaddem, 2022). Additionally, strategies on how to respond to supply and price shocks is particularly important, as is the ability to comprehensively harness local energy resources. With respect to the third perspective, household energy facilities are measured by

ownership of microwave ovens, air-conditions, refrigerators, and hot-water heaters per hundred urban households. Utilization of these energy facilities can reflect that energy is reasonably priced, and is appropriately distributed and stored.

(3) Energy sustainability. Energy sustainability performance is measured by taking together energy efficiency, energy intensity, and air pollution caused by residential energy use. The key to improving energy efficiency lies in efficient energy consumption and efficient carbon emissions, which can be viewed as the degree of decarbonization (Grubert and Zacarias, 2022; Plazas-Niño *et al.*, 2022; Vatalis *et al.*, 2022). Similarly, the second indicator, energy intensity, is gauged by energy consumption intensity and carbon emission intensity. In addition, to realize energy suitability, we need to mitigate climate change and harness energy pollution. Therefore, sulfur dioxide, nitrogen oxide, and smoke and dust emission are used to measure air pollution caused by energy utilization. Zero-carbon technologies as well as carbon-intensive removal technologies have been developed in recent decades, and energy sustainability requires us to deliver both reliable and sustainable quality energy (Chen *et al.*, 2022; Darkwa and O'Callaghan, 1997; Hasanbeigi *and Price*, 2015).

By summarizing the measurements of the ET in the current literature and combining the specific situation in China, we present a complicated, elaborate, and sophisticated ET index system comprising three pillars to assess China's ET performance. This novel ET index system applies more to China's situation than other countries in that we consider primary energy consumption, disparities between rural and urban energy utilization, and specific pollution caused by primary energy use. By comparison, the index calculated by the WEC is more appropriate for developed countries, and thus the indicator system we propose is more comprehensive and specific. We accessed the necessary data for calculating the level of the ET from the following data sources: China Statistical Yearbook (CSY, 2020); China Energy Statistical Yearbook (CESY, 2020); China City Statistical Yearbook (CCSY, 2020); China Agricultural Statistics Report (CASR, 2020); and China Emission Accounts and Datasets (CEAD, 2020). Accordingly, we have creatively proposed an indicator system that consists of three dimensions, nine indicators, and 24 measurements, as shown in Table 1.

3.2 Spatio-temporal analysis of energy trilemma

Having identified the measurements for assessing China's ET situation, we then perform a detailed spatial analysis as well as a temporal analysis to clarify the specific changing patterns and regional imbalance of China's ET. We calculate the score of the ET via the entropy weight method, and the results are employed to plot Figure 2, which exhibits China's ET performance and its three sub-indexes for the period 2000–2019. The downward trends of the ET and its three sub-indexes in China presented in Figure 2 show that the levels of our energy security, energy equity, and energy sustainability are improving, which may due to our recent efforts. To be more specific, many state-owned energy institutions have invested a lot in clean energy, such as large-scale wind and solar capacity, which benefits energy sustainability. Green hydrogen, a kind of low-carbon technology, has also gained attention from state-owned energy institutions. Moreover, research and development (R&D) in the grid system has guaranteed resilient and stable electricity for the remote areas in the southeast. Our energy security and energy equity are thus dramatically promoted.

From Figure 3 we can see that Ningxia, Shanxi, and Inner Mongolia, which lie in the backward and remote northwest, are the three provinces with the highest level of the ET. By comparison, Beijing, Tianjin, and Shanghai show the lowest level of the ET. Figure 3 shows the time-trend chart of China's ET for the full sample and the three regions. Similarly, the eastern areas perform better than the western regions, which is also obvious in Figure 4,

Table 1. Indicator system for measuring china's integrated ET index

Indicator dimension	Specific indicators	Indicator measurement	Indicator property	Data source
Energy security	Energy supply security (Capability)	Per capita natural gas supply in cities	Negative	China City Statistical Yearbook (CCSY, 2020)
		Per capita liquefied petroleum gas supply in cities	Negative	
	Energy consumption security (Dependency)	Per capita gasoline consumption	Negative	
		Per capita kerosene consumption	Negative	
		Per capita diesel oil consumption	Negative	
		Per capita fuel oil consumption	Negative	
		Per capita electricity consumption	Negative	
	Energy system security (Resilience)	Fixed asset investment in state-owned economy and energy industry per unit of GDP	Negative	
		Per capita investment in energy industry	Negative	
Energy equity	Rural energy investment and management (Affordability)	Per capita energy investment for rural residents	Negative	China Agricultural Statistics Report (CASR, 2020)
		Number of rural energy management agencies per million people	Negative	
	Modernization of energy consumption structure (Cleanness)	Number of rural household biogas digesters	Negative	
		Number of household solar water heaters	Negative	
	Household energy facilities (Accessibility)	Ownership of microwave oven per hundred urban households	Negative	China Statistical Yearbook (CSY, 2020)
		Ownership of refrigerator per hundred urban households	Negative	
		Ownership of air-conditioner per hundred urban households	Negative	
		Ownership of hot water heater per hundred urban households	Negative	
Energy sustainability	Energy efficiency (Decarbonization)	Energy consumption efficiency	Negative	China Energy Statistical Yearbook (CESY, 2020)
		Carbon emissions efficiency	Negative	China Emission Accounts and Datasets (CEAD, 2020)
	Energy intensity (Productivity)	Energy consumption intensity	Positive	China Energy Statistical Yearbook (CESY, 2020)
		Carbon emissions intensity	Positive	China Emission Accounts and Datasets (CEAD, 2020)
	Air pollution caused by residential energy use	Per capita sulfur dioxide in waste gas from residential sector	Positive	China City Statistical Yearbook (CCSY, 2020)
		Per capita nitrogen oxide in waste gas from residential sector	Positive	
		Per capita smoke and dust emission in waste gas from residential sector	Positive	

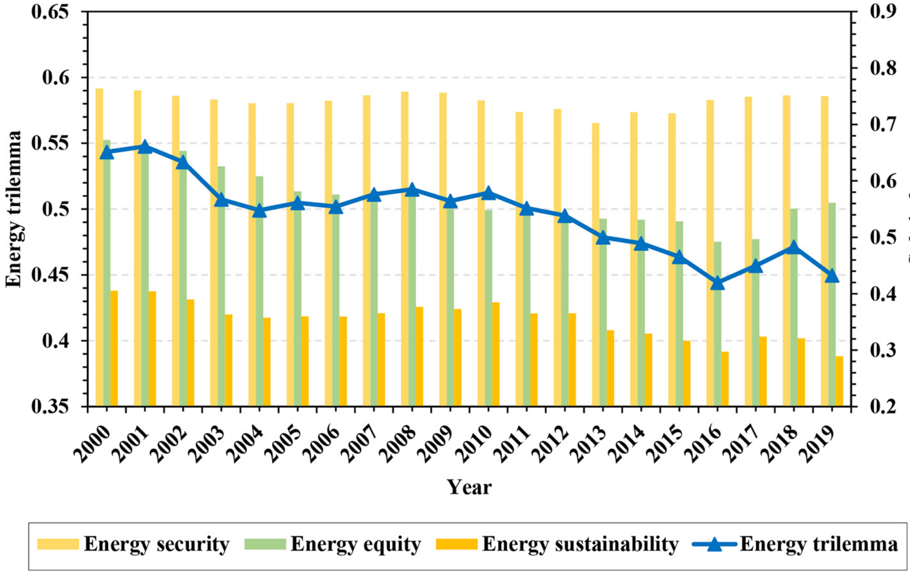
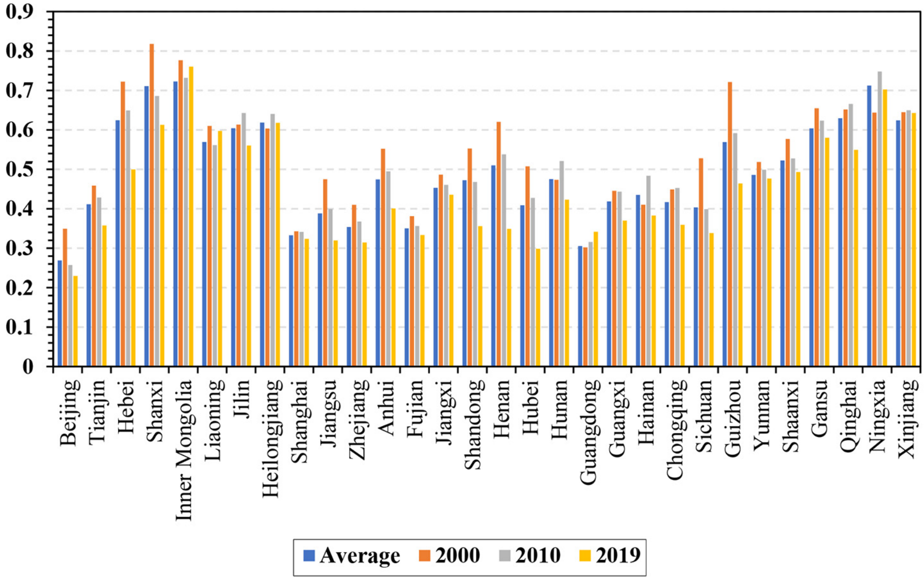
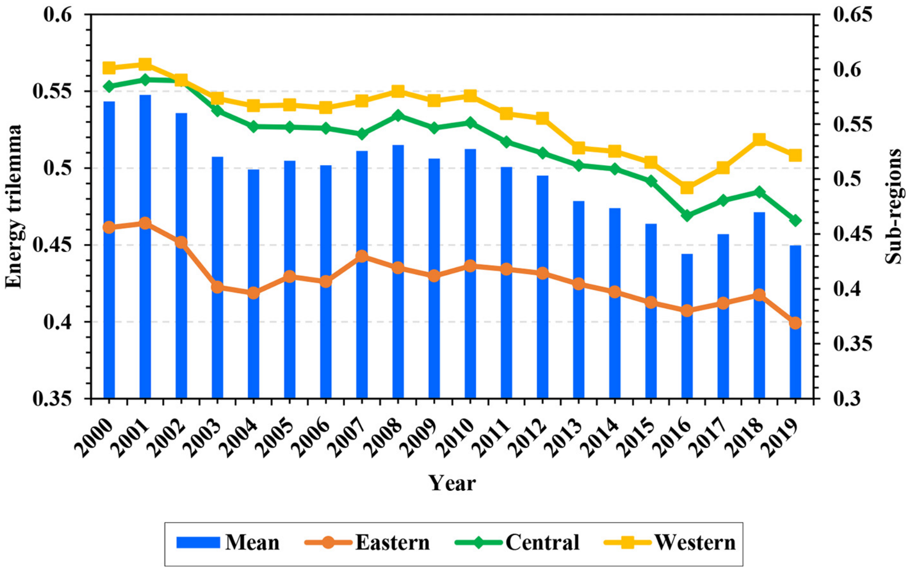


Figure 2.
Time-trend chart of the ET and its three sub-indexes in China for the period 2000–2019

which presents the distribution maps of China's ET in 2002, 2007, 2012, and 2017. The above four time points are chosen in this paper because 2002 marks the beginning of this study and 2017 is the last period. To show the specific changes of the ET during our total study period, we add two time periods in the middle (i.e. 2007 and 2012). Thus, the four years shown here constitute an arithmetic progression every five years. On the one hand, the eastern coastal areas own comparatively more developed technology and human resources, and have a higher economic level. These advantages enable the eastern areas to be the top performers and achieve a balanced score in the three dimensions of the ET. To be more specific, provinces in the east have more established, resilient, and sophisticated energy systems and energy infrastructure. Moreover, they have invested many advanced technologies in energy diversification and energy decarbonization. The governments in cities such as Beijing and Shanghai pay more attention to the energy system and production diversification and decarbonization. At the same time, they try their best to minimize negative environmental impacts by consuming ultra-low-emission energy resources and infrastructure. These regions are also economically stable and have the highest capacity to diversify energy resources. In this regard, the eastern provinces have been successful in providing reliable, affordable, and environmentally sensitive sources of energy.

On the other hand, the situation of the ET in northwest China, especially Inner Mongolia and Shaanxi province, is not good. These areas may have the so-called resource curse: they are rich in energy resources, but due to their excessive reliance on existing resources for economic development, the slow upgrading of industrial structure and the development of the manufacturing and mining industry, they consume a lot of energy, resulting in serious environmental pollution. Coupled with the poor level of infrastructure, these areas eventually have a relatively high level of the ET. It is possible that those western regions should develop more renewable energy sources such as wind and solar energy because low-carbon and diversified sources of energy will help to improve environmental sustainability and energy security.





Notes: The graph above exhibits the average level of ET in each province in 2000, 2010, and 2019, respectively. While the graph below shows the time-trend chart of average ET in the whole China as well as the eastern, central, and western regions

Figure 3.
Spatial and temporal of the ET in China's provinces and regions

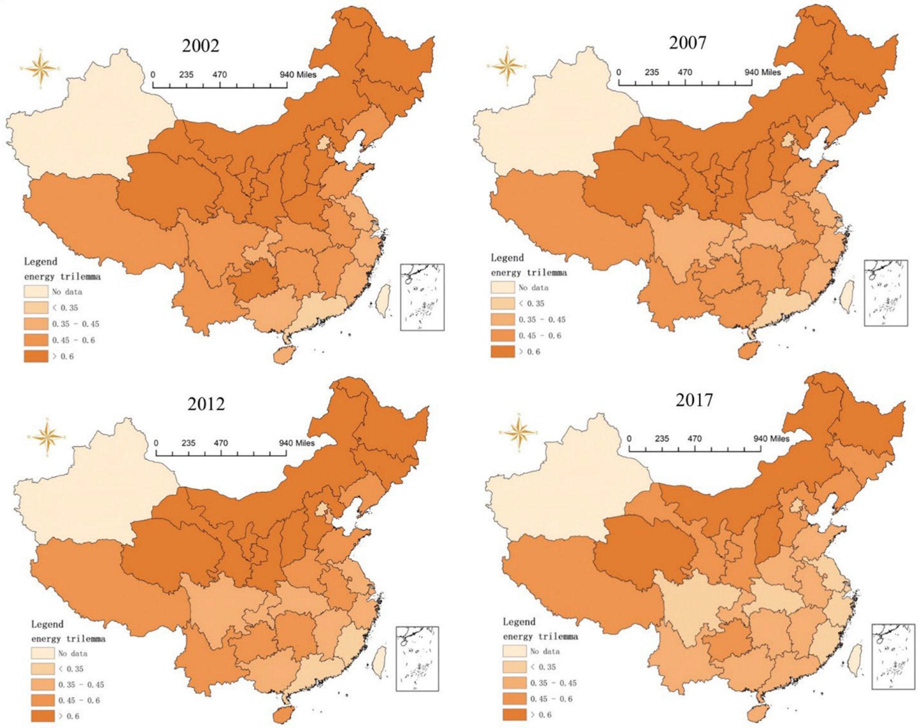


Figure 4.
Spatial distribution of China's ET for selected years

To summarize the above, the analysis we perform is based on three dimensions, nine indicators, and 24 measurements. Moreover, by further analyzing the results through derived spatial and temporal characteristics, we find that significant differences exist not only in China's various regions, but also over the past years. Therefore, the government should persevere in its commitment to continue strong environmental regulation and maintain energy environmental sustainability.

4. Methodology and data

4.1 Econometric model

To investigate the impact of ST on the ET in China, we adopt a multivariate methodology based on the experience of previous researches. The specific multivariate equation can be expressed as follows:

$$ET_{it} = f(ST_{it}, Pgdp_{it}, Ser_{it}, ECE_{it}, Fin_{it}) \quad (1)$$

This study considers five independent variables, among which ST_{it} is our core independent variable, which indicates the level of smart transportation in China. Moreover, we consider the control variables from the aspects of economy, industry structure, energy consumption, and government regulation. Specifically, $Pgdp_{it}$ stands for overall economic growth, Ser_{it} indicates the ratio of tertiary output to total output, ECE_{it} refers to energy consumption efficiency, and Fin_{it} means government financial expenditure. In addition, energy trilemma (denoted as ET_{it}) is our dependent variable. The subscript i and t are cross-section unit and time unit, respectively. We then use the natural logarithm of these variables in that the natural logarithm form is useful for tracking data volatility and the potential heteroscedasticity problem. Thus, the above equation can be rewritten as follows:

$$\ln ET_{\mathrm{it}} = \beta_0 + \beta_1 \ln ST_{it} + \beta_2 \ln Pgdp_{it} + \beta_3 \ln Ser_{it} + \beta_4 \ln ECE_{it} + \beta_5 \ln Fin_{it} + \pi_i + \mu_t + \varepsilon_{it} \tag{2}$$

where all variables are explained as the last equation, $\beta_0 - \beta_5$ are the parameters to be estimated and $\beta_1 - \beta_5$ reflects the marginal effect of the independent variables on the dependent variables (i.e. ET_{it}). Moreover, β_1 is expected to be negative. We also take the individual fixed effect (denoted as π_i) and the time fixed effect (denoted as μ_t) into consideration. Moreover, the independent and identically distributed error term is ε_{it}.

In addition to the static estimation, we believe a dynamic nexus between ST and the ET may also exist because energy utilization and energy distribution are difficult to change in the short term, and thus the ET may have the attribute of hysteresis. In other words, the situation of the ET in the last term has an influence on the ET in this term. In this regard, the estimation results of ordinary least squares (OLS) may be incorrect and inaccurate. Therefore, by referring to Arellano and Bond (1991) and Arellano and Bover (1995), we further utilize the differential-generalized method of moments (DIF-GMM) method and the system-generalized method of moments (SYS-GMM) method. The above two dynamic estimation methods are widely applied in the current literature and deal scientifically with potential endogeneity problems caused by the dynamic panel data model (Blundell and Bond, 1998). In the dynamic estimation approaches, the lagged term of the dependent variables is adopted as instrumental variables. Accordingly, the dynamic estimation equation in our paper can be written as follows:

$$\ln ET_{\mathrm{it}} = \beta_0 + \beta_1 \ln ET_{i,t-1} + \beta_2 \ln ST_{it} + \beta_3 \ln Pgdp_{it} + \beta_4 \ln Ser_{it} + \beta_5 \ln ECE_{it} + \beta_6 \ln Fin_{it} + \pi_i + \mu_t + \varepsilon_{it} \tag{3}$$

Where we add $ST_{i,t-1}$ as the lagged term of ST_{it} according to the requirements of the dynamic econometric model. The explanation of the other variables is the same as equation (2). $\beta_0 - \beta_6$ are the parameters to be estimated, and β_2 is also expected to be negative. Moreover, we prefer the SYS-GMM method because its results are more inconsistent and efficient when the cross-section units are large (Dong *et al.*, 2022).

4.2 Variables and data

Our essential dependent variable (i.e. ET) data is obtained through the calculation process elaborated in Section 3. Moreover, although ST has been studied for several years, research on quantifying ST is still insufficient, especially for the case of China. In this regard, we acquire the data on ST by referring to the work of Zhao *et al.* (2022), who measured the level of ST in China by constructing a comprehensive index system covering six aspects of ST. We employ four control variables, namely gross domestic product per capita, industry structure measured by the proportion of tertiary output to total output, energy consumption efficiency indicating the energy utilization rate, and government financial expenditure showing the degree of government support for social development. The China Statistical Yearbook (CSY, 2021) provides data for these control variables.

This study uses a provincial panel database in China for the period 2002–2017 to investigate the impact of ST on the ET. Notably, the data in Hong Kong, Macao, Taiwan, and Tibet are excluded in our sample. Table 2 shows the descriptive statistics of the independent, dependent, and other variables.

5. Estimation results and analysis

In this section, we technically estimated the impact of ST on the ET via static estimation models and dynamic estimation models, respectively (see Section 5.1). Afterwards, we also conducted robustness checks to further verify our baseline regression results (see Section 5.2).

5.1 Baseline regression results

To empirically investigate the impact of ST on the ET, we conduct static and dynamic econometric approaches simultaneously; the corresponding results are shown in Table 3. As shown in the statistics of Table 3, the coefficients of our core independent variable (i.e. ST) are all significant at the 1% significance level, irrespective of static or dynamic estimation methods. In other words, ST has an effective impact on ET eradication. In addition, DIF-GMM and SYS-GMM need two tests: the Arellano-Bond test and the Sargan test. The results of AR (1) are both significant in two dynamic estimation approaches, while the results of AR (3) and Sargan are both insignificant, meaning they pass the preliminary conditions of the dynamic models (Che *et al.*, 2013; Roodman, 2009). As the first three columns indicate, an increase of ST by 1% can reduce the ET by more than 0.10%. In comparison, the marginal effect of ST on the ET is much smaller when using the dynamic estimation model, which suggests that the results estimated by the DIF-GMM and SYS-GMM models are more accurate and appropriate. From the results in the last column, we can see that an increase of ST by 1% can reduce the ET by approximately 0.0683%, which implies that developing China's ST will effectively accelerate the process of ET elimination. Schorn *et al.* (2021) and Guo *et al.* (2021) have also confirmed our primary findings. As an intensive transportation mode, ST is essential for breaking the extensive energy-based vicious circle of development by replacing more efficient energy utilization with traditional low-efficiency energy utilization. In this regard, ST contributes greatly to the upgrading of the transportation sector towards a more energy-intensive mode (Baygin *et al.*, 2022; Shi *et al.*, 2021a, 2021b). In addition, with the popularization and development of smart public transportation, energy saving can be achieved when users change their daily travel behavior. More importantly, massive transportation technologies enable ST system improvement. To be more specific, Ad-hoc NETworks (VANETs) are useful for dealing with abrupt urban transportation

Table 2.
Descriptive statistics of the variables (after the logarithm)

Variable	Mean	SD	Min.	Median	Max.
lnET	−0.7405	0.2719	−1.4209	−0.7274	−0.1547
lnST	−1.4681	0.4727	−2.6835	−1.4981	−0.2127
lnPgdp	10.1096	0.7444	8.0886	10.2275	11.8321
lnSer	−2.3450	0.7793	−4.8003	−2.2762	−0.4603
lnECE	−0.0681	0.5682	−1.5157	−0.0553	1.4389
lnFin	7.4382	1.0131	4.5246	7.5359	9.6183

Notes: Mean refers to the average value of the variables, Std. Dev. represents standard deviation, Min, Median, and Max indicate the minimum, median, and maximum values of the variables, respectively

Table 3. Baseline regression results of the ST-ET nexus

Variable	OLS	RE	FE	FGLS	DIF-GMM	SYS-GMM
$lnET_{i,t-1}$					0.4540*** (18.4294)	0.6875*** (35.9706)
$lnST$	−0.1881*** (−11.8197)	−0.1529*** (−6.7770)	−0.1063*** (−4.3451)	−0.0499*** (−5.4659)	−0.0637*** (−4.4242)	−0.0683*** (−7.0682)
$lnPgdp$	0.0409*** (2.6409)	−0.1085*** (−3.5471)	−0.1846*** (−4.9474)	−0.0417*** (−2.7838)	0.1285*** (8.0827)	0.1284*** (9.2847)
$lnSer$	0.0511*** (5.1497)	−0.0078 (−0.5594)	−0.0319** (−2.1689)	0.0573*** (9.3476)	−0.0643*** (−6.3958)	0.0098 (0.9561)
$lnECE$	−0.4524*** (−30.6267)	−0.2278*** (−9.8138)	−0.1601*** (−6.4838)	−0.3947*** (−35.7678)	−0.2012*** (−17.9808)	−0.2684*** (−21.2283)
$lnFin$	0.1120*** (11.6378)	0.1240*** (6.3280)	0.1473*** (6.1474)	0.0899*** (9.6759)	−0.0267*** (−2.7316)	0.0139** (2.2292)
$Constant$	−2.1741*** (−18.4632)	−0.8243*** (−4.3618)	−0.2112 (−0.9381)	−0.8676*** (−7.3836)	−1.7696*** (−18.8934)	−1.7404*** (−19.0360)
$AR(1)$					0.0001	0.0001
$AR(2)$					0.0062	0.0152
$AR(3)$					0.1322	0.3967
$Sargan$					0.3184	0.8918

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively; the values in parentheses represent t statistics

issues around traffic congestion and vehicle parking, while Global Positioning Systems (GPSs) play an important role in accelerating efficient transport mobility (Aloqaily *et al.*, 2022; Wang *et al.*, 2020; Zia, 2021). Thanks to those transport technologies, transportation efficiency is promoted, less energy is required for transportation, and thus the ET is relieved. Due to the technology spillover effects, the above advanced technologies may also be helpful for developing the energy sector, and further contribute to the mitigation of the ET (Li *et al.*, 2022; Nti *et al.*, 2022; Wang *et al.*, 2022; Zheng *et al.*, 2022).

Regarding the control variables, in addition to GDP per capita, all other control variables have a significant negative impact on the ET, and their coefficients are also significant at the 1% significant level. In this regard, industrial structure upgrading, energy consumption efficiency, and government fiscal support all have the potential to restrain ET. The financial support provided by the government improves residents' purchasing power and gives them the opportunity to obtain cleaner, more modern energy equipment. Moreover, upgrading the industrial structure enhances the allocation of resources, especially energy resources. In addition, the development of tertiary industry will also contribute to the optimization of current resources, technology, and human resources, which is beneficial for ET mitigation (Dong *et al.*, 2022; Zhang *et al.*, 2020).

5.2 Robustness checks

To check the credibility and reliability of the above baseline results, we further conduct three kinds of robustness checks. The first uses the same variables while shortening the years of the sample period; the second is changing other control variables, and the third is using the Instrumental Variables (IV) method. Since the development of ST relies on artificial intelligence and other advanced technologies, it is a new type of transportation that has only emerged in recent years; thus, we only keep the data for the period 2006–2017, which can better reflect the impact of advanced ST on the ET. In addition, for the second robustness check, we change GDP per capita into total GDP, the ratio of tertiary industry output to total industry output and the ratio of secondary industry output to total industry output. We also remove government fiscal expenditure, and then add urbanization evolution. These new variables can also be effectively control variables in the nexus between ST and the ET. Moreover, although we have considered control variables from the aspects of economy, industry, energy, and social inequity, there may still be omitted variables, such as trade openness. To tackle potential endogeneity caused by omitted variable bias, we further adopt the IV method as a robustness check. The corresponding results are presented in Table 4, 5, and 6, respectively.

From Table 4 we can see that the coefficients and significance of all the variables remain consistent with the baseline regression. In particular, the marginal impact of ST on the ET has barely changed, suggesting that the results of the baseline regression are robust, despite some time excerpts. In Table 5, ST remains significant at the 1% significance level in both the static and dynamic models, which once again verifies that ST exerts a curbing effect on the ET. In addition, the impact of GDP on ET is basically positive, indicating that China's current economic development still depends on energy consumption. And the coefficient of industrial structure and urbanization is also positive. This is because manufactures need to consume a lot of energy during their production processes. Urbanization intensifies residents' energy consumption, increases energy inequity in rural areas, and causes more energy unsustainability. In sum, the results of the above two robustness checks correspond with our primary findings.

We further employ two IV methods, namely the instrumental variable- generalized method of moment (IV-GMM) approach, and the Lewbel two-stage least squares (2SLS) estimation approach, which have also been adopted in recent studies (Mishra and Smyth, 2015; Saha *et al.*, 2021). As for the former, the IV-GMM is important in this paper because it

Table 4. Robustness tests using subsamples

Variable	OLS	RE	FE	FGLS	DIF-GMM	SYS-GMM
$lnET_{i,t-1}$					0.3253*** (7.4015)	0.7512*** (37.6958)
lnST	−0.1597*** (−7.5567)	−0.1619*** (−5.9070)	−0.1089*** (−3.6223)	−0.1669*** (−7.4742)	−0.0086 (−0.4389)	−0.0224* (−1.8711)
lnPgdp	0.0453** (2.2659)	−0.1070*** (−2.9670)	−0.2115*** (−4.6606)	−0.0344 (−1.0244)	0.0294 (1.1534)	0.0959*** (6.5661)
lnSer	0.0487*** (4.3199)	−0.0196 (−1.2869)	−0.0418** (−2.5584)	0.0151 (1.0805)	−0.0933*** (−5.4938)	0.0008 (0.0971)
lnECE	−0.4381*** (−25.6392)	−0.2134*** (−7.4265)	−0.1156*** (−3.5544)	−0.3466*** (−11.6406)	−0.1386*** (−9.0634)	−0.1898*** (−25.2269)
lnFin	0.0869*** (6.4383)	0.0966*** (4.4483)	0.1205*** (4.6678)	0.0496*** (2.6113)	−0.0189 (−1.1804)	−0.0066 (−0.7539)
Constant	−1.9813*** (−9.7975)	−0.6596** (−2.4694)	0.2548 (0.7708)	−0.9416*** (−3.1790)	−0.8885*** (−5.7202)	−1.1570*** (−13.4736)

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively; the values in parentheses represent t statistics

Table 5.
Robustness tests using other variables

Variable	OLS	RE	FE	FGLS	DIF-GMM	SYS-GMM
$lnET_{i,t-1}$					0.4202*** (20.3421)	0.7226*** (37.2168)
$lnST$	−0.2892*** (−14.9796)	−0.1673*** (−7.1631)	−0.1153*** (−4.5811)	−0.0673*** (−7.4554)	−0.0553*** (−4.5091)	−0.1253*** (−11.1464)
$lnGDP$	0.2088*** (12.1890)	0.0962*** (3.9195)	0.0379 (1.3016)	−0.0161* (−1.7141)	0.0008 (0.0653)	0.1413*** (13.0238)
$lnInd$	−0.0655*** (−5.4050)	−0.0147 (−0.8093)	0.0143 (0.6967)	0.0104* (1.7860)	0.0757*** (7.5483)	−0.0388*** (−5.0023)
$lnECE$	−0.4442*** (−28.5203)	−0.2471*** (−10.4642)	−0.2057*** (−7.7936)	−0.2265*** (−17.5871)	−0.2279*** (−18.5052)	−0.2074*** (−26.2259)
$lnUrban$	0.0674*** (3.8627)	−0.0217 (−1.0154)	−0.0188 (−0.8232)	0.0642*** (5.0355)	0.0457*** (4.5194)	0.0906*** (8.3999)
Constant	−2.4648*** (−21.4987)	−1.6955*** (−12.8199)	−1.3987*** (−9.6203)	−0.7855*** (−14.4157)	−1.3908*** (−29.3907)	−1.3820*** (−22.0351)

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively; the values in parentheses represent *t* statistics is robust to autocorrelation and delivers consistent and efficient results in the presence of unknown heteroscedasticity (Acheampong *et al.*, 2021). In terms of the latter, the Lewbel 2SLS estimator is essential for identifying structural parameters in the regression models with endogenous or mismeasured regressors in the absence of traditional identifying information (Lewbel, 2012). The corresponding results are listed in Table 6. From the results in the first column, on the one hand, the probability value of the Kleibergen-Paap Lagrange Multiplier test shows that the instrument is not under identification; on the other hand, the Cragg-Donald and Kleibergen-Paap Wald F statistics tell us that the instruments are not weak. Therefore, the above two IV methods are appropriate and feasible. The coefficients of ST are both negative and significant, implying that our baseline results are robust.

6. Mediation effect analysis

6.1 Model specification

Having found that ST plays a significant role in inhibiting the ET, we then wonder what the possible influence mechanisms are in the ST-ET nexus. To this end, we employ the mediation effect model for further empirical analysis. Based on the current literature covering the topics of the ET and ST, we reckon that innovation, technical efficiency, as well as total energy consumption may be crucial factors influencing the nexus between ST and the ET. Accordingly, the specific mediation estimation equations are as follows:

$$\begin{cases} \ln Innovation_{it} = \alpha_1 + \delta_1 \ln ST_{it} + Controls_{it} + \varepsilon_{it} \\ \ln ET_{2it} = \beta_1 + \gamma_1 \ln ST_{it} + \theta_1 \ln Innovation_{it} + Controls_{it} + \varepsilon_{it} \end{cases} \tag{4}$$

$$\begin{cases} \ln Efficiency_{it} = \alpha_2 + \delta_2 \ln ST_{it} + Controls_{it} + \varepsilon_{it} \\ \ln ET_{2it} = \beta_2 + \gamma_2 \ln ST_{it} + \theta_2 \ln Efficiency_{it} + Controls_{it} + \varepsilon_{it} \end{cases} \tag{5}$$

$$\begin{cases} \ln Scale_{it} = \alpha_3 + \delta_3 \ln ST_{it} + Controls_{it} + \varepsilon_{it} \\ \ln ET_{2it} = \beta_3 + \gamma_3 \ln ST_{it} + \theta_3 \ln Scale_{it} + Controls_{it} + \varepsilon_{it} \end{cases} \tag{6}$$

where *Innovation*, *Efficiency*, and *Scale* are three mediating variables. δ_1, δ_2, and δ_3 capture the impact of ST on them, while θ_1, θ_1, and θ_3 capture the impact of the mediating variables

Variable	IV-GMM	Lewbel two-stage least square
lnST	−0.2103*** (0.0175)	−0.1881*** (−6.7770)
lnPgdp	0.0524*** (0.0163)	0.0409*** (−3.5471)
lnSer	0.0473*** (0.0092)	0.0511 (−0.5594)
lnECE	−0.4549*** (0.01333)	−0.4524*** (−9.8138)
lnFin	0.1199*** (0.0110)	0.1120*** (6.3280)
Constant	−2.3980*** (0.1256)	−2.1741*** (−4.3618)
KP LM (*P value*)	0.0000	
CD Wald F	4738.073	
KP Wald F	4115.204	

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively; the values in parentheses represent heteroscedasticity robust standard errors statistics

Table 6. Robustness tests using other methods

on the ET. Specifically, *Innovation* is calculated by domestic patent application authorizations, *Efficiency* is measured by carbon emissions efficiency, and *Scale* is gauged by the total volume of energy consumption. The empirical results of the mediating effect model by estimating eqs. (4) – (6) are presented in Table 7. Additionally, the corresponding visual result is presented in Figure 5.

6.2 Mediation model results

According to Table 7, notably all coefficients of ST and the mediating variables are significant, indicating that our argument about the channels through which ST affects the ET is correct. Put differently, innovation, technical efficiency, and energy consumption affect the ET eradication effect of ST. Specifically, regarding the innovation effect, an increase of 1% in ST leads to an increase of approximately 1.17% in innovation, and then an increase in innovation by 1% is linked to a reduction of the ET by about 0.18%. Strengthening scientific and technological innovation, especially in the field of energy, can reduce people's dependence on traditional energy such as oil and coal, and improve the exploitation and utilization rate of renewable energy and clean energy. Technological innovation in the power grid helps to improve the power generation efficiency of hydropower, solar energy, and wind energy. Due to the spillover effect of science and technology, scientific and technological research and development in the field of transportation also helps drive the development of science and technology in the field of energy. Furthermore, improved innovation can accelerate the aging of sunset industries and promote the rise of emerging industries such as intelligent transportation, which then drive the transformation and upgrading of traditional labor-intensive industries. Based on the development of ST, capital-intensive and technological-intensive industries will become the mainstream (Liu *et al.*, 2021; Shi *et al.*, 2021a, 2021b; Zailani *et al.*, 2014).

When it comes to the technical efficiency effect, for a 1% increase in ST will enhance efficiency by 0.66%. Afterwards, every addition of efficiency results in a decrease of around 0.28% in the ET. Improving energy efficiency can reduce energy consumption and promote high-quality economic and energy development. Improved energy efficiency is particularly important for the development of rural areas. China is a typical agricultural country, and the role of rural energy consumption cannot be ignored. In this regard, improved efficiency will promote the use of clean energy in the rural areas, which will contribute to an increase of energy equity and energy sustainability (Hassan *et al.*, 2022).

Results in the last three columns in Table 7 verify that an energy scale effect also exists. Specifically, with the development of ST, total energy consumption will be greatly enhanced, which will then also contribute to the deterioration of the ET. An increase in ST by 1% can trigger scale effect to increase by 0.40%, and then an increase of energy scale effect by 1% will result in a 0.34% increase in the ET. To be more specific, although ST is essential for strengthening energy security and energy equity, at the same time the development of ST is essentially the continuous expansion of transportation scale, and will inevitably consume more energy. The rise of total energy demand may also bring instability to the energy system and cause certain environmental pollution, which is not conducive to the sustainable development of energy and will aggravate the ET (Yin *et al.*, 2015; Zhang *et al.*, 2015).

7. Conclusions and policy implications

Through the analysis of China's provincial data for the period 2002–2017, we empirically explore the ST-ET nexus. To this end, we first gauge an intricate indicator system of the ET by balancing the trade-off among energy security, equity, and sustainability, and then

Table 7. Estimation results of the internal impact mechanisms between ST and the ET

	Explained variables: lnET in (1), (3), (4), (6), (7), and (9); while lnInno, lnEff, and lnEC in (2), (5), and (8) respectively								
		Innovation effect			Efficiency effect			Scale effect	
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
lnST	−0.3307*** (−12.6076)	1.1670*** (15.7972)	−0.1238*** (−4.4046)	−0.3307*** (−12.6076)	0.6553*** (8.6136)	−0.1492*** (−8.8723)	−0.3307*** (−12.6076)	0.4009*** (8.9887)	−0.4672*** (−20.1677)
lnInno			−0.1773*** (−12.5511)						
lnEff						−0.2769*** (−29.3540)			
lnEC									0.3404*** (15.4503)
lnPgdp	−0.1596*** (−6.6041)	−0.0099 (−0.1451)	−0.1614*** (−7.6982)	−0.1596*** (−6.6041)	0.5315*** (7.5810)	−0.0125 (−0.8157)	−0.1596*** (−6.6041)	−0.7167*** (−17.4365)	0.0843*** (3.3353)
lnSer	−0.0144 (−0.8594)	−0.2906*** (−6.1763)	−0.0659*** (−4.3754)	−0.0144 (−0.8594)	0.1875*** (3.8691)	0.0376*** (3.7120)	−0.0144 (−0.8594)	−0.2334*** (−8.2156)	0.0651*** (4.4648)
lnFin	0.0724*** (4.4018)	1.0724*** (23.1530)	0.2626*** (12.6179)	0.0724*** (4.4018)	−0.0808* (−1.6949)	0.0500*** (5.0831)	0.0724*** (4.4018)	0.8410*** (30.0721)	−0.2139*** (−9.3461)
Constant	−0.1843 (−1.0886)	2.0478*** (4.2945)	0.1788 (1.1949)	−0.1843 (−1.0886)	−1.9052*** (−3.8798)	−0.7120*** (−6.9418)	−0.1843 (−1.0886)	10.1563*** (35.2780)	−3.6414*** (−13.8451)

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively; the values in parentheses represent t statistics

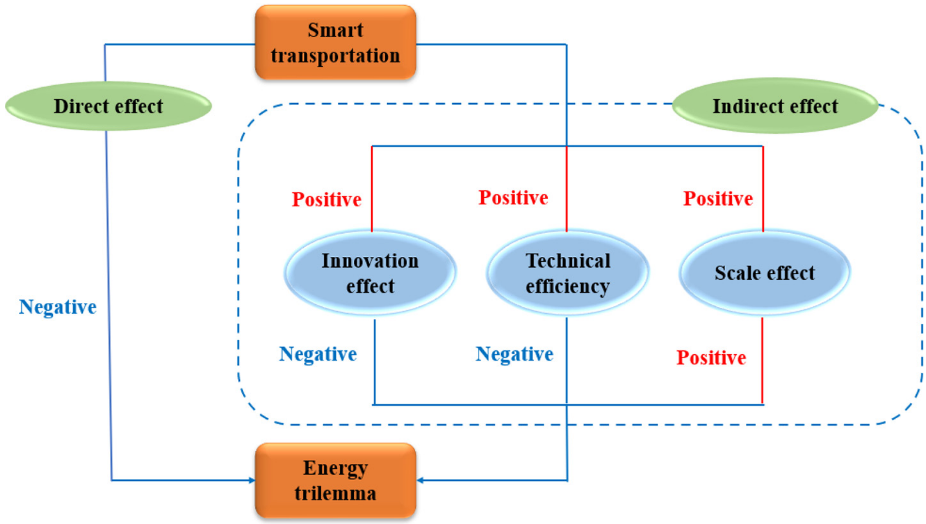


Figure 5.
The influence mechanisms between ST and the ET

illustrate its spatial and temporal patterns. Based on these measures and analysis, we further investigate the marginal effect of ST on the ET, as well as the potential influence mechanisms. The main findings are highlighted as follows:

- The ET index and its three sub-indicators show a significant downward trend in Chinese provinces in the past decades, indicating that our efforts on mitigating the ET have been effective.
- The spatial distribution of the ET and its three components are uneven. More importantly, the top-performing provinces in the eastern coastal areas have well-established, resilient energy systems. In contrast, the situation in the northwestern regions is not good.
- The baseline regression results provide strong evidence on the positive effect of China's ST on ET eradication, which remains robust after a series of tests.
- The mediation effect analysis reveals that both direct and indirect effects of ST on the ET exist; put differently, innovation, technical efficiency, and energy consumption are three channels between the nexus of ST and the ET.

Based on these findings, our empirical investigation has brought some fresh insights into China's energy situation. First, in terms of energy security, although we have achieved full coverage of energy power generation, we still need to pay attention to the outdated infrastructure. To meet the challenge of energy supply security, coordinated and unified national energy security policies are urgently needed. It is also important to improve the regional integration of the energy infrastructure and energy network system, especially the power grid system.

Second, from the results of the spatio-temporal analysis we can see that regional energy development is unbalanced. More specifically, solar energy is distributed mainly in northwestern China while the southwestern region is rich in hydropower.

Therefore, we can make use of the resource advantages of different regions to achieve a more balanced energy distribution. Moreover, despite the fact that we have made great progress in establishing comprehensive access to energy, we still need to focus not only on providing basic energy access, but also on providing access to affordable, high-quality energy.

Third, our mediation results indicate that although ST in China exacerbates the ET by increasing the amount of energy consumption, at the same time ST has a more prominent eliminating effect on the ET through innovation and technical efficiency. By implication, the rapid development of innovation and technical efficiency are efficient and useful measures to address the shortage of energy insecurity, energy inequity, and energy unsustainability. It is also necessary to control the rapid growth of demand and cultivate consumers' awareness of consumption. In addition, the government needs to strengthen supporting policies on non-fossil energy, such as abolishing non-fossil fuel taxes and encouraging the promotion of research and development of zero-carbon energy resources.

The importance of our empirical findings notwithstanding, they are limited by the following points. First, in addition to the three internal impact mechanisms proposed in this paper, other factors, such as industrial structure, may also be valid ways for ST to affect the ET. And regional heterogeneous impacts can also be considered. Second, considering that spatial differences exist in the current level of the ET in various provinces in China, a spatial econometric model may be further utilized in future research.

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