

RESEARCH

Open Access



Identifying the superposition effect of clean air policy and new energy demonstration city pilot policy on energy transition in China

Fangkun Liu¹, Jiaxin Zhang², Wenmin Zhan², Shilei Hu³ and Yanchao Feng^{2,4*}

Abstract

Against the backdrop of intensifying climate change and air pollution, Clean Air Policy (CAP) and the New Energy Demonstration City (NEDC) pilot policy serve as foundational pillars of China's strategy to realize energy transition (ET). While the individual effects of each policy have been extensively studied, their potential superposition effect on ET remains unexplored. To investigate this superposition effect, we employ panel data covering 278 Chinese cities from 2010 to 2021. Our baseline regression results demonstrate a positive superposition effect of the two policies in promoting ET. The findings remain robust after a series of robustness tests. Mechanism analysis reveals that energy consumption reduction, industrial structure upgrading, and energy efficiency improvement are three transmission channels. Moreover, we find that the superposition of the two policies on ET exhibits heterogeneity across regions, urban scales, levels of economic development, resource endowments, environmental regulation intensity, and officials' promotion pressure, highlighting how local conditions shape policy effectiveness. These findings shed new light on the logical nexus among policy design, impact, and mechanism in this field, offering both theoretical insights and policy guidance for economies striving to achieve similar multi-dimensional goals.

Keywords Superposition effect, Energy transition, Energy consumption, Industry structure, Energy efficiency

Introduction

The rapid progression of industrialization, characterized by the widespread utilization of fossil fuels [40], has precipitated a significant escalation in carbon emissions. These emissions are a principal catalyst for global warming and broader environmental degradation. According to the World Meteorological Organization (WMO),

the mean global temperature for the 2014–2023 decade registered $1.20 \pm 0.12^\circ\text{C}$ above the pre-industrial baseline. This climatic shift has amplified the frequency and intensity of extreme weather phenomena, thereby posing a systemic threat to the human environment. Beyond its climatic impacts, excessive carbon emissions are a major contributor to severe air pollution, which in turn adversely affects public health and economic productivity [55]. It is reported that air pollution leads to more than 4.5 million premature deaths worldwide on an annual basis, imposing a substantial economic and environmental burden. As detailed in the China Climate Change Blue Book (2025), China is situated in a region acutely sensitive to and profoundly affected by global climate change, exhibiting a rate of warming that exceeds the global average over the corresponding period. Notably,

*Correspondence:

Yanchao Feng
m15002182995@163.com

¹Business School, Nanning University, Nanning 530299, China

²Business School, Zhengzhou University, Zhengzhou 450001, China

³School of Economics and Management, Harbin Institute of Technology at Weihai, Weihai 264209, China

⁴School of Public Policy & Management, Tsinghua University, Beijing 100084, China



© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

the China Climate Risk Index featured in the Blue Book has ascended to its highest level since 1961, with the risks of floods and extreme heat being particularly prominent. This underscores the intensifying climate-related challenges confronting the nation. In conjunction with the immense pressure to curtail carbon emissions and address climate warming, China is confronted with a severe air pollution crisis. During 2022, the average concentration of PM_{2.5} was recorded at 29 µg/m³, a level approximately six times higher than the 5 µg/m³ standard recommended by the World Health Organization. Such critical levels of environmental pollution pose a considerable hazard to public health. Estimates suggest that air pollution is linked to over 20% of the national burden of disease and mortality, a figure that escalates to nearly 40% in heavily impacted industrial zones like the Beijing metropolitan area and its surrounding provinces [46].

Confronted with the tasks of climate problems and environmental issues, the 26th UN Climate Change Conference of the Parties (COP26) reasserts the objective of restricting the increase in global temperature to 1.5°C and calls on nations to hasten the coordinated advancement of low-carbon and green energy transition (ET) and sustainable development. ET is a crucial pathway for mitigating climate change and achieving sustainable development [22], and represents a core strategy for transitioning the global economy towards green growth [53]. As major economies are committed to adopt a broad array of measures to address climate change and environmental problems, frequent shifts in climate policies will unavoidably heighten policy unpredictability. Decision-making under such profound uncertainty is a central challenge [48], as it interacts intricately with market and economic conditions, significantly impacting economic activities [60], energy consumption (EC) [33], and carbon emissions [34].

China's current EC structure remains dominated by fossil fuels, creating a complex challenge. Facing pressures from international emissions reduction obligations and economic transition, China has not yet achieved the goal of carbon releases peaking. To reach the goal, it is essential to introduce significant adjustments in the energy system that drive the expansion of a green economy [12]. Being the largest energy consumer and emitter of carbon dioxide (CO₂) in the world [19], the progress and quality of urban ET in China not only directly affect domestic ecological construction and economic structure upgrading, but also exert an irreplaceable impact on fighting against climate change and improving environmental quality.

A global consensus has been reached on taking measures to tackle global warming and environmental pollution. With energy demand continuing to grow as the backdrop, the progress of China's ET exhibits a distinct

characteristic of advancing through dual-pronged efforts. On the one hand, to combat air pollution and climate change, a range of end-of-pipe regulatory measures have been implemented [50]. These policies have established a restrictive framework for ET by strictly limiting the development of industries with high EC and high emissions, tightening pollutant discharge standards, and promoting the substitution of coal with natural gas or electricity. The framework forces cities to reduce their reliance on traditional pollution sources. On the other hand, key approaches to achieving ET and sustainable development have emerged in the form of developing and promoting new energy technologies [29]. China has put the New Energy Demonstration City (NEDC) initiative into practice to drive technological progress, industrial structure (IS) upgrading and the improvement of energy efficiency (EE). New energy sources like solar and wind energy have been widely adopted in power generation, transportation, and other fields, which has significantly enhanced the quality of environment, promoted ecosystem conservation, and simultaneously fulfilled the growth of economy [20].

While the two types of policies each have their own focuses, their intrinsic connection is profound. Clean air policy (CAP), by compressing the living space of traditional energy sources, frees up room for advancing new energy, while NEDC provides support for emissions reduction goals by expanding the scenarios of application of new energy. Under the overarching target of ET, they form a policy combination of constraint and incentive. However, this superposition effect is not a simple "1 + 1". At the level of policy tools, there may be budgetary competition between environmental protection investment and new energy subsidies, leading to conflicts in resource allocation. At the level of implementation effects, emissions reduction pressures may accelerate the implementation of new energy technologies, potentially resulting in superposition effect. Meanwhile, short-term environmental protection costs may squeeze the willingness to invest in new energy, possibly leading to mutual offsetting. Therefore, we attempt to explore the superposition effect of clean air policy and new energy demonstration city pilot on the dynamic mechanism, path selection, and ultimate effectiveness of urban ET.

Cities, as microcosms of residents' production and daily activities, are the core carriers of EC and carbon emissions. High concentrations of emissions are found in cities across many countries, and urban areas contribute approximately 75–80% of global carbon emissions [7]. This paper explores the superposition effect of the two policies on ET by analyzing panel data from 278 cities in China. Additionally, robustness tests are conducted in this paper. Finally, mechanism tests and heterogeneity analysis are also carried out.

This study yields several significant conclusions. First, the two policies have a superposition effect on promoting ET of cities. Second, this superposition effect is realized through three channels: the reduction of EC, the promotion of IS upgrading, and the improvement of EE. Third, the magnitude of this superposition effect is heterogeneous across different contexts. Specifically, the effect is more pronounced in the central and western regions compared to the eastern region. It is also significantly stronger in large cities relative to smaller ones and in less economically developed cities. Furthermore, the effect is more potent in non-resource-dependent cities, whereas its impact is constrained in resource-based urban centers. Finally, the superposition effect is amplified in municipalities with stringent environmental regulations and where government officials face greater pressure for career advancement.

This paper makes threefold contributions. First, we make a theoretical contribution to the literature on policy superposition effects within the context of ET. While existing studies have separately established the constraint effect of CAP on high-pollution EC [47] and the incentive effect of the NEDC policy on green technological innovation [27], research that systematically constructs a theoretical framework for a “constraint-incentive” policy superposition and explores its combined mechanism on ET remains limited. This study addresses this theoretical lacuna by elucidating the inherent complementary relationship between CAP and NEDC and demonstrating that their superposition creates a virtuous cycle. Consequently, our findings provide a robust theoretical foundation for the superposition application of multiple environmental and energy policies to promote the ET.

Second, extending the theoretical analysis, we empirically identify and test the key mechanisms through which the policy superposition influences ET. While the existing literature acknowledges that EC, IS, and EE are crucial for ET, it has not yet explored how these factors function as transmission channels for the combined effects of the two policies. This study addresses this gap by demonstrating that the policy superposition actively enhances these three channels. In doing so, we elucidate the specific causal pathway linking the “constraint-incentive” policy combination to the advancement of ET.

Third, this study contributes by systematically investigating the heterogeneous impacts of the policy superposition effect across six key dimensions: geographical region, city size, level of economic development, resource endowments, environmental regulation intensity, and the incentive structures for public officials. Prior research has established direct relationships between these contextual factors and ET [23, 52]. In this study, we attempt to examine whether these factors can moderate the link between the superposition of the two policies and ET.

The heterogeneity analysis presented here thus represents an integration and extension of such existing research, which will not only add to the relevant literature but also strengthen the link between policy implementation and urban behavioral responses.

The rest of this study is organized as follows: In Sect. "Literature review", we provide a review and evaluation of prior studies. Section "Institutional backdrop and research assumptions" elaborates on the institutional context and formulates research hypotheses regarding the superposition effect of two policies on ET. Section "Research design" outlines the sources of data and analytical approaches utilized. Empirical findings are laid out in Sect. "Empirical results and discussion", covering the superposition effect of the two policies on ET, robustness tests, exploration of intrinsic mechanisms, and analysis of heterogeneous effects. Lastly, Sect. "Conclusions, policy recommendations, and further research directions" sums up the key conclusions, puts forward policy recommendations, and sketches potential paths for further research. This structure is depicted in Fig. 1.

Literature review

The interconnection of CAP and ET

China confronts a formidable challenge in its ET, navigating the dual imperatives of mitigating climate change and ensuring sustained socio-economic development. An extensive body of scholarly work identifies CO₂ emissions as a primary driver of global climate instability and underscores their reduction as a central objective of international policy frameworks. In response, China has implemented a series of clean air initiatives, which frequently employ end-of-pipe control measures to address environmental pollution. These policies, in turn, compel urban centers to reconfigure their production models and reduce their reliance on fossil fuels. Within this context, the concept of ET has gained significant traction, particularly in developed and emerging economies, as it offers a paradigm for reconciling economic growth with ecological preservation [2].

Extensive empirical research demonstrates that CAP directly facilitates the reduction of pollutants and carbon emissions by curbing high-pollution EC and promoting optimization of the energy structure, thereby acting as a key driver of ET. Harrison et al. [14] empirically confirmed that CAP exhibits a significant positive influence on improving air quality. Xu et al. [47] provided empirical verification that CAP substantially reduces emissions of pollutants through measures including restricting coal combustion and phasing out high-pollution facilities. Huang et al. [18] constructed a composite indicator of CO₂ and atmospheric pollutant emissions control, further revealing the policies' dual driving role in pollution reduction and emissions mitigation. It is precisely

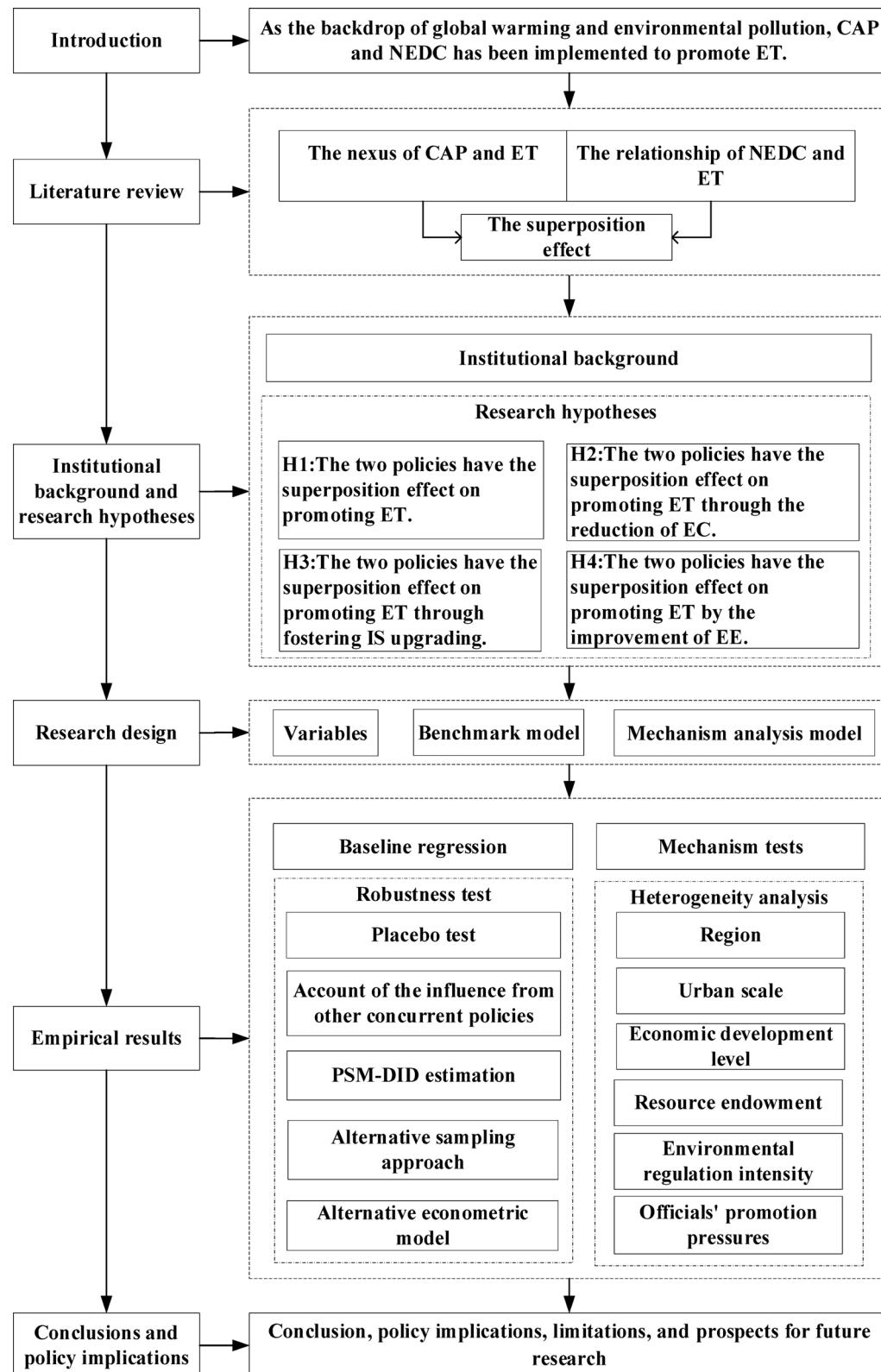


Fig. 1 Research structure

through cities' adjustment of EC structures that pollutant emissions are reduced and air quality is improved.

Spatial heterogeneity in policy implementation intensity produces regionally differentiated outcomes in air quality improvement. For instance, Xiao et al. [44] demonstrated that monitored urban areas, subject to stricter enforcement, experience significantly greater reductions in PM_{2.5} concentrations compared to their non-monitored rural counterparts. This finding underscores the critical importance of a robust monitoring-to-enforcement pipeline for policy efficacy. Furthermore, Huang et al. [18] identified the presence of spatial spillover effects associated with CAP. Their research indicates that through regional collaborative governance, CAP can exert positive externalities, contributing to pollutant reduction in adjacent areas. This provides a strong empirical rationale for the implementation of regional joint prevention and control strategies.

Beyond its direct environmental benefits, CAP also serves as an implicit driver for ET by facilitating economic restructuring and generating social co-benefits, such as improved public health. Xu et al. [46], using the Beijing-Tianjin-Hebei region as a sample, found that after CAP reduced emissions from residential and industry combustion, the disease burden related to air pollution decreased significantly, achieving the improvement of people's livelihood welfare through promoting health via environmental protection. Vrontisi et al. [38], based on research in the European Union, showed that CAP results in positive macroeconomic impacts on economy. Peng et al. [30], through an analysis combining public opinion and institutional factors, found that CAP possesses high political feasibility due to their responsiveness to people's livelihood needs and alignment with national green development strategies. By analyzing data from 278 Chinese cities, Zhou et al. [55] revealed that CAP significantly boosts green total factor productivity. Similarly, Wang [39] demonstrated that CAP indirectly reduces PM2.5 density through promoting environmental innovation. Beyond promoting the development of green economy, CAP also drives macroeconomic growth [38]. Green innovation drives the progress of new energy technologies, facilitates the shift of the energy supply side toward clean energy, and thus provides technical support for ET [10]. As a new economic growth engine, the green economy attracts substantial investments into the green energy sector, offering financial support for ET [4]. Additionally, Liu et al. [25] revealed that green finance provides financing channels and financial guarantees for ET by reducing financing costs and increasing investment returns for new energy projects.

CAP and ET are intricately linked through a "constraint-incentive" framework, which promotes the structural transformation of the energy system from being

fossil-dominated to clean and low-carbon. On the constraint side, CAP erodes the market viability of traditional fossil fuels by imposing restrictions on coal consumption and increasing the costs associated with pollution. Concurrently, on the incentive side, CAP promotes initiatives such as coal-to-electricity or oil-to-gas. These initiatives not only curtail decentralized coal combustion but also stimulate demand for the integration of renewable energy sources like wind and photovoltaic power, thereby accelerating ET away from a coal-centric model toward one increasingly supplemented by renewable energy.

The relationship of NEDC and ET

As a crucial pilot initiative in China's ET, NEDC has gained significant interest from industry and academic fields. As a core policy instrument for adjusting China's energy structure, the NEDC pilot drives ET and green development through multiple mechanisms. Technological innovation serves as a key engine for the policy's effectiveness. Ma et al. [27] explored that NEDC efficiently elevates environmental innovation levels by optimizing new energy behaviors and enhancing carbon emissions efficiency, with its mechanism manifested in increased investment in new energy technology R&D and large-scale development of low-carbon technologies. Wang and Sun [39] further pointed out that NEDC facilitates regional green technological progress. At the enterprise level, Li et al. [61] found that NEDC promotes corporate green mergers and acquisitions by fostering green innovation, alleviating financing constraints, and reducing information asymmetry, thereby generating economies of scale and driving green technology integration and industry chain upgrading.

Improving EE constitutes another core objective of the policy. Based on an analysis of total factor EE, He et al. [15] found NEDC drives the advancement of EE in pilot areas by optimizing energy structures and land use patterns. This conclusion is validated in studies on energy system optimization. NEDC enhances the overall efficiency of energy generation and EC by guiding the rational allocation of energy resources and reducing energy losses. Lee and Ogata [21] further emphasized that NEDC drives the sustainable development of pilot regions through the effects of technological innovation, EE optimization, and IS adjustment, forming a mutually beneficial situation for economic and environmental gains.

NEDC realizes ET through a composite transmission pathway of "technology-industry-finance". Zhang et al. [51] proposed that NEDC increases green EC by three transmission channels: the innovation of technology, specialized financial support, and IS upgrading. This mechanism is particularly prominent in market-oriented reforms. NEDC guides resource allocation, stabilizes

expectations for power generation and consumption by establishing electricity market trading mechanisms, and simultaneously promotes new energy participation in inter-provincial spot trading, enhancing the capacity for cross-regional optimal allocation of energy resources. In terms of financial support, green financial innovation provides funding guarantees for new energy projects by developing products such as carbon sink loans and micro-green loans, thereby facilitating technological innovation and industry upgrading.

Despite the policy's notable effectiveness, its potential adverse consequences warrant careful consideration. One significant risk is the manifestation of the "pollution haven effect" through policy-induced, intra-firm pollution transfer. As demonstrated by Lee and Ogata [21], NEDC may inadvertently incentivize regulated enterprises to shift polluting activities to affiliated entities or to adjacent, less-regulated regions, thereby offsetting some of the emissions reduction achievements. Moreover, the environmental burden may shift to rural communities with insufficient medical resources, exacerbating environmental health inequalities. Such a transfer mechanism also exists in NEDC. Although pilot areas promote local emissions reduction, adjacent regions may face environmental pressures due to undertaking energy-intensive industries.

The superposition effect

Since the Porter Hypothesis was proposed, many studies have conducted in-depth explorations into the relationship between environmental regulation and corporate innovation. A majority of scholars argue that stringent environmental supervision can offset compliance costs and enhance corporate competitiveness. However, most existing studies focus on the impact of a single type of environmental regulation, such as command-and-control or market-incentive instruments on enterprises, while neglecting the interactive effects of policy mixes. Even studies involving multiple policies rarely examine how constraint and incentive tools jointly shape the innovation compensation effect. A single incentive policy may lead to subsidy dependence [35]. In contrast, the superposition of CAP and NEDC forms a "constraint-incentive" dual driver: CAP compels enterprises to withdraw from traditional high-pollution operations, while NEDC provides the necessary resources for enterprises to transition to the new energy sector. This transforms the one-dimensional stimulation of individual policies into the multi-dimensional traction of the policy system.

Policy instrument theory classifies instruments into three categories: regulatory, market-based, and voluntary [17]. Early studies focused on comparing the effectiveness of single instruments, while recent literature has shifted toward policy mixes. For instance, Managi

et al. [28] found that the combination of regulations is more effective in promoting technological innovation than single instrument. Most of these studies remain at the "instrument matching" level and fail to explain how different instruments reconstruct the behavioral logic of micro-subjects through institutional interaction. The superposition effect, however, involves changes at the level of institutional logic: CAP reconstructs the cost constraint mechanism for traditional energy use, and NEDC establishes the benefit incentive mechanism for new energy development. These two mechanisms form a closed loop where phasing out outdated capacity creates space for new energy, and developing new energy consolidates emissions reduction achievements.

Current research on the synergistic effect of policy mixes places greater emphasis on static goal consistency Zha et al. [62], whereas the superposition effect reveals a dynamic reciprocal relationship. The space freed up by CAP through restricting traditional energy increases market demand for new energy technologies supported by NEDC, and the large-scale application of new energy technologies helps CAP achieve its emissions reduction targets. This positive feedback not only avoids the policy frictions that the coordination effect aims to resolve but also realizes the effect amplification of the entire policy system, representing a more advanced form of policy interaction.

In summary, by integrating insights from the Porter Hypothesis, policy instrument theory, and the literature on policy mix, we conceptualize the superposition of CAP and NEDC as a "constraint-incentive" policy framework. This framework is characterized by its ability to achieve institutional complementary, foster collaboration among diverse actors and policy instruments, and reduce overall transaction costs. We argue that the superposition effect is fundamentally distinct from simpler notions of policy interaction, such as additive effects, basic interaction effects, or mere coordination.

Gaps in the literature

Existing studies have made substantial progress in exploring the relationship between CAP, NEDC, and ET, laying a solid theoretical and empirical foundation. However, there remain obvious gaps and limitations that need to be addressed.

First, most studies concentrate on the independent effects of single policy. Studies on CAP have thoroughly demonstrated its role in constraining high-pollution EC, promoting green innovation, and optimizing energy structures, while also revealing spatial spillover effects and economic welfare impacts. Research on NEDC has highlighted its driving forces in technological innovation, EE improvement, and industry chain upgrading, as well as potential risks such as pollution transfer. However, few

papers have explored the superposition effect of the two policies. In practice, CAP, as a constraint-oriented tool, and NEDC that is an incentive-oriented tool, often coexist in the process of urban ET, forming a policy mix of constraint-incentive. The lack of research on their interaction has become a critical theoretical gap.

Second, the mechanism analysis of policy effects remains fragmented. Existing studies have clarified the respective transmission paths of CAP and NEDC. However, they fail to explore the internal logic that links their superposition effect to ET. For example, it is unclear how the compression of traditional energy living space by CAP interacts with the expansion of new energy application scenarios by demonstration policy, or whether there is a transmission channel where one policy amplifies or weakens the mechanism of the other. This lack of integrated mechanism analysis limits the understanding of the complex dynamic between the superposition of the two policies in promoting ET.

Third, heterogeneity analysis in existing research is insufficiently linked to the superposition effect. Although scholars have noted that factors such as regional differences, urban scale, and resource endowments affect the effectiveness of single ET policy, there is a dearth of research on how these factors moderate the superposition effect of the two policies. For instance, it remains unclear whether the superposition effect of the two policies varies significantly between eastern and western regions, or between non-resource-dependent and resource-based cities, which hinders the formulation of targeted policy recommendations.

In summary, the existing literature provides valuable insights into single policy effects but falls short in analyzing the superposition, integrated mechanisms, and heterogeneous performance of the two policies. This study is intended to fill these blanks by systematically examining the superposition impact of the two policies on urban ET, exploring their internal transmission mechanisms, and clarifying the heterogeneous effects under different urban contexts, thereby enriching the theoretical system of ET policy research and providing empirical support for optimizing policy combinations.

Institutional backdrop and research assumptions

Institutional backdrop

Against the background of growing environmental challenges, the urgency of ET is increasingly shaping the prospects for global sustainable development. Energy plays a driving role in the current improvement of economy [16]. Rapid urbanization and industry expansion, particularly in emerging economies like China, have intensified energy demand, while the dominance of fossil fuels has intensified climate change and air pollution [41]. Over-reliance on fossil fuels not only drives greenhouse gas

(GHG) emissions [3] but also degrades air quality, threatening public health [11] and ecological stability [57]. To address the mounting pressure to address environmental pollution and reduce GHG emissions, advocating the transformation of traditional fossil fuel-intensive energy sectors toward green and new energy has become a consensus among the vast developed and emerging nations. In the process of climate governance, the Paris Agreement and the Kyoto Protocol are of milestone significance, laying the foundation for low-carbon ET [9]. ET has thus emerged as a new frontier in tackling environmental pollution and global warming. In response to environmental pollution and climate change, the Chinese government has formulated action goals and departmental plans, regulated and monitored markets through governmental means, and developed dual complementary policy instruments: CAP and NEDC. Their institutional interactions have shaped urban energy structures.

The objectives of atmospheric governance have undergone a continuous tightening process, shifting from the regulation of individual pollutants to the systematic management of multiple pollutants, and further advancing toward a developmental pathway aimed at overall air quality improvement [8]. Concurrently, China's clean air policies have evolved from fragmented pollution control toward an integrated system of governance, with ET embedded as a core institutional goal. Early instruments such as the Air Pollution Prevention and Control Law (revised in 2000) primarily emphasized end-of-pipe treatment, characterized by broad coverage but limited specificity in targeting particular regions, industries, or issues. A significant transition occurred with the introduction of the Air Pollution Prevention and Control Action Plan in 2013, which institutionalized source control through measures such as fossil EC caps and the establishment of cross-regional joint governance mechanisms. The plan also narrowed its focus to 80 key cities, encompassing the Beijing-Tianjin-Hebei region and its surrounding areas, the Yangtze River Delta, and the Pearl River Delta. It further introduced binding targets for PM2.5 reduction, specifying, for instance, a 20% reduction in the Beijing-Tianjin-Hebei area and 15% in the Pearl River Delta, thereby compelling municipal governments to prioritize energy structure adjustments. Specific measures included promoting high-quality, low-emission upgrades in key sectors such as steel and cement. By 2025, over 80% of national steel production capacity is expected to achieve ultra-low emissions, with full coverage in key regions and the basic completion of ultra-low emission retrofits for coal-fired boilers. Subsequently, energy indicators were incorporated into environmental impact assessments and the performance evaluations of local officials, reinforcing the connection between air quality improvement and energy decarbonization (Measures for

the Evaluation and Assessment of Ecological Civilization Construction Objectives, 2016). In 2019, the Ministry of Ecology and Environment launched the National Clean Air Programme, aiming to comprehensively mitigate air pollution nationwide. Initially targeting a 20–30% reduction in PM10 concentrations by 2024–2025 relative to the 2017–2018 baseline, the goal was later revised to a 40% reduction (based on 2019–2020 levels) or attainment of the national standard of $60 \mu\text{g}/\text{m}^3$ by 2025–2026. A major institutional milestone was reached in 2020, when the Central Economic Work Conference formally advocated for continued efforts in pollution prevention and control and, for the first time, proposed the coordinated achievement of pollution reduction and carbon mitigation. This marked the formal alignment of clean air policies with the dual-carbon goals, establishing an institutional framework in which reducing dependence on fossil energy has become central to both air quality management and climate change mitigation.

Parallel to CAP, China's NEDC serves as a key instrument to advance ET and green innovation, covering multiple fields including wind energy, solar energy, hydrogen energy, and smart grids [45]. Concentrated on the coordinated advancement of policy backing, technological R&D, and industrial promotion [13], China has realized large-scale adoption of new energy across many cities through programs like National New Energy Demonstration Cities and Green Low-Carbon Pilot Cities [56]. The growth in output value of new energy manufacturing enterprises, the development pace of new energy service industries, and the penetration degree of new energy in the urban EC structure across these cities, such as Beijing, Shanghai, have all maintained a steady upward trend. Furthermore, with the progressive advancement of NEDC, an increasing number of cities that possess the foundational conditions for new energy development are being incorporated into the scope of policy implementation. The government has reduced the initial investment required for new energy projects through financial subsidies, tax reductions and exemptions, and green financial instruments. It has also guided enterprises and research institutions to pursue technological breakthroughs in new energy technology fields such as wind energy, solar energy, and hydrogen energy. Meanwhile, by constructing new energy industrial parks and introducing related enterprises, the government has promoted the development of urban new energy industries, thereby driving the green upgrading and innovation of relevant industrial chains. These measures have propelled the high-quality development of China's green economy and stimulated the green upgrading and innovation of relevant industrial chains [5]. Among the diverse policy measures deployed globally to promote ET, China's NEDC stands out as a major driver of urban ET.

Analysis of mechanisms and research hypotheses

For the above mentioned effect of CAP and NEDC on ET, the exiting literature has investigated abundantly and formed several useful implications for our study. For further study, we decide to study the superposition effect of the two policies.

The fundamental objective of integrating these two policies is to alleviate environmental pollution and foster the large-scale deployment of new energy, thereby accelerating urban ET. However, the superposition effect of the two policies on ET is not limited to replacing fossil fuels with new energy and thereby directly reducing fossil fuel consumption. Beyond direct effect, the two policies exert superposition effect through different transmission channels, including reducing EC scale, fostering IS and improving EE, ultimately achieving ET.

The superposition effect of the two policies on ET

The superposition of the two policies forms a “constraint-incentive” policy mix that promotes urban ET. CAP, as a constraint-oriented tool, restricts the expansion of high-pollution and energy-intensive industries [50], compressing the survival space of traditional fossil energy, indirectly accelerating energy structure adjustment. NEDC, as a incentive-oriented tool, drives technological innovation and industry upgrading in new energy fields by tax incentives, financial subsidies, and green financial support [39].

The superposition of the two policies precisely creates a complementary mechanism. The constraining role of CAP clears the path for new energy development by phasing out outdated capacity, while the incentive effect of NEDC fills the ensuing energy supply gap, establishing a positive cycle of eliminating fossil fuel and fostering the new energy. Specifically, the space freed up by CAP through restricting traditional energy is just right for the advancement of new energy promoted by NEDC. Meanwhile, the large-scale application of new energy helps achieve the emission reduction targets required by CAP, thus strengthening the implementation effect of both. The two policies are inherently linked. Their combination avoids the limitations of single policies and forms a complementary mechanism. This superposition not only reduces fossil energy dependence but also accelerates the large-scale application of new energy, thereby effectively promoting urban ET. Given this, we put forward the following hypothesis:

Hypothesis 1 The two policies have the superposition effect on promoting ET.

The transmission channel of EC

CAP and NEDC have been widely recognized as important drivers of reducing EC, which is critical in driving the promotion of ET. The two policies influence EC

through multiple channels, specifically including constraint mechanism, incentive mechanisms, and technology diffusion.

Firstly, CAP directly constrains EC through restrictive measures, which limits coal consumption, phases out inefficient production capacity, and tightens EE standards for high-emission industries [47], thereby reducing overall energy demand. For example, the Air Pollution Prevention and Control Action Plan mandates the use of regional coal, directly curbing fossil energy use. Secondly, NEDC encourages that financial institutions offer green financial products, like green bonds and low-carbon loans, to support companies in developing new energy technologies and reducing carbon emissions [51]. Thirdly, NEDC reduces EC through technology diffusion. By promoting renewable energy technologies and green technological innovation, NEDC enhances energy utilization efficiency. For example, large-scale application of wind and solar power reduces energy loss in traditional power generation and transmission, improving EE [36].

The existing literature highlights the pathway through which the reduction of EC promotes ET. The pathway is through reducing the total scale of EC, weakening the demand base for fossil energy and creating conditions for a shift to clean energy [18], thereby facilitating ET. Then, this study proposes the following hypothesis:

Hypothesis 2 The two policies have the superposition effect on promoting ET through the reduction of EC.

The transmission channel of IS

Apart from reducing EC, the superposition of the two policies also makes a prominent contribution to IS upgrading, which constitutes another important channel for promoting ET. Specifically, CAP forces IS adjustment by raising the threshold for high-pollution industries. Strict emissions standards and environmental assessments increase the operating costs of energy-intensive sectors, prompting cities to phase out outdated production capacity and shift toward low-carbon industries [55]. This forced upgrading reduces the proportion of secondary industry and increases reliance on service and technology sectors, which have lower energy intensity.

Moreover, NEDC actively fosters IS upgrading by supporting green industries. They attract investment in new energy sectors through subsidies and tax incentives, boosting the development of high-tech and service industries [51]. IS upgrading has reduced the dependence of the economy on high-energy-consuming industries [43, 54]. This transformation brings a gradual change in the way resources are allocated, shifting from heavily polluting industries to low-carbon ones. This incentive-driven upgrading not only expands the scale of low-carbon industries, but also creates a more sustainable economic structure, thereby improving the level of ET.

While, CAP eliminates backward industries to free up resources, while NEDC directs these resources toward green sectors. The superposition policy strengthens this upgrading effect.

The improvement of the IS is a key factor in promoting ET, and transforming energy demand from fossil fuels to renewable energy is where its operational mechanism resides. Because industries intensive in energy use phase out over time, the ratio of new EC improves accordingly, which in turn promotes significant progress in ET. Existing studies have illustrated that IS not only improves EE [6] but facilitates the improvement of low-carbon industries [49]. Given this, we put forward the following hypothesis:

Hypothesis 3 The two policies have the superposition effect on promoting ET through fostering IS upgrading.

The transmission channel of EE

As a pivotal indicator reflecting the conversion efficiency of energy input to output, EE serves as the core transmission channel through which CAP and NEDC exert a combined influence on ET. Despite their distinct policy orientations, these two policies are functionally complementary.

As a command and control policy, CAP elevates the costs of inefficient energy use through stringent regulatory measures, thereby forcing enterprises to upgrade energy-saving technologies and optimize production processes. In contrast, NEDC, as an incentive-oriented policy, leverages tools including fiscal subsidies, tax reductions, and green finance to drive EE improvement from both the supply and demand sides. It not only subsidizes R&D and application of high-efficiency energy-saving technologies but also encourages market entities to adopt energy-efficient products. Notably, He et al. [15] have empirically verified that the NEDC can enhance the total-factor EE of pilot cities by optimizing energy allocation and facilitating technology diffusion.

The superposition of these two policies fosters a positive cycle and their superposition effect far surpasses that of a single policy. On one hand, improved EE reduces energy demand per unit of economic output, diminishes reliance on fossil energy, frees up space for clean energy development, and concurrently lowers the economic costs of ET. On the other hand, enhanced EE accelerates the substitution of traditional energy with clean energy by optimizing the development and application of new energy technologies, thereby strengthening the competitiveness of clean energy. Then, we propose the following hypothesis:

Hypothesis 4 The two policies have the superposition effect on promoting ET by the improvement of EE.

Research design

Data source

We employ a balanced panel dataset comprising 278 prefecture-level cities in China from 2010 to 2021. Data for the key variables are primarily sourced from official statistical yearbooks, including the China City Statistical Yearbook, the China Energy Statistical Yearbook, and commercial databases such as CSMAR and EPS. Additionally, we integrated data from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) and Suomi National Polarorbit Partnership's Visible Infrared Imaging Radiometer Suite (SNPP/VIIRS) to obtain corrected nighttime light data. By integrating multi-source data, we have been able to establish a dataset that is both comprehensive and high-quality, so as to meet the needs of subsequent empirical analysis.

Dependent variable

The dependent variable is ET. Referring to the study of Lin and Cheung [24], we calculate ET from three perspectives, including EC, IS, and EE. In particular, EC is calculated by electricity usage. IS is constructed by cosine angle method. EE is measured by improvements in input-output efficiency. As for the details of calculate, we have not repeated them due to the limitation of space constrains.

Independent variable

The core independent variable is D, which is the sum of variable CAP and variable NEDC. The variable CAP is a policy dummy variable that manifests whether city i implements the CAP. If the city i implemented or has implemented the policy in year t , it takes the value 1 and is part of the treatment group, otherwise, it is 0 and falls into the control group. Some cities gradually implemented the CAP in 2014. In this study, cities with an annual average reduction target of 15% or higher for inhalable particulate matter are categorized into the treatment group. Included in this group are Beijing, Shanghai, Tianjin, along with every city in Shandong, Shanxi, Hebei, Henan, Qinghai, Shaanxi, Xinjiang, Jiangsu, Zhejiang, Chongqing, and Guangdong. The control group consists of all other cities.

Meanwhile, the variable NEDC is also a policy dummy with a binary value either of 1 or 0. NEDC=1 indicates that city i has been listed as new energy demonstration city in year t and is part of the treatment group. Conversely, NEDC=0 signifies that city i has not been listed as new energy demonstration cities in year t , placing it in the control group. In the sample we studied, 68 cities were listed as new energy demonstration cities in 2014.

Control variables

Building on the theoretical analysis outlined earlier and existing research, we integrate a range of control variables into the model to mitigate potential bias attributed to missing variables.

Population Concentration Level (PD): Calculated as the number of permanent urban residents per square kilometer. Higher population density areas may push ET more urgently because of higher energy demand and population pressure, and reduce the transition cost owing to scale effect.

Urbanization Rate at the Regional Level (URB): Defined as the proportion of a region's total population that resides in metropolitan areas. Higher urbanization often has more concentrated IS and more advanced energy technology, which may promote ET.

Economic Policy Uncertainty (EPU): Constructed by taking the monthly EPU indexes' arithmetic average for each year. EPU may inhibit enterprises' long-term investment in new energy projects, affecting the process of ET.

GDP growth (GDP_growth): Obtained from CSMAR database. Higher GDP growth areas often lead to increased energy demand, which is more necessary to meet the demand through transition. What's more, higher GDP growth areas are easier to support the transition with sufficient funds.

Energy finance (EF): Measured by local energy conservation and environmental protection expenditures to capture the carrot and stick strategies, respectively.

Public environmental attention (Public): formed by annual Baidu search volume of environment-related keywords, including pollution, environmental protection, carbon neutrality, carbon peaking, and carbon emissions.

Credit amount (Car): Calculated by the loans used to develop energy economy and other related ET.

Table 1 presents the descriptive statistics of the sample data. Such statistical measures offer crucial insights into the fundamental attributes of the sample data.

Empirical strategy

Baseline model

The phenomenon of an increasing number of cities committing energy transition provides a unique quasi-nature experimental environment for the research. The specific model setup for this study is presented in the following equation:

$$ET_{i,t} = \alpha_0 + \alpha_1 CAP_{i,t} + \alpha Control_{i,t} + u_i + \varepsilon_{i,t} \quad (1)$$

$$ET_{i,t} = \beta_0 + \beta_1 NEDC_{i,t} + \beta Control_{i,t} + u_i + \varepsilon_{i,t} \quad (2)$$

$$ET_{i,t} = \gamma_0 + \gamma_1 D_{i,t} + \gamma Control_{i,t} + u_i + \varepsilon_{i,t} \quad (3)$$

Table 1 Descriptive statistics of the selected variables

VARIABLES	Obs	SD	Mean	Min	Max
D	2,924	0.644	0.448	0	2
CAP	2,924	0.451	0.285	0	1
NEDC	2,924	0.370	0.164	0	1
EC	2,924	96.49	146.3	8.836	764.3
IS	2,924	34.59	653.6	557.0	765.7
EE	2,924	22.60	59.61	21.31	180.1
ET	2,924	9.918	40.91	19.21	80.95
PD	2,924	0.879	5.804	1.517	7.882
URB	2,924	0.264	4.003	3.018	4.605
EPU	2,924	105.8	193.3	92.11	390.4
GDP_growth	2,924	1.954	107.2	102.2	110.6
EF	2,892	0.743	5.395	2.036	8.037
Public	2,924	1.010	4.063	0	6.727
Cra	1,963	1.344	-0.899	-9.970	0

where the subscripts i and t denote city and year, respectively. The dependent variable, $ET_{i,t}$ measures the ET level of city i in year t . The coefficients of α_1 , β_1 , and γ_1 capture the impacts of the CAP, NEDC, and their superposition on ET, respectively. $Control_{i,t}$ denotes a set of control variables that may influence ET, including population concentration level (PD), urbanization rate at the regional level (URB), economic policy uncertainty (EPU), GDP growth (GDP_growth), energy finance (EF), public environmental attention (Public), and credit amount (Cra). Finally, u_i denotes city-fixed effects, which account for time-invariant city-level heterogeneity, and $\epsilon_{i,t}$ stands for the random error term.

Mechanistic analysis model

As addressed in Sect. "The transmission channel of EC" and "The transmission channel of IS", the two policies may exert an indirect superposition impact on ET through a number of potential mechanisms. For the empirical testing of these transmission channels, we adopt the method put forward by Baron and Kenny [1] and construct a stepwise regression model. The model is configured as follows:

$$M_{i,t} = \mu_0 + \mu_1 D_{i,t} + u_i + \epsilon_{i,t} \quad (4)$$

$$ET_{i,t} = \varphi_0 + \varphi_1 M_{i,t} + \varphi_2 D_{i,t} + \varphi Control_{i,t} + u_i + \epsilon_{i,t} \quad (5)$$

where the subscripts i and t represent city and year. Identifying the potential transmission pathways through which the two policies have the superposition effect on ET, $M_{i,t}$ stands for a series of transmission channel. In detail, we include EC, IS and EE. The remaining variables in Eqs. (4)-(5) are consistent with those specified in Eqs. (1)-(3).

In these models, if the coefficient u_1 and the coefficient φ_1 are both significant, it indicates that EC, IS and EE

play the role of transmission channel. Apart from these coefficients, when the interaction term's φ_2 coefficient is also significant, it suggests that EC, IS and EE play the partially role of transmission channel.

Empirical results and discussions

Multicollinearity test

Before carrying out the baseline regression, an assessment of the interrelationships among variables is required to reduce the likelihood of multicollinearity. As noted by Farrar and Glauber [58], multicollinearity can hinder the model from accurately determining how the explaining variable influences the explained variable by masking the effects among variables. Following existing studies, we utilize the variance inflation factor (VIF) method to evaluate whether multicollinearity exists.

Appendix B contains the findings of the multicollinearity appraisal, with all VIF values falling beneath the 10 threshold. This reveals that multicollinearity across the chosen variables does not pose a primary issue.

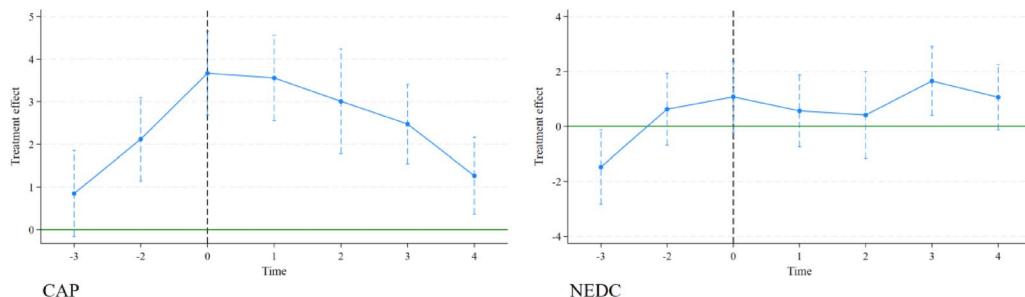
Parallel trend test

Conducting a parallel trend analysis is a essential step to ensure the effectiveness of the Difference-in-Differences (DID) estimation. In line with the parallel trends assumption, we check that pilot and non-pilot cities showed similar trends in their ET levels prior to the respective implementation of CAP and NEDC. After the two policies are implemented, the treatment group and control group are expected to deviate from these parallel trends.

We illustrate the annual trends of the treatment group and control group pre- and post- implementation the two policies in Fig. 2. The findings show that prior to the introduction of CAP and NEDC in 2014, pilot and non-pilot cities displayed almost parallel trends. After the two policies were put into effect, the ET level in non-pilot cities continued to grow at the previous pace, whereas pilot cities saw a faster rate of growth. After both policies were put into effect in 2014, it is worth noting that the difference in ET levels between pilot cities and non-pilot ones expanded markedly.

Benchmark regression results

In Table 2, the outcomes of the benchmark regression are presented. The results of baseline regression of CAP are displayed in Column (1). The coefficient of D is significantly positive, suggesting that CAP has remarkably promoted ET. Column (2) of Table 2 presents the result concerning how NEDC affects ET, with a positive regression coefficient. This indicates that to a certain degree, NEDC has improved the level of ET. As presented in Column (3), the interaction term coefficient ($D_{i,t}$) displays statistical significance and a positive influence, and its significance level is not lower than 1%. This implies that

**Fig. 2** Visualizing the results of parallel trends tests**Table 2** The regression results of baseline

VARIABLES	(1) ET	(2) ET	(3) ET
CAP	0.414 (1.293)		
NEDC		1.503*** (3.939)	
D			0.645*** (3.050)
PD	-1.813* (-1.865)	-1.845* (-1.873)	-1.916* (-1.877)
URB	17.292*** (10.884)	16.492*** (10.489)	16.641*** (10.354)
EPU	0.017*** (12.160)	0.018*** (12.338)	0.018*** (12.269)
EF	1.172*** (4.748)	1.181*** (4.937)	1.135*** (4.671)
GDP_growth	0.279*** (4.135)	0.293*** (4.306)	0.296*** (4.377)
Public	-0.338 (-1.309)	-0.335 (-1.294)	-0.350 (-1.355)
Cra	-0.143 (-0.786)	-0.178 (-0.986)	-0.158 (-0.873)
Constant	-56.617*** (-4.803)	-54.983*** (-4.707)	-55.261*** (-4.640)
Observations	1,943	1,943	1,943
R-squared	0.854	0.855	0.854
City FE	YES	YES	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

the two policies have an effective superposition effect on promoting ET within the specified pilot areas. The coefficient of D indicates that the announcement of the superposition of the two policies results in an approximately 60% increase in ET. Taken together, the overall results of the baseline regression model confirm Hypothesis 1, which reveals that the two policies have the superposition effect on promoting ET.

Robustness tests

Placebo test

In view of the fact that some unobservable and time-varying urban features may interfere with the estimation

results, it is necessary to conduct indirect placebo test to mitigate the influence of these unobservable features. Pitman [31, 59] proposed the permutation test, a widely used method of statistical inference, whose null hypothesis holds that there is no statistically significant link between the superposition of the two policies and ET within the test scenario. Specifically, in this paper, we randomly generated the list of pilot cities for CAP and NEDC to obtain the distribution of 500 spurious estimates (Fig. 3). It was found that all these estimates are distributed around 0 and follow a normal distribution, which is consistent with what the placebo test anticipates, thereby validating the estimation results' robustness.

Account of the influence from other concurrent policies

Additionally, within the sample period, the central authorities issued several other policies that may affect ET. Prominent cases include the pilot policy for low-carbon cities (LCC), the carbon emissions trading pilot policy (CET), and the national innovative city pilot strategy (NIC). To reduce the underlying effect of these concurrent policies on the estimation outcomes, this study adopts the method, which involves adding dummy variables for interfering policies to the model. The value assignment rules for the dummy variables of the three policies work like this. Cities approved for pilot programs within the specified period receive a value of 1 in the policy's implementation year and all following years. In contrast, cities not approved for pilot programs are given a value of 0. The estimation results accounting for the impact of these extra interfering policies are shown in Table 3. When LCC, CET, NIC, and the combination of the three policies are incorporated into the model, their respective estimation results are displayed in Columns (1) to (4). It turns out that even with the influence of other concurrent policies taken into account, the coefficients of the interaction terms remain statistically significantly positively correlated. This firmly suggests that the identified superposition effect between CAP and NEDC is not driven by other major contemporary environmental or innovation policies, greatly enhancing the credibility of our core finding.

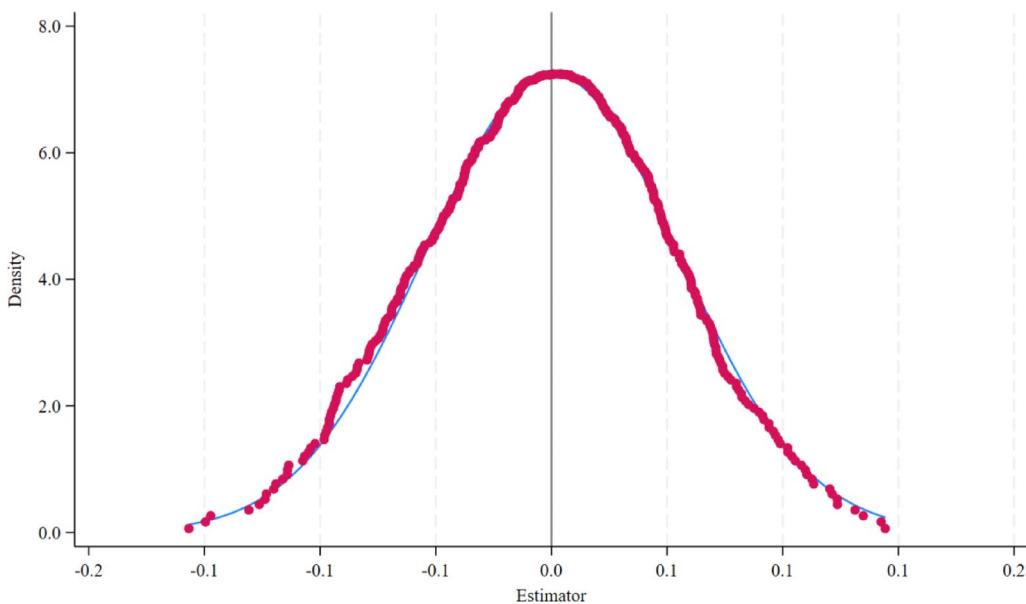


Fig. 3 Visualizing the results of placebo tests

Table 3 Estimation outcomes after accounting for the exclusion of impacts from other concurrent policies

VARIABLES	(1)	(2)	(3)	(4)
	<i>ET</i>	<i>ET</i>	<i>ET</i>	<i>ET</i>
D	0.605*** (2.876)	0.644*** (3.046)	0.623*** (3.024)	0.579*** (2.826)
LCC	2.156*** (4.355)			2.179*** (4.334)
NIC		0.224 (0.372)		-0.117 (-0.193)
CET			0.391 (0.672)	0.459 (0.788)
Constant	-57.291*** (-4.796)	-55.275*** (-4.639)	-55.123*** (-4.621)	-57.143*** (-4.777)
Control	Yes	Yes	Yes	Yes
Observations	1,943	1,943	1,943	1,943
R-squared	0.856	0.854	0.854	0.856
City FE	YES	YES	YES	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

PSM-DID Estimation

Since the selection of pilot cities for CAP and NEDC may not be entirely random, endogenous problems might stem from sample selection bias. To tackle this problem, Logit is employed for propensity score matching (PSM), and the radius matching method is applied in our analysis. Control variables from the benchmark model serve as the covariates utilized for matching. To statistically examine whether there are disparities between the matched treatment and control groups, a balance test is carried out, thereby assessing the effectiveness of the matching process. The standardized differences before and after matching are visualized in Fig. 4, with the figure

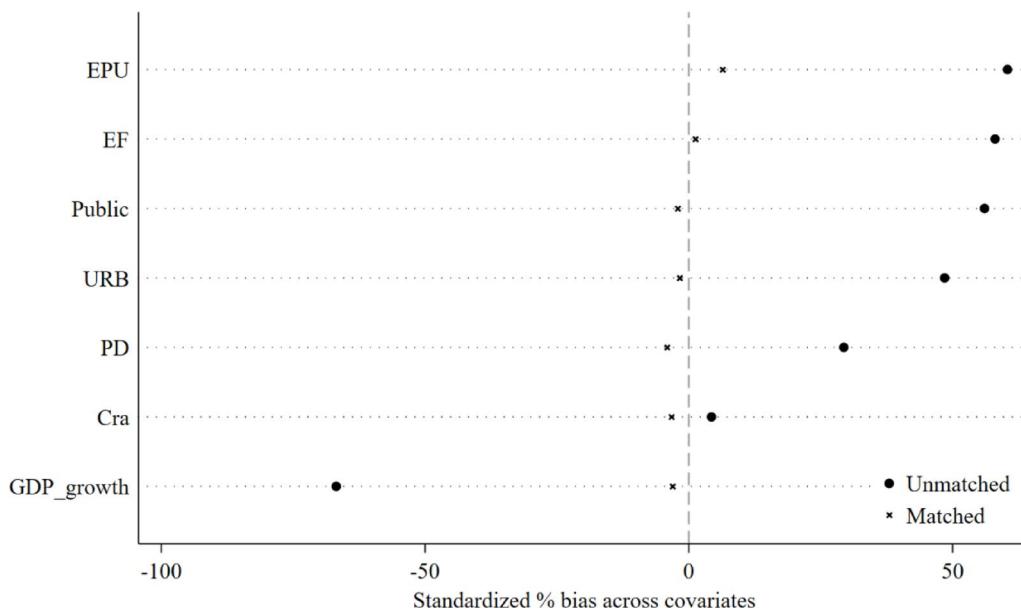
revealing a marked reduction in deviation post-matching. Subsequently, the DID was re-estimated shown in Column (1) of Table 4. The findings reveal that the results of the benchmark regression analysis remain reliable even considering the differences of urban characteristics across the treatment and control groups.

Alternative sampling approach

When analyzing the superposition effect of the two policies on ET, variations in urban administrative levels must be taken into account. In China, centrally administered municipalities and provincial capitals possess relatively high administrative ranks, enabling them to secure more policy backing and resource allocations from central authorities. Boasting a more advanced level of economic development, these cities are also likely to have superior infrastructure facilities. We excluded data related to provincial capitals and the four centrally administered municipalities, then recalculated the baseline regression. After excluding these provincial capitals and municipalities, Column (2) of Table 4 indicates that the coefficient, in line with the baseline results, stays positive and significant at the 1% level. This validates that the baseline results retain their robustness under this alternative sampling approach.

Alternative econometric model

To confirm the robustness of the results, we further adjusted the model specifications. In terms of ET level, a dummy variable (*ET_Dummy*) was adopted, where a value of 1 is assigned to regions with a high ET level (i.e., exceeding the median) and 0 is given otherwise. With the application of a Logit model, the coefficient of D shown

**Fig. 4** Visualization of bias before and after matching**Table 4** Estimated results of PSM-DID Estimation and other robustness tests

VARIABLES	(1)	(2)	(3)
	<i>ET</i>	<i>ET</i>	<i>ET_Dummy</i>
D	0.633*** (2.867)	0.645*** (3.050)	2.587*** (2.691)
Constant	-61.925*** (-5.119)	-55.261*** (-4.640)	-98.729*** (-4.183)
Observations	1,850	1,943	1,227
R-squared	0.853	0.854	
City FE	YES	YES	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

in Column (3) of Table 4 is 3.725, displaying a positive effect at the 1% level. This suggests that compared with cities having a low ET level, those with a high ET level stand a greater chance of being positively influenced by the superposition of the two policies.

The study also verifies the robustness of the results using three additional regression models (Appendix C, D and E). (1) Alternative dependent variable: Following Song et al. [37, 42], we use coupling and coordination model to construct ETNew which captures the dynamic evolution of EC, IS, and EE. (2) Alternative control variable: To more thoroughly validate the baseline results, we use different control variable, including industry level (IL), human capital level (Hcp), fixed asset investment (Fai), financial development level (Fin), whose detailed explanations are shown in Appendix A. (3) Sensitivity analysis of policy implementation time windows: Given the subjectivity of time window setting, we assume that the policy will be implemented in 2013, and the results show that the coefficient of D is still significantly positive.

Elaborate on the influence mechanism from a multi-dimensional perspective

Having confirmed the superposition effect of the two policies on ET, we proceed to examine the intrinsic mechanisms through which CAP and NEDC exert their mitigating effects. The concept of ET is multifaceted, with EC, IS, and EE recognized as its three core dimensions. In existing research, scholars have also conceptualized these as transmission channels for the effects of ET. In this study, we integrate these perspectives, treating EC, IS, and EE as both the constituent components of ET and as its transmission channels. While this dual approach could potentially introduce endogeneity issues, this risk is mitigated through a coupled analysis of the three variables' effects. The empirical results ultimately validate our initial hypothesis.

The superposition effect of the two policies on EC

Regarding the transmission channel of EC, the estimation results are presented in Column (1) and Column (2) of Table 5. This study reveals that the superposition of the two policies lowers EC, thereby facilitating ET in pilot cities. This could find explanation in the fact that the superposition of the two policies assists pilot cities in optimizing their energy structure, advancing green technology, and transforming consumption patterns, all of which contribute to reduced EC. Furthermore, in Column (2), the coefficient of EC is significantly negative, indicating that the reduction of EC is conducive to promoting ET. Specifically, lower EC directly weakens the demand foundation for fossil energy, reduces dependence on nonrenewable energy sources, and boosts the use of

Table 5 The results of mechanism test

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	<i>EC</i>	<i>ET</i>	<i>IS</i>	<i>ET</i>	<i>EE</i>	<i>ET</i>
D	-8.132*** (-6.474)	0.567*** (2.704)	15.841*** (37.493)	-0.078 (-0.371)	1.846*** (3.936)	0.739*** (10.247)
<i>EC</i>		-0.014*** (-3.566)				
<i>IS</i>				0.183*** (13.699)		
<i>EE</i>						0.323*** (88.389)
Constant		-53.792*** (-4.494)		-114.223*** (-9.504)		-33.374*** (-7.415)
Observations	2,924	1,943	2,924	1,943	1,943	1,943
R-squared	0.922	0.856	0.853	0.875	0.734	0.981
City FE	YES	YES	YES	YES	YES	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

new energy, thereby enhancing the level of ET. This evidence provides further support for Hypothesis 2.

The superposition impact of the two policies on IS

In Column (3) of Table 5, the coefficient of D is positive and statistically significant, indicating that the superposition of the two policies promotes the upgrading of IS. Furthermore, the coefficient for IS in Column (4) remains significantly positive, suggesting that IS upgrading helps to boost ET. Additionally, this significantly positive coefficient for IS in Column (4) demonstrates that IS serves as a partial transmission channel in the link between the superposition of the two policies and ET. A possible reason is that the upgrading of IS has developed new industries like new energy automobiles, which increases the demand for clean energy and thus drives ET forward. This evidence provides further support for Hypothesis 3.

The superposition impact of the two policies on EE

As for the transmission channel of EE, the results are shown in Column (5) of Table 5, which suggests that the superposition of the two policies promotes the improvement of EE. At the level of 1%, the coefficient of EE is positive in Column (6) of Table 5, indicating that the improvement of EE promotes ET. Moreover, the significantly positive coefficient for IS in Column (6) demonstrates that EE serves as another transmission channel in the relationship between the two policies and ET. This evidence provides further support for Hypothesis 4.

Heterogeneity analysis

Given the potential regional variations in the superposition effect of the two policies on ET, we perform a heterogeneity analysis from various angles. In detail, we investigate how the connection differs based on geographic position, urban size, urban economic

development level, endowment of resource, environmental regulation, and officials' promotion pressure. This analysis seeks to decide whether urban characters affect the effectiveness of the superposition impact on enhancing ET, along with whether environment-specific conditions impact the superposition effect.

Region heterogeneity

To examine whether geographic location affects the relationship between the superposition of the two policies and ET, this study initially examines the superposition effect of the two policies across various regions. We divide the sample into two subgroups: eastern areas and central-western classification. In Columns (1) and (2) of Table 6, the results indicate that the superposition of the two policies significantly promotes ET in central-western regions, while its effects in eastern region are relatively limited. From the perspectives of spatial economics and development economics, this regional disparity originates from differences in regional development level and factor endowments, which collectively shape policy transmission efficiency. The eastern regions, characterized by a relatively high baseline of ET and a mature clean energy market, exhibit a diminishing marginal effect of the superposition policy. This can be attributed to the fact that the policy impact is prone to being overshadowed by other diverse environmental and energy policies simultaneously implemented in these regions. In contrast, the central and western regions, which have a weak ET baseline, an urgent need for the transformation of traditional energy-intensive industries, and abundant new energy resources, witness a significant promotion of ET driven by the superposition policy. The "constraint-incentive" combination inherent in the superposition policy generates a focused effect, leading to a marked improvement in ET against the backdrop of a low baseline.

Table 6 Estimated outcomes of heterogeneity tests

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>Eastern</i>	<i>Central-western</i>	<i>Small</i>	<i>Large</i>	<i>High level</i>	<i>Low level</i>	<i>Resource-based</i>	<i>Non-Resource-based</i>
D	0.391 (1.27)	0.963*** (3.21)	0.540* (1.89)	0.757** (2.37)	0.243 (0.57)	0.956*** (2.97)	1.260*** (4.13)	0.549** (2.02)
Constant	-17.621 (-0.90)	-69.156*** (-4.86)	-43.912*** (-3.10)	-74.674*** (-2.87)	-45.578*** (-2.91)	-55.931** (-2.30)	24.282 (0.77)	-66.795*** (-4.84)
Observations	865	1,078	1,129	814	946	955	765	1,178
R-squared	0.873	0.845	0.833	0.879	0.875	0.895	0.743	0.889
City FE	YES	YES	YES	YES	YES	YES	YES	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

Urban scale heterogeneity

Furthermore, this paper evaluates whether urban scale affects the superposition effect of the two policies on ET by splitting cities into two categories: large cities (populations over 5 million) and small cities (populations under 5 million). As shown in Columns (3) and (4) of Table 6, the two policies are associated with a superposition promotion in ET in small cities, and this impact is statistically significant. Similarly, the superposition of the two policies also appears to enhance ET in large cities, with this impact being significant as well, and its coefficient is larger than that in small cities. A potential explanation is that large cities, with their higher concentration of resources, more complex industrial structures, stronger policy execution capabilities, and larger market demand, can better leverage the superposition effect on promoting ET. Moreover, the large population and high EC demand in large cities create a broader market space for new energy products and services, accelerating the pace of ET. In contrast, although small cities can also promote ET under the superposition influence of the two policies, they are relatively insufficient in financial resources, industrial supporting capabilities, and market scale, which to some extent limits the superposition effect on ET.

Economic development level heterogeneity

We adopt urban GDP as an indicator of economic growth and divide the sample into two subgroups according to the median of urban GDP: cities with high economic development and those with low economic development. As shown in Columns (5) and (6) of Table 6, the two policies have a more significant superposition effect on less economically developed cities, while its effect in developed cities is less pronounced. This could be due to differences in development stages and transformation potential between economically developed and less

developed cities. Less developed cities often have a more extensive economic structure with higher dependence on traditional energy, leaving greater space for ET. In contrast, developed cities have already completed IS upgrading, with a relatively low proportion of industries with high EC. Therefore, the marginal impact of further promoting ET through the two policies are weakened, resulting in less significant superposition policy impacts.

Resource endowment heterogeneity

Furthermore, we investigate how cities with different resource endowments respond to the superposition impact of the two policies. The sample is divided into two subgroups: resource-based cities and non-resource-dependent cities. Our findings indicate that the implementation of the two policies have a more significant superposition positive influence on promoting ET in resource-dependent cities. Resource-based cities, featured by a weak ET foundation and an urgent demand for the transformation of traditional energy-intensive industries, can leverage the constraint effect of CAP to break the path dependence on traditional resources, while relying on the incentive effect of NEDC to obtain alternative paths for industrial and ET. Meanwhile, the dual pressures of industrial transformation and environmental protection faced by resource-dependent cities drive them to prioritize the implementation of the superimposed policies and concentrate more resources on related initiatives, thus forming a policy focus effect. Conversely, non-resource-dependent cities, which already have a relatively sound ET foundation, tend to disperse their policy resources across multiple concurrent environmental and energy policies. As a result, the promoting effect of the superposition policy on ET in such cities is relatively limited.

Table 7 Estimated outcomes of heterogeneity tests

VARIABLES	(1)	(2)	(3)	(4)
	Weak regulation	Strong regulation	Immense Pressure	Light Pressure
D	0.089 (0.30)	0.766 (1.61)	0.470** (2.16)	0.434 (0.57)
Constant	41.982 (0.91)	-81.006*** (-6.45)	-61.819*** (-5.13)	4.382 (0.08)
Observations	828	1,091	1,824	113
R-squared	0.888	0.902	0.813	0.923
City FE	YES	YES	YES	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

Environmental regulation intensity heterogeneity

This section examines how variations in environmental regulation affect the relationship between the superposition of the two policies and ET. To explore this, the sample is split into two subgroups on the basis of the median level of sulfur dioxide emissions: one consisting of cities with weak environmental regulations and the other of cities with strong environmental regulations. As shown in Columns (1) and (2) of Table 7, the two policies have a more marked superposition impact in regions with strict environmental restrictions compared to those with less stringent ones. This could be due to the superposition of the two policies in regions with strong environmental regulations, which together drive ET forward. Strict environmental regulations may stimulate enterprises and investors to demand more green technologies [26], while the superposition of the two policies provide support and incentives to satisfy this demand, thereby increasing the use of new energy and accelerating ET.

Officials' promotion pressures heterogeneity

To address the issue of air pollution amid China's ongoing economic development, the evaluation of environmental development and ecological protection has been incorporated into the assessment framework for officials in local governments, serving as a key criterion in the comprehensive evaluation of government official advancement [32]. We have constructed a composite index to measure the promotion pressure faced by officials in regional governments. The sample is subsequently split into two subgroups: cities with intense pressure and those with slight pressure. The results in Columns (3) and (4) of Table 7 indicate that the two policies have a statistically significant superposition influence on advancing ET in cities with immense pressure. However, no significant effect of these policies on ET is observed in cities with light pressure. In cities where promotion pressure is immense,

where environmental performance is crucial to officials' career advancement, there is stronger motivation to implement policies, thereby enhancing the policies' impact on ET.

Conclusions, policy recommendations, and further research directions

Conclusions

This study examines the superposition impact of China's CAP and NEDC pilot policy on ET. Utilizing a dynamic panel model and data from 278 Chinese cities spanning 2010 to 2021, the study arrives at the following conclusions:

First, the simultaneous implementation of these two policies significantly promotes ET. A clear superposition effect emerges, demonstrating that their joint action is more effective in advancing urban energy systems toward green and low-carbon development than either policy acting alone. The robustness of this superposition effect is confirmed through a series of validation tests, underscoring its reliability in supporting ET goals.

Second, the superposition effect operates through three key transmission channels: reducing EC, upgrading IS, and enhancing EE. Through these mechanisms, the policy combination accelerates the shift toward a low-carbon economy.

Third, the impact of the policy superposition on ET exhibits heterogeneity across regions and urban characteristics. The superposition of the two policies yields greater effectiveness in eastern areas and large cities, where the development of economy creates conducive conditions for policy enforcement. Furthermore, cities with developing economies and non-resource-dependent cities demonstrate a stronger ability to utilize the superposition of the two policies to drive ET. In addition, the two policies exert a more notable superposition effect in cities with strict environmental regulations and those facing immense official promotion pressure.

Policy recommendations

Based on these results, the following policy recommendations can be put forward.

First, policy superposition should be reinforced to enhance governance. On one hand, efforts are needed to continuously refine the regulatory framework of clean air policies. This includes stringent enforcement of pollutant discharge standards, introduction of stricter environmental regulations to phase out high-pollution industries, and support for technological transformation in traditional sectors. On the other hand, the scope

of pilot initiatives should be expanded to accelerate the adoption of new energy technologies through fiscal subsidies, tax incentives, and other supportive mechanisms. Meanwhile, an inter-departmental coordination mechanism ought to be established to prevent budgetary competition between environmental protection investments and new energy subsidies, thereby optimizing the efficiency of public resource allocation.

Second, institutional safeguards should be strengthened to activate endogenous drivers for ET. In the domain of EC control, the deployment of smart grids should be accelerated, coupled with the establishment of a dynamic urban EC management system. Concerning IS upgrading, green industry investment funds ought to be established to channel social capital into sectors such as new energy, environmental protection, and energy conservation, while concurrently refining compensation mechanisms for the phasing-out of obsolete production capacity. Regarding EE enhancement, priority should be given to reinforcing research and development (R&D) and promoting key energy-saving technologies. The government should augment investment in the development of high-efficiency energy-saving technologies, thereby providing robust support for enterprises and research institutions to pursue technological innovation.

Third, region-specific and differentiated policy implementation should be strengthened. Eastern regions, with their relatively mature green industrial foundations, should leverage cross-city green technology sharing platforms to disseminate proven technologies and management experience to neighboring areas through mechanisms including technical patent sharing and joint enterprise initiatives. Moreover, unified ET assessment standards should be established within major urban agglomerations (e.g., Beijing-Tianjin-Hebei, Yangtze River Delta). In central and western regions, the government may establish dedicated ET funds to foster distinctive green industries aligned with local resource endowments, thereby reducing reliance on traditional energy through targeted industrial development. Large cities should capitalize on their resource concentration advantages to integrate upstream and downstream segments of the new energy industrial chain, form innovation alliance, and establish closed-loop systems spanning R&D, production, and application. To address the capital and technological constraints in small cities, targeted subsidies for new energy projects and streamlined approval procedures should be introduced. A city-pairing assistance mechanism linking large and small cities can also facilitate talent cultivation and project matching, supporting the design of localized ET pathways in smaller municipalities. Resource-based and economically less developed cities require tailored industrial transition plans. For instance, Datong in Shanxi Province could be

encouraged to develop coalbed methane extraction and pursue green upgrading of its coal chemical industry, supported by tax exemptions for participating enterprises. In contrast, non-resource-dependent and economically advanced cities should prioritize innovation incentives, such as through the establishment of green technology innovation funds, while guiding financial institutions to develop green financial products that provide long-term, low-cost financing for new energy companies. In regions with stringent environmental regulations, environmental impact assessment standards for new energy projects should be refined in accordance with existing legal frameworks. Market-based regulatory instruments and an enterprise environmental credit rating system should be introduced, linking credit performance to subsidies and loan quotas to stimulate corporate environmental responsibility. In regions where officials face high promotion pressure, ET indicators should be integrated into the core performance evaluation criteria for local leaders, complemented by a fault-tolerant mechanism for transitional reforms to encourage proactive engagement in ET.

Fourth, the policy implementation environment should be strategically optimized. To alleviate the fiscal pressures encountered during policy execution, the Public-Private Partnership (PPP) model should be actively leveraged to channel private capital into new energy projects, thereby mitigating the financial burden on local governments. In addressing technological bottlenecks, a specialized research and development program for new energy technologies ought to be established, prioritizing critical domains such as energy storage and hydrogen energy. Substantial incentives should be granted to enterprises that achieve breakthroughs in core technologies. Furthermore, it is imperative to institute a nationally unified monitoring system for the transfer of high-energy-consumption industries. A standardized filing and review process should be implemented for the cross-regional relocation of such projects, with strict prohibitions on their transfer to regions with insufficient environmental carrying capacity, in order to forestall strategic gaming among local jurisdictions.

Further research directions

While this study provides crucial insights into the nexus between the superposition of the two policies and ET, several limitations should be acknowledged, which in turn offer avenues for future research.

First, the empirical scope of this research is primarily confined to Chinese cities, for which a measurement system for ET was specifically constructed. Future studies should endeavor to broaden this analysis to a global scale to investigate cross-national variations in the superposition effect. Nevertheless, the index system employed

herein may necessitate adjustments to accommodate such international disparities.

Second, although this study validates the transmission channels of EC, IS, and EE, several dimensions remain under-explored. These include the dynamic evolution of policy effects over time and potential nonlinear relationships in the superposition effect on ET. Moreover, the present analysis does not adequately consider the potential interactions and transmission channels among EC, IS, and EE. Future research should focus on compiling more granular, cross-industry urban energy datasets and developing an analytical framework capable of capturing these interconnected mechanisms. Such efforts would help to elucidate how policy superposition induces systemic transformation through the interactive effects of multiple transmission channels.

Finally, this study does not explicitly account for the spatial spillover effects stemming from the superposition of the two policies. The superposition effect of the two policies is likely to extend beyond municipal boundaries, affecting adjacent regions through policy diffusion, industrial linkages, and energy commerce. Future research could employ spatial econometric models to quantitatively assess the magnitude and scope of these spillover effects. Such an approach would afford a more comprehensive understanding of the regional interactions within the policy implementation process and contribute to the design of targeted and efficient policy packages tailored to cities at different stages of development.

Appendix A: Variable definitions

Classifications	Variables	Symbol	Description
Explanatory Variable	The Superposition of the Two Policies	D	specific details about the explanation can be found in Sect. " Independent variable "
Explained Variable	Energy Transition	ET	figured out through the entropy weighting method, with EC, IS, and EE taken into account
Transmission Channel variables	Energy Consumption	EC	
	Industrial Structure	IS	
	Energy Efficiency	EE	
Control variables	Population Concentration Level	PD	conceptualized as the count of permanent urban residents per square kilometer
	Urbanization Rate at the Regional Level	URB	defined as the proportion of a region's total population that resides in metropolitan areas
	Economic Policy Uncertainty	EPU	constructed by taking the monthly EPU indexes' arithmetic average for each year
	GDP growth	GDP-growth	sourced from CSMAR database
	Energy Finance	EF	measured by local energy conservation and environmental protection expenditures to capture the carrot and stick strategies, respectively
	Public Environmental Attention	Public	formed by annual Baidu search volume of environment-related keywords, including pollution, environmental protection, carbon neutrality, carbon peaking, and carbon emissions
	Credit Amount	Car	calculated by the loans used to develop energy economy and other related ET
Alternative Control variables	Industry Level	IL	expressed by the ratio of employment in the secondary industry to the total quantity of urban employees
	Human Capital Level	Hcp	based on the relative representation of specialist and undergraduate students among the local population
	Fixed Asset Investment	Fai	sums up the total value of all invested fixed assets and Increased fixed asset investment
	Financial Development Level	Fin	measured by the proportion of overall deposits and loans from financial institutions to the regional GDP

Appendix B: Results of the multicollinearity assessment

VARIABLES	VIF
D	1.34
PD	1.52
URB	1.57
EPU	2.01
GDP_growth	1.95
EF	1.54
Public	1.73
Car	1.01
Mean VIF	1.58

Appendix C: Results of alternative dependent variable

VARIABLES	ETNew
D	0.430*** (2.792)
Constant	-9.109 (-1.054)
Observations	1,943
R-squared	0.828
City FE	YES

Appendix D: Results of alternative control variable

VARIABLES	ET
D	0.837*** (4.096)
IL	-8.404*** (-10.590)
Hcp	1.747*** (5.134)
Fai	0.994*** (7.107)
Fin	5.430*** (10.535)
Constant	48.052** (11.276)
Observations	2,912
R-squared	0.833
City FE	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

Appendix E: Results of sensitivity analysis of policy implementation time windows

VARIABLES	ET
D_late	0.942*** (3.543)
Constant	-56.608*** (-4.741)
Observations	1,943
R-squared	0.855
City FE	YES

Significance at 1%, 5%, and 10% is indicated with ***, **, and *, respectively

Acknowledgements

We acknowledge the financial support from the National Natural Science Foundation of China (72404249), the Social Science Foundation of Guangxi Zhuang Autonomous Region in China (24GLF028), the Natural Science Foundation of Shandong Province (ZR2023QG083), and the Fundamental Research Funds for the Central Universities (HIT.HSS.202227).

Author contributions

Fangkun Liu: Validation, Methodology, Writing-review&editing. Jiaxin Zhang: Data curation, Software, Writing-original draft. Wenmin Zhan: Investigation, Resources, Writing-review&editing. Shilei Hu: Writing-review&editing, Resources. Yanchao Feng: Conceptualization, Formal analysis, Writing-review&editing.

Data availability

Data will be made available on reasonable request.

Declarations

Ethics and consent to participate declarations

Not applicable.

Consent to publication

Not applicable.

Disclosure of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Received: 22 August 2025 / Accepted: 2 November 2025

Published online: 15 December 2025

References

- Baron RM, Kenny DA. The moderator–mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. *J Pers Soc Psychol*. 1986;51(6):1173.
- Boulanouar Z, Essid L, Ullah S. Energy transition investments and carbon emissions: asymmetric and dynamic effects across developed and emerging economies. *Financ Res Lett*. 2025;83:107746.
- Buteau S, Doucet M, Tétreault LF, Gamache P, Fournier M, Brand A, et al. A population-based birth cohort study of the association between childhood

- onset asthma and exposure to industrial air pollutant emissions. *Environ Int.* 2018;121:23–30.
- 4. Cao WJ, Zhang XW, Iqbal K. Using green finance to study energy elasticity, coal subsidy, energy transition and energy dependence in E7 economies: an efficiency analysis with data envelopment analysis. *Energy Strategy Rev.* 2025;60:101794.
 - 5. Chai C, Zhang B, Li Y, Niu W, Zheng W, Kong X, et al. A new multi-dimensional framework considering environmental impacts to assess green development level of cultivated land during 1990 to 2018 in China. *Environ Impact Assess Rev.* 2023;98:106927.
 - 6. Chen L, He L, Liu R, Fu Y. Mapping risk transmission in China's energy industry chain: insights derived from the industry chain structure. *Econ Anal Policy.* 2025. <https://doi.org/10.1016/j.eap.2025.07.001>.
 - 7. Cheng H, Wu BY, Jiang XK. Study on the spatial network structure of energy carbon emission efficiency and its driving factors in Chinese cities. *Appl Energy.* 2024;371:123689.
 - 8. Cheng J, Tong D, Liu Y, Geng GN, Davis SJ, He KB, et al. A synergistic approach to air pollution control and carbon neutrality in China can avoid millions of premature deaths annually by 2060. *One Earth.* 2023;6(8):978–89.
 - 9. Diaz-Rainey I, Gehricke SA, Roberts H, Zhang R. Trump vs. Paris: the impact of climate policy on US listed oil and gas firm returns and volatility. *Int Rev Financ Anal.* 2021;76:101746.
 - 10. Dong M, Li C, Sampene AK. Exploring the impact of green finance, technological innovation, mineral resources, and carbon tax on the green energy transition. *Smart Energy.* 2025;19:100189.
 - 11. Fernández-Navarro P, García-Pérez J, Ramis R, Boldo E, López-Abente G. Industrial pollution and cancer in Spain: an important public health issue. *Environ Res.* 2017;159:555–63.
 - 12. Geels FW, Sovacool BK, Schwanen T, Sorrell S. The socio-technical dynamics of low-carbon transitions. *Joule.* 2017;1(3):463–79.
 - 13. Guo Q, Zeng D, Lee C-C. Impact of smart City pilot on energy and environmental performance: China-based empirical evidence. *Sustain Cities Soc.* 2023;97:104731.
 - 14. Harrison RM, Brunekreef B, Keuken M, van der Gon HD, Querol X. New directions: cleaning the air: will the European commission's clean air policy package of December 2013 deliver? *Atmos Environ.* 2014;91:172–4.
 - 15. He Y, Zhang XY, Zhang YL. Can new energy policy promote corporate total factor energy efficiency? Evidence from China's new energy demonstration city pilot policy. *Energy.* 2025;318:Article134782.
 - 16. Hepburn C, Qi Y, Stern N, Ward B, Xie CP, Zenghelis D. Towards carbon neutrality and China's 14th Five-Year plan: clean energy transition, sustainable urban development, and investment priorities. *Environ Sci Ecotechnol.* 2021;8:100130.
 - 17. Howlett M. Moving policy implementation theory forward: A multiple streams/critical juncture approach. *Public Policy Adm.* 2019;34(4):405–30.
 - 18. Huang ZN, Jia HH, Shi XH, Xie ZY, Cheng JP. Revealing the impact of China's clean air policies on synergistic control of CO₂ and air pollutant emissions: evidence from Chinese cities. *J Environ Manage.* 2023;344:118373.
 - 19. Kartal MT, Pata UK. Impacts of renewable energy, trade globalization, and technological innovation on environmental development in China: evidence from various environmental indicators and novel quantile methods. *Environ Dev.* 2023;48:100923.
 - 20. Khan I, Zakari A, Dagar V, Singh S. World energy trilemma and transformative energy developments as determinants of economic growth amid environmental sustainability. *Energy Econ.* 2022;108:105884.
 - 21. Lee C, Ogata S. Every coin has two sides: dual effects of energy transition on regional sustainable development—a quasi-natural experiment of the new energy demonstration city pilot policy. *Appl Energy.* 2025;390:125772.
 - 22. Lee CC, Wang EZ. Energy regulation and industrial robot adoption: the role of human capital. *Energy Econ.* 2025;146:108499.
 - 23. Lin YY, Cheung A. Climate policy uncertainty and energy transition: evidence from prefecture-level cities in China. *Energy Econ.* 2024;139:107938.
 - 24. Lin YY, Cheung A. Climate policy uncertainty and energy transition: evidence from prefecture-level cities in China. *Energy Econ.* 2024;139(16):107938.
 - 25. Liu FQ, Kang YX, Guo K, Sun XL. The relationship between air pollution, investor attention and stock prices: evidence from new energy and polluting sectors. *Energy Policy.* 2021;156:112430.
 - 26. Luo Y, Salman M, Lu Z. Heterogeneous impacts of environmental regulations and foreign direct investment on green innovation across different regions in China. *Sci Total Environ.* 2021;759:143744.
 - 27. Ma D, Zhu YJ, Lee CC. The impact of new energy pilot city policies on urban green innovation: evidence from China's city level. *Econ Anal Policy.* 2025;87:585–604.
 - 28. Managi S, Opaluch JJ, Jin D, Grigalunas TA. Environmental regulations and technological change in the offshore oil and gas industry. *Land Econ.* 2005;81(2):303–19.
 - 29. Moustakas K, Loizidou M, Klemes J, Varbanov P, Hao JL. New developments in sustainable waste-to-energy systems. *Energy.* 2023;284:Article129270.
 - 30. Peng W, Kim SE, Purohit P, Urpelainen J, Wagner F. Incorporating political-feasibility concerns into the assessment of India's clean-air policies. *One Earth.* 2021;4(8):1163–74.
 - 31. Pitman EJ. Significance tests which May be applied to samples from any populations. *Supplement J Royal Stat Soc.* 1937;4(1):119–30.
 - 32. Qian X, Cao T, Li W. Promotion pressure, officials' tenure and lending behavior of the city commercial banks. *Econ Res J.* 2011;46(12):72–85.
 - 33. Ren XH, Li JY, He F, Lucey B. Impact of climate policy uncertainty on traditional energy and green markets: evidence from time-varying Granger tests. *Renew Sustain Energy Rev.* 2023;173:Article113058.
 - 34. Ren XH, Zhang X, Yan C, Gozgor G. Climate policy uncertainty and firm-level total factor productivity: evidence from China. *Energy Econ.* 2022;113:106209.
 - 35. Saltari E, Travaglini G. The effects of environmental policies on the abatement investment decisions of a green firm. *Resour Energy Econ.* 2011;33(3):666–85.
 - 36. Seyedrezaei M, Becerik-Gerber B, Kohut TJ. Exploring energy consumption in energy-efficient, affordable housing in Southern California: behavioral insights and financial implications. *Energy Build.* 2025;331:115369.
 - 37. Song Q, Zhou N, Liu T, Siehr SA, Qi Y. Investigation of a coupling model of coordination between low-carbon development and urbanization in China. *Energy Policy.* 2018;121:346–54.
 - 38. Vrontisi Z, Abrell J, Neuwahl F, Saveny B, Wagner F. Economic impacts of EU clean air policies assessed in a CGE framework. *Environ Sci Policy.* 2016;55:54–64.
 - 39. Wang H, Sun HP. New energy pilot policy, financial subsidies and green technology progress. *Int J Hydrogen Energy.* 2025;115:400–9.
 - 40. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Beagleby J, Belesova K, et al. The 2020 report of the Lancet countdown on health and climate change: responding to converging crises. *Lancet.* 2021;397(10269):129–70.
 - 41. Wu T, Qiao Z. Synergistic governance of urban heat islands, energy consumption, carbon emissions, and air pollution in China: evidence from a spatial Durbin model. *Environ Pollut.* 2025;372:126025.
 - 42. Xia D, Zhang L. Coupling coordination degree between coal production reduction and CO₂ emission reduction in coal industry. *Energy.* 2022;258:124902.
 - 43. Xia LL, Fu WQ, Ke YH, Wang RW, Liang S, Yang ZF. China's economic restructuring helps improve land-use resilience of carbon metabolism: evidences from three Chinese megacities. *Appl Energy.* 2025;377:124686.
 - 44. Xiao QY, Geng GN, Liang FC, Wang X, Lv Z, Lei Y, et al. Changes in spatial patterns of PM_{2.5} pollution in China 2000–2018: impact of clean air policies. *Environ Int.* 2020;141:105776.
 - 45. Xie Y, Wu D, Zhu S. Can new energy vehicles subsidy curb the urban air pollution? Empirical evidence from pilot cities in China. *Sci Total Environ.* 2021;754:142232.
 - 46. Xu M, Qin ZF, Zhang SH. Integrated assessment of cleaning air policy in China: a case study for Beijing-Tianjin-Hebei region. *J Clean Prod.* 2021;296:126596.
 - 47. Xu M, Wang MH, Zhao MD, Weng ZX, Tong F, Pan YJ, et al. Uncovering the differentiated impacts of carbon neutrality and clean air policies in multi-provinces of China. *iScience.* 2024;27(6):109966.
 - 48. Yalew SG, van Vliet MT, Gernaat DE, Ludwig F, Miara A, Park C, Byers E, De Cian E, Piontek F, Iyer G. Impacts of climate change on energy systems in global and regional scenarios. *Nat Energy.* 2020;5(10):794–802.
 - 49. Yu B, Fu J, Dai Y, Luo X, Chen Y, Wu Y, et al. Industry chain risks for the diffusion of low-carbon technologies in the cement industry. *J Environ Manage.* 2025;382:125404.
 - 50. Yu YJ, Dai C, Wei YG, Ren HM, Zhou JW. Air pollution prevention and control action plan substantially reduced PM_{2.5} concentration in China. *Energy Econ.* 2022;113:106206.
 - 51. Zhang QN, Huang XW, Xu Y, Bhuiyan MA, Liu P. New energy demonstration city pilot and green energy consumption: evidences from China. *Energy Rep.* 2022;8:7735–50.
 - 52. Zhang S, Yang DW, Meng HS, Wan M, Ji YJ, Zhang JM, et al. Spatiotemporal pattern evolution and driving factors of China's energy transition from a heterogeneity perspective. *J Clean Prod.* 2025;487:144624.

53. Zhao LH, Rasoulinezhad E. Role of natural resources utilization efficiency in achieving green economic recovery: evidence from BRICS countries. *Resour Policy*. 2023;80:103164.
54. Zhao X-g, Zhu J. Industrial restructuring, energy consumption and economic growth: evidence from China. *J Clean Prod*. 2022;335:Article130242.
55. Zhou L, Fan JS, Hu MZ, Yu XF. Clean air policy and green total factor productivity: evidence from Chinese prefecture-level cities. *Energy Econ*. 2024;133:107512.
56. Zhu C, Lee CC. The effects of low-carbon pilot policy on technological innovation: evidence from prefecture-level data in China. *Technol Forecast Soc Change*. 2022;183:121955.
57. Zivin JG, Neidell M. The impact of pollution on worker productivity. *Am Econ Rev*. 2012;102(7):3652–73.
58. Farrar DE, Glauber RR. Multicollinearity in regression analysis: the problem revisited. *Rev Economic Stat*. 1967; 49(1): 92–107.
59. Fisher RA. (1960). The design of experiments.
60. Gavrilidis K. (2021). Measuring climate policy uncertainty. Available at SSRN 3847388.
61. Li Z, Tang X, Xu Z, Mi F. How does the new energy demonstration City pilot affect corporate green M&A: evidence of A-share listed companies in China. *Finance Res Lett*. 2025; 85: 107909.
62. Zha DL, Jiang PS, Zhang CQ, Xia D, Cao Y. Positive synergy or negative synergy: an assessment of the carbon emission reduction effect of renewable energy policy mixes on china's power sector. *Energy Policy*. 2023;183(20):113782.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.