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Research article

Assessing the rebound effects of clean energy sectors and carbon tax on fossil fuels: A dynamic CGE-based analysis

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ABSTRACT

Improving the efficiency of clean energy sectors is widely recognized as a key strategy for accelerating the low-carbon transition. While efficiency gains in fossil fuels often raise concerns about rebound effects, similar effects in clean energy may instead support cleaner production and energy structure optimization. This study aims to quantify the macroeconomic and environmental impacts of rebound effects resulting from clean energy efficiency improvements, with particular attention to sectoral differences and policy interactions.

Using a dynamic computable general equilibrium (CGE) model, we evaluate how efficiency gains in hydropower, wind, solar, and nuclear energy affect economic output, energy demand, and carbon emissions. Unlike previous studies that treat clean energy as a single category, we disaggregate across technologies and incorporate a carbon tax scenario to explore potential policy synergies. The results show that clean energy efficiency improvements can lead to backfire effects, especially in the short term, by significantly increasing clean energy consumption. Carbon taxation reinforces these effects by further reducing fossil fuel use and supporting long-term climate goals. These findings highlight the importance of technology-specific analysis and demonstrate that aligning energy efficiency strategies with carbon pricing can produce complementary economic and environmental benefits, contributing to more effective and sustainable energy policy design.

1. Introduction

In pursuing sustainable development and effective environmental management, the international community has increasingly focused on clean and renewable energy sources as fundamental to transitioning toward a low-carbon future and enhancing energy security (Hu and Cheng, 2017; Ji et al., 2022). These energy sources minimize environmental pollution during their production processes and help alleviate the depletion of conventional energy resources. As the world's largest energy consumer, China accounted for 27.7 % of the global primary energy consumption, 30.6 % of the global renewable energy consumption, and 32.1 % of the worldwide carbon dioxide emissions from energy in2023.[1] As a result, improving the efficiency of clean energy usage holds significant implications for achieving green economic growth in China and globally (Fell et al., 2022; Jia and Lin, 2022a).

While the rebound effect has been extensively studied in fossil fuel systems, its occurrence and implications in the clean energy context remain underexplored and often misunderstood. For instance, Brockway et al. (2021) stated that more than half of the anticipated energy savings from efficiency improvements in traditional energy sectors could be eroded by rebound effects. Likewise, Du et al. (2020) analyzed the rebound effects in China's transportation sector and revealed how varying policies and technological advancements influence the magnitude of these effects following a 10 % improvement in energy efficiency. Turner and Hanley (2011) also highlighted that rebound effects arise from a confluence of general equilibrium effects, adding depth to our understanding of their complexity. Collectively, these studies emphasized the intricate relationship between energy efficiency improvements

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[1] 2024 Statistical Review of World Energy, https://www.energyinst.org/statistical-review.

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and energy consumption, shaped by economic, technological, or political factors. Importantly, clean energy rebound effects differ from fossil fuel rebound effects. The latter tends to increase emissions and fossil dependence, whereas the former—if properly understood and guided—may enhance clean energy deployment, optimize the energy mix, and reduce emissions. Recognizing this distinction is critical to designing effective energy policy.

The analysis surrounding enhancing clean energy efficiency and its potential energy rebound effects in China is necessary and urgent. Notably, China has made remarkable strides in its energy transformation, with clean energy consumption reaching 26.4 % of the total energy mix in 2023—an increase of 10.9 % from2013.[2] This shift underscores the critical role of clean energy efficiency in achieving China's dual carbon goals: peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, as pledged during the 75th United Nations General Assembly. However, the complexity of energy efficiency improvements and the potential for rebound effects introduce significant uncertainty regarding their effectiveness in reducing carbon emissions. The improved energy efficiency of fossil fuel often results in lower energy costs, which can incentivize increased energy consumption, partially offsetting the energy-saving effects (Kong et al. (2023).

Additionally, sector-specific analyses provide further insight into the rebound phenomenon. Studies by Jia and Lin (2022a) and Liu et al. (2021a,b) examined the energy efficiency rebound effect in China's coal industry, highlighting its potential impact on national energy security and achieving the 2060 carbon neutrality goal. However, the rebound effect in clean energy differs from that in fossil fuels. While fossil fuel rebound increases carbon emissions, clean energy rebound can optimize the energy mix and reduce emissions. To deepen understanding, this study explores whether combining energy efficiency improvements with carbon taxation can mitigate fossil fuel use while leveraging the positive spillovers of clean energy rebound.

Theoretically, by increasing the costs of fossil fuels, a carbon tax can decrease their consumption, enhance the competitiveness of clean energy, and potentially stimulate innovation in energy technology (Galvin et al., 2021; Li et al., 2017). In 2023, China's total primary energy production reached 4.83 billion tons of standard coal, with coal accounting for 66.6 % of the overall production and 55.3 % of total primary energy consumption.[3] Given these substantial energy demands and a coal-dominated structure, examining the interplay between carbon tax policies and their impact on mitigating the rebound effect becomes crucial. Existing research has predominantly focused on the rebound effect of fossil fuels such as coal and coke (Chen et al., 2021; Liu et al., 2021a,b; Lu et al., 2017). However, limited studies have explored the macroeconomic impact of the rebound effect in clean energy from both consumption and production perspectives or how carbon tax policies can be integrated to enhance the benefits of the rebound effect.

This study presents a quantitative analysis to assess the complex rebound effects of efficiency improvements in clean energy sectors on energy consumption, economic growth, and environmental protection. Using a dynamic CGE model, we evaluate both short-term and long-term macroeconomic rebound effects from efficiency improvements in four key clean energy types: hydroelectric, wind, solar, and nuclear energy. By comparing rebound effects at both the production and consumption levels, this study aims to provide a comprehensive understanding of their impacts under various energy policies, offering valuable data support for energy efficiency strategies. Additionally, we explore the scenario of imposing a carbon tax rate of 50 yuan/ton on fossil fuels, examining how this tax affects fossil fuel consumption and the potential role of clean energy efficiency improvements in reducing fossil fuel dependency and promoting cleaner production.

Dynamic CGE model application: We employ a dynamic CGE model to analyze the economic and environmental impacts of efficiency improvements in clean energy sectors, with a focus on clean energy rather than fossil fuels (Chen et al., 2021; Liu et al., 2021a,b; Lu et al., 2017). By adopting this model, we assess the direct and indirect effects of energy efficiency improvements, offering critical insights for energy policy and environmental protection strategies. This comprehensive approach enables a nuanced understanding of the rebound effects in clean energy sectors.

Technology-specific analysis of clean energy: Unlike previous studies that aggregated clean energy sources into a single category (Tian et al., 2023) or focused on the rebound effects of a single energy type (Ghaedi et al., 2024; Fell et al., 2022; Zhang et al., 2021), we differentiate among wind, hydropower, solar, and nuclear energy. By incorporating these distinct sectors into the dynamic CGE framework, we highlight the varying responses of different clean energy technologies at both production and consumption levels. This approach reveals the importance of technology-specific analyses and addresses the limitations of treating clean energy as a homogeneous category.

Carbon tax policy simulation: We also integrate a carbon tax policy into the analysis to examine its impact on improvements in clean energy efficiency. By simulating a carbon tax on fossil fuels, we assess how taxation can optimize energy market structures, influence consumer behavior, and support environmental sustainability. While carbon taxes have been explored in the context of fossil fuels (Du et al., 2020; Wei et al., 2022), this study is among the few to consider the interaction between carbon taxation and sector-specific clean energy efficiency improvements. This integrated approach sheds light on the role of carbon taxation in reducing fossil fuel dependence and promoting clean energy, emphasizing the strategic importance of clean energy in achieving energy security and environmental goals.

These innovations contribute to a deeper understanding of clean energy policy adjustments, showing that pursuing economic growth and enhancing environmental protection is possible. The simulated results offer fresh perspectives and empirical evidence for policymakers, reinforcing the importance of clean energy in the global transition to a sustainable future. This study is structured as follows: Section 2 provides a literature review. Section 3 details the model structure, including the measurement of rebound effects, the dynamic CGE model structure, and the preferred scenario settings. Section 4 reports simulation results and related discussions. Section 5 presents the research conclusions.

2. Literature review

2.1. The energy rebound effect

The rebound effect arising from energy efficiency improvements has always been an important research topic, with existing research mainly focusing on fossil energy. While enhanced efficiency aims to reduce energy consumption, actual savings often fall short due to substitution, income, or output effects (Jevons, 1865; Sorrell, 2009; Gillingham et al., 2016). The CGE models have become one of the primary tools for studying energy rebound effects due to their comprehensiveness and flexibility in analyzing the interactions between economic policies and energy consumption (Brockway et al., 2021; Lu et al., 2017).

Specifically, Du et al. (2020) and Jia and Lin (2022a) analyzed the energy rebound effects in China after energy efficiency improvements through a CGE model, revealing the impact of different policies and technological improvements on the magnitude of rebound effects. Their research highlights the practicality of CGE models in predicting and analyzing the implications of energy policies, particularly in assessing long-term and complex economic feedback mechanisms. Other research also focuses on the rebound effects of energy efficiency improvements in fossil fuels and typically analyses these effects at the industry and

[2] National Energy Administration, China's Energy Transition (2024), https://www.nea.gov.cn/2024-08/29/c_1310785406.htm.

[3] Ministry of Natural Resources of the People's Republic of China, China Mineral Resources Report, https://www.mnr.gov.cn/sj/sjfw/kc_19263/zgkczybg/202410/t20241022_2871217.html.

macroeconomic levels (Li et al., 2017; Li and Lin, 2015; York et al., 2022).

Energy security is widely recognized as a complex and multi-dimensional issue, involving economic, environmental, and geopolitical considerations. In the context of renewable energy expansion, increasing the share of clean energy can enhance energy security by lowering dependence on imported fossil fuels and reducing exposure to external supply risks. However, it may also introduce new concerns such as grid stability and market volatility (Bigerna et al., 2021). The 4As framework—Availability, Affordability, Acceptability, and Adaptability—is commonly used to describe these dimensions (APERC, 2007). Cherp and Jewell (2014) further argued that focusing only on this checklist may overlook underlying systemic risks.

Despite these discussions, few studies clarify which aspect of energy security they address, and most overlook the potential link between clean energy rebound effects and energy security outcomes. Existing research tends to treat rebound effects as purely economic or environmental issues, without considering their implications for national energy resilience. This study addresses this gap by focusing on the Acceptability dimension and defining energy security as a nation's ability to maintain a stable and sustainable energy supply through improved efficiency and greater use of domestic clean energy.

Building on this perspective, a growing number of studies have begun to explore rebound effects within clean energy systems. For instance, Vélez-Henao et al. (2020) explored the environmental rebound effect in the household sector from increased shares of wind power into the Colombian power grid. Deng and Newton (2017) established a dynamic panel model to evaluate the rebound effect of solar photovoltaics on electricity use. These studies reveal the complex rebound effects that may accompany the environmental benefits of promoting renewable energy and provide essential insights for formulating energy policies and environmental protection strategies. Subsequently, Wang et al. (2018) studied the direct energy rebound effect using the LMDI decomposition model and the CD lifecycle assessment model. They found that significant rebound effects still exist even with promoting renewable energy, indicating that merely improving energy efficiency is insufficient to fully achieve energy conservation and emission reduction goals. Furthermore, Galvin et al.(2021) proposed a theoretical framework to explain how renewable electricity rebound effects impact the power sector's decarbonization process. Their framework extended the traditional literature on energy efficiency to include discussions on renewable energy, emphasizing the complexity and necessity of understanding this phenomenon. However, the study does not sufficiently consider variations in market interaction and sectoral production and consumption conditions.

Few studies utilize dynamic CGE models to investigate the rebound effects of clean energy. Previously, Liang et al. (2009) employed a static multi-sector CGE model to calculate the rebound effects of improved end-use energy efficiency in China's hydropower and nuclear power sectors. Their research indicated that efficiency improvements in both sectors resulted in varying backfire effects. However, it should be critiqued that a static model may not fully capture modern energy systems' dynamic complexities and evolving nature, possibly leading to an oversimplification of rebound effects. Jia and Lin (2022a) developed a dynamic CGE model to study the emission reduction effects of technological advancements in the thermal and clean energy power generation sectors. CGE models, by encompassing all sectors and markets within an economy, can capture the transmission effects of policy changes throughout the economic system. This comprehensive perspective is crucial for understanding the potential positive and negative feedback mechanisms following improvements in energy efficiency (Du et al., 2020; Kahouli and Pautrel, 2023; Lu et al., 2017; Yu et al., 2015; Zimmermann et al., 2021). For example, Böhringer and Rutherford (2008) emphasized the advantages of CGE models in integrating technological details with macroeconomic interactions, enabling accurate predictions of interactions between energy markets and other economic sectors. Additionally, CGE models can simulate various environmental and energy policies, such as carbon taxes and subsidy policies, and their economic impacts. The results of these models assist policymakers in assessing the economic implications of different policy options, especially in predicting potential rebound effects post-policy implementation (Fu et al., 2021; Guo et al., 2014; Nong, 2020; Zou et al., 2018). For instance, Nong (2020) assessed the impact of carbon tax policies on South Africa's industrial sectors and overall economy, finding that while carbon tax policies incur higher economic costs, they also expand clean energy sector production, promoting a shift towards a low-carbon and sustainable economy in South Africa. Wissema and Dellink (2007) used a CGE model to evaluate the impact of a carbon tax on the Irish economy, revealing that improvements in energy efficiency could lead to increased economic activity and rebound effects.

2.2. Carbon tax

Carbon taxation has attracted considerable attention as a policy instrument to balance economic growth with environmental objectives, generating increasing interest in its potential for achieving a "double dividend" effect—simultaneously reducing carbon emissions while fostering economic efficiency (Jia et al., 2025; Liu et al., 2021a,b; Nong et al., 2021).

In China, many studies have focused on assessing the effects of carbon tax implementation, exploring its comprehensive impact on energy efficiency, economic growth, and environmental protection. For example, Yu et al. (2020) analyzed the effect of a carbon tax on China's power industry using a differentiated input-output model, finding that a carbon tax effectively encourages enterprises to take measures to reduce CO_2 emissions. Additionally, Dong et al. (2017) utilized a CGE model to evaluate the future impact of a carbon tax on CO_2 reduction and inter-provincial differences in China, providing policy recommendations for carbon tax implementation. Du et al. (2020) constructed a CGE model to assess the rebound effects of energy efficiency improvements in the transportation sector and examined the mitigation effects of carbon tax and environmental regulatory policies on backfire effects.

In recent studies, scholars have paid more attention to the optimal carbon tax rate. For instance, Zhou et al. (2018) investigate carbon taxation in the transport sector and identify 50 RMB per ton of CO_2 as an optimal rate that balances energy demand reduction, carbon mitigation, and social welfare improvement. Their findings underscore the nuanced interplay between tax policy and sector-specific characteristics. Du et al. (2020) further confirm that a 50 RMB/ton carbon tax can diminish rebound effects linked to energy efficiency enhancements in transportation, thus moving closer to the dual goals of environmental protection and economic well-being. Similarly, Shi et al. (2019) conclude that a rate of 60 RMB per ton for the construction sector is most appropriate, successfully lowering emissions while containing negative macroeconomic impacts to a minimal level.

When analyzed through a CGE model, carbon taxes can be assessed in conjunction with macroeconomic variables such as prices, wages, and aggregate output, thereby offering a holistic view of policy repercussions across an entire economy(Dong et al., 2018; Du et al., 2020; Lin and Jia, 2018; Wei et al., 2022). This comprehensive framework enables a dynamic assessment of how a carbon tax simultaneously influences production costs, consumer behavior, and environmental outcomes. As a result, adopting a CGE perspective facilitates the design of robust carbon tax policies that incorporate long-term economic growth trajectories, promoting balanced environmental and economic outcomes in the transition toward a low-carbon future. However, while existing studies have extensively explored the macroeconomic effects of carbon taxation, few have investigated how carbon taxes can be leveraged alongside improvements in clean energy efficiency to accelerate decarbonization.

2.3. Literature gaps

This study addresses several key research gaps related to carbon taxes, rebound effects, and clean energy. First, while previous studies focus on rebound effects in fossil fuel contexts (Jia et al., 2025; Du et al., 2020; Li et al., 2017; Lu et al., 2017), there is limited research on sector-specific rebound effects for clean energy, especially for wind, solar, hydropower, and nuclear, using a dynamic CGE framework. Most existing analyses rely on static models, leaving a gap in understanding the dynamic interactions of efficiency improvements in clean energy. Second, we integrate carbon tax with clean energy efficiency improvements into an integrated framework (Jia and Lin, 2022a). Yet current literature often examines carbon taxes and renewable energy efficiency improvements separately, neglecting the potential synergies of these two. At the same time, many studies group clean energy technologies together, ignoring the distinct technological and economic characteristics of wind, solar, hydropower, and nuclear energy. This study differentiates between these sectors to provide a more accurate assessment of their respective rebound effects. Lastly, while carbon taxes and renewable energy deployment are commonly discussed, there is a lack of research on policy implications that link economic efficiency, environmental goals, and the specific dynamics of different clean energy technologies. This study provides valuable insights for designing effective policies to guide sustainable energy transitions.

In summary, this study's unique contribution lies in examining the rebound effects in multiple clean energy subsectors within a dynamic CGE framework while incorporating the role of carbon taxation. It provides critical insights for promoting sustainable, low-carbon energy transitions. Table 1 presents the relevant literature related to the rebound effect.

3. The model and scenarios

3.1. Measurement of rebound effect

We focus on the energy rebound effect on the macroeconomy resulting from improvements in clean energy efficiency. The energy rebound effect again suggests the phenomenon where anticipated energy saving from improved energy efficiency may be partially or wholly offset or surpassed by the increase in energy demand. The definition proposed by Saunders (2008) is among the most widely used in studies (Du et al., 2020; Lu et al., 2017) measuring the energy rebound effect at the macroeconomic level. Let's set the production function as $Y = f(k, L, \tau E)$, where Y means output, K represents capital, L denotes labor, and E is energy. The parameter τ denotes energy efficiency, The elasticity of energy use relative to energy efficiency is defined, η, as follows:

$$\eta = \frac{d \ln E}{d \ln \tau} \tag{1}$$

The formula for the rebound effect resulting from improvements in energy efficiency is as follows:

$$RE = 1 + \eta \tag{2}$$

Saunders (2008) demonstrated that the rebound effect could manifest in five distinct scenarios:(1) Backfire Effect: energy use increases beyond the baseline due to strong rebound forces, meaning efficiency gains paradoxically lead to greater energy consumption, $\eta > 0$, $RE > 1$; (2) Full rebound: the entire potential energy saving is offset, leaving actual energy consumption unchanged despite improved efficiency, $\eta = 0$, $RE = 1$; (3) Partial rebound: only part of the technical saving is offset; energy consumption still decreases, but by less than expected, $-1 < \eta < 0$, $0 < RE < 1$; (4) Zero rebound: no behavioral or economic offset occurs, efficiency gains fully translate into energy saving, $\eta = -1$, $RE = 0$; (5) Super rebound: efficiency improvements are reinforced by complementary effects (e.g., structural change, regulation), leading to greater-than-expected reductions in energy use, $\eta < -1$, $RE < 0$.

The backfire effect, commonly associated with fossil energy, indicates that improvements in energy efficiency led to an increase in actual energy usage rather than achieving fossil energy savings, resulting in counterproductive outcomes. However, this backfire effect can work favorably in the context of improved clean energy efficiency, as it contributes to amplifying clean energy usage. Regarding the rebound effect quantification, we follow Lecca et al. (2014) and Lu et al. (2017) and adopt efficiency units rather than physical units to measure the energy value E. The macroeconomic rebound effect is further decomposed into consumption and production components for more detailed analysis. Therefore, the rebound effect in the clean energy sector is expressed as follows:

$$R_{clean} = 1 + \frac{\overline{E}_{clean}}{\tau} \tag{3}$$

where $\overline{E}_{clean} = \frac{\Delta E_{clean}}{E_{clean}}$ represents the rate of change in energy use due to improvements in energy efficiency in the clean energy sector, including hydropower, wind power, nuclear power, and solar energy. We can further adjust the expression to derive the specification used for representing the macroeconomic rebound effect, expressed as,

$$R_T = 1 + \frac{\overline{E}_T}{\alpha_{clean}\tau} \tag{4}$$

Here R_T is the macroeconomic rebound effect. $\alpha_{clean} = \frac{E_{clean}}{E_T}$ represents the rate of change in energy use due to efficiency improvements in the clean energy sector. Then, we further decompose the total energy use $\frac{\overline{E}_T}{\alpha_{clean}\tau}$ into the production and consumption sectors, with the consumption sector including domestic consumption[4] and exports. The formula for the macroeconomic rebound effect is as follows:

$$R_T = 1 + \frac{\sigma E_T}{E_{clean}\tau} \tag{5}$$

where σE_T represents the absolute change in economic-wide energy use.

Table 1
Summary table related to the rebound effects.

Classification	Model	Ref.	Findings
Methodology	Static CGE	Liang et al. (2009); Wissema and Dellink (2007); Lu et al. (2017)	Employed to assess rebound in fossil or nuclear energy; may overlook evolving market dynamics.
	Dynamic CGE	Jia and Lin (2022a); Dong et al. (2018)	More suited for capturing long-term evolutions and intertemporal effects.
	Empirical Analysis	Deng and Newton (2017); Vélez-Henao et al. (2020)	Often focused on a single sector or technology but may miss broader economy-wide feedback loops.
Energy Type	Fossil Fuels	Du et al. (2020); Li et al. (2017); Lu et al. (2017)	Focus on oil, coal, and gas; typically find notable rebound driven by substitution and income effects.
	Clean energy (Wind, Solar, Hydro, Nuclear)	Vélez-Henao et al. (2020); Wang et al. (2018); Galvin et al. (2021); Vélez-Henao and García-Mazo (2022)	Increasing interest in non-fossil rebounds can still produce backfire effects without robust policy.

[4] Since there is no data related to the non-renewable energy sector for government consumption and investment, this study measures the consumption-side rebound effect using household consumption and export data.

To decompose σE_T into $\sigma E_T = \sigma E_{re} + \sigma E_{op} + \sigma E_C$ and substitute into formula (5), we derive the following:

$$R_T = R_{clean} + \left[\frac{\sigma E_{OP}}{E_{clean}\tau} + \frac{\sigma E_C}{E_{clean}\tau}\right] = R_{clean} + R_{op} + R_c \tag{6}$$

Here, subscript OP means the other production sectors; subscript C means the consumption ends, including household consumption and exports. $R_{OP} = \frac{\sigma E_{OP}}{E_{clean}\tau}$ represents the ebound effects in production sectors; $R_C = \frac{\sigma E_C}{E_{clean}\tau}$ means the rebound effects in consumption ends.

3.2. CGE model framework

3.2.1. Model structure

This study extends the China Energy-Environment-Economic Analysis (CEEEA) 2.0 dynamic CGE model (Jia and Lin, 2022b). The model encompasses 21 industries and three input factors (capital, labor, and energy). Table 2 presents the sector codes, with industry details provided in Appendix 1.

Due to its distinct advantages over other recursive dynamic CGE models—such as greater contextual relevance to China, more detailed representation of the energy sector, multi-layer nesting of different energy types, and the disaggregation of non-fossil energy into multiple clean energy subsectors—the CEEEA2.0 model has been widely applied in simulating carbon and energy policies. For instance, Jia et al. (2024a) employed the CEEEA2.0 model to examine the impact of carbon policies on energy cleanliness, economic growth, and energy security, highlighting the critical role of renewable energy strategies. Jia et al. (2024b) further extended the model to assess the effectiveness of carbon border adjustment mechanisms in mitigating carbon leakage. In light of the model's strengths in representing energy systems and simulating carbon policy instruments, our study adopts the CEEEA2.0 framework, optimizes the structure of clean energy sectors, and incorporates dedicated modules to evaluate improvements in clean energy efficiency and associated rebound effects.

The model comprises six modules: the production module, the economic entity module, the trade module, the environment module, the market clearing module, and the closure module. Since this study primarily focuses on the rebound effect of clean energy, Fig. 1 is provided to visualize the CGE model framework. Fig. 1 displays that the model nests energy as an input factor alongside labor and capital using CES functions. The energy sector is further detailed, with the power sector divided into thermal and clean energy sectors. Our dynamic CGE model explicitly distinguishes between domestic clean energy sources (hydro, wind, solar, nuclear) and fossil fuel energy inputs. By modeling improvements in the efficiency of domestic clean energy sectors, our approach explicitly captures how enhancing clean energy efficiency can effectively reduce the overall dependence on fossil fuels.

In the production module, all components utilize a Constant Elasticity of Substitution (CES) production function, except for intermediate inputs, which are modeled using a Leontief production function. Construct production relations through the CES production function and the demand functions of two inputs, which can be presented by:

$$Y_j = \alpha_j\left[\sigma_j X1_j^{\rho_j} + (1-\sigma_j)X2_j^{\rho_j}\right]^{\frac{1}{\rho_j}} \tag{7}$$

$$X1_j = \left(\frac{\alpha_j^{\rho_j}\sigma_j py_j}{p1_j}\right)^{1/(1-\rho_j)} Y_j \tag{8}$$

$$X2_j = \left[\frac{\alpha_j^{\rho_j}(1-\sigma_j)py_j}{p2_j}\right]^{\left(1/1-\rho_j\right)} Y_j \tag{9}$$

where $X1_j$ and $X2_j$, $p1_j$ and $p2_j$ are two input factors, as well as their price; Y_j and py_j are the output and its price; α_j and σ_j are the scale and share parameters; ρ_j denotes the elasticity parameter.

We investigate the rebound effect of improvements in clean energy efficiency by subdividing the clean energy sector into hydropower, wind power, nuclear power, and solar power. These sub-sectors also follow a CES production function, expressed as below:

$$Clean_j = \alpha_j^{clean}\left(\sigma_j^{hyp}X_{(HyP'',j)}^{\rho_j^{clean}} + \sigma_j^{wdp}X_{(WdP'',j)}^{\rho_j^{clean}} + \sigma_j^{sop}X_{(SoP'',j)}^{\rho_j^{clean}} + \sigma_j^{ncp}X_{(NcP'',j)}^{\rho_j^{clean}}\right)^{\frac{1}{\rho_j^{clean}}} \tag{10}$$

$$X_{(''HyP'',j)} = \left(\frac{\alpha_j^{clean\,\rho_j^{clean}}\sigma_j^{hyp}p_j^{clean}}{p^x_{''hyp''}}\right)^{1/1-\rho_j^{clean}} Clean_j \tag{11}$$

$$X_{(''WdP'',j)} = \left(\frac{\alpha_j^{clean\,\rho_j^{clean}}\sigma_j^{wdp}p_j^{clean}}{p^x_{''wdp''}}\right)^{1/1-\rho_j^{clean}} Clean_j \tag{12}$$

$$X(Sop'',j) = \left(\frac{\alpha_j^{clean}\rho_j^{clean}\sigma_j^{sop}}{P^x_{''sop''}}\right)^{1/1-p_j^{clean}} Clean_j \tag{13}$$

$$X_{(NcP'',j)} = \left(\frac{\alpha_{j_{clean}}{}^{\rho_{j_{clean}}}\sigma_j^{ncp}p_j^{clean}}{P^x_{''ncp''}}\right)^{1/1-\rho_j^{clean}} Clean_j \tag{14}$$

where $Clean_j$ regulates the total clean energy input; $X_{(clean'',j)}$ means the different types of clean energy input; p_j is the price of the output from sector j; α_j^{clean} and σ_j are the scale and share parameters; ρ_j^{clean} denotes the elasticity parameter specific to the clean energy sector.

To simulate the impact of energy efficiency improvements on the macroeconomy, we adopt the method of Du et al. (2020) by introducing an exogenous variable τ in each clean energy sector to represent the efficiency improvements at the energy output level. Taking the hydropower sector as an example, the production function for the clean energy sector is modified as follows:

$$Clean_j = \alpha_j^{clean}\left[\sigma_j^{hyp}\left(\tau X_{(HyP'',j)}\right)^{\rho_j^{clean}} + \sigma_j^{wdp}X_{(''WdP'',j)}^{\rho_j^{clean}} + \sigma_j^{sop}X_{(''SoP'',j)}^{\rho_j^{clean}} + \sigma_j^{ncp}X_{(NcP'',j)}^{\rho_j^{clean}}\right]^{\frac{1}{\rho_j^{clean}}} \tag{15}$$

$$X_{(HyP'',j)} = \left(\frac{\alpha_j^{clean\,\rho_j^{clean}}\tau^{\rho_j^{clean}}\sigma_j^{hyp}p_j^{clean}}{p^x_{''hyp''}}\right)^{1/1-\rho_j^{clean}} Clean_j \tag{16}$$

The income and expenditure module includes households, firms, and government entities. To better study the long-term energy rebound

Table 2
Code of sectors (commodities).

Definition	Sectors (commodities)	Definition	Sectors (commodities)
AGR	Agriculture related sectors	*MTL&P*	Metal and the products
COL	Coal production	*MFT*	Manufacturing
COLP	Coal processing	*THP*	Thermal power
O_G	Oil and gas production	*HYP*[a]	Hydropower
REFO	Refined oil	*WDP*[b]	Wind power
REFG	Refined gas	*NCP*[b]	Nuclear power
OMIN	Other mining products	*SOP*[b]	Solar power
LGT	Light industry	*CST*	Construction
CMC	Chemicals	*TSPT*	Transportation
BMTL	Building materials	*SER*	Service
STL	Steelmaking		

[a] Clean energy sector.

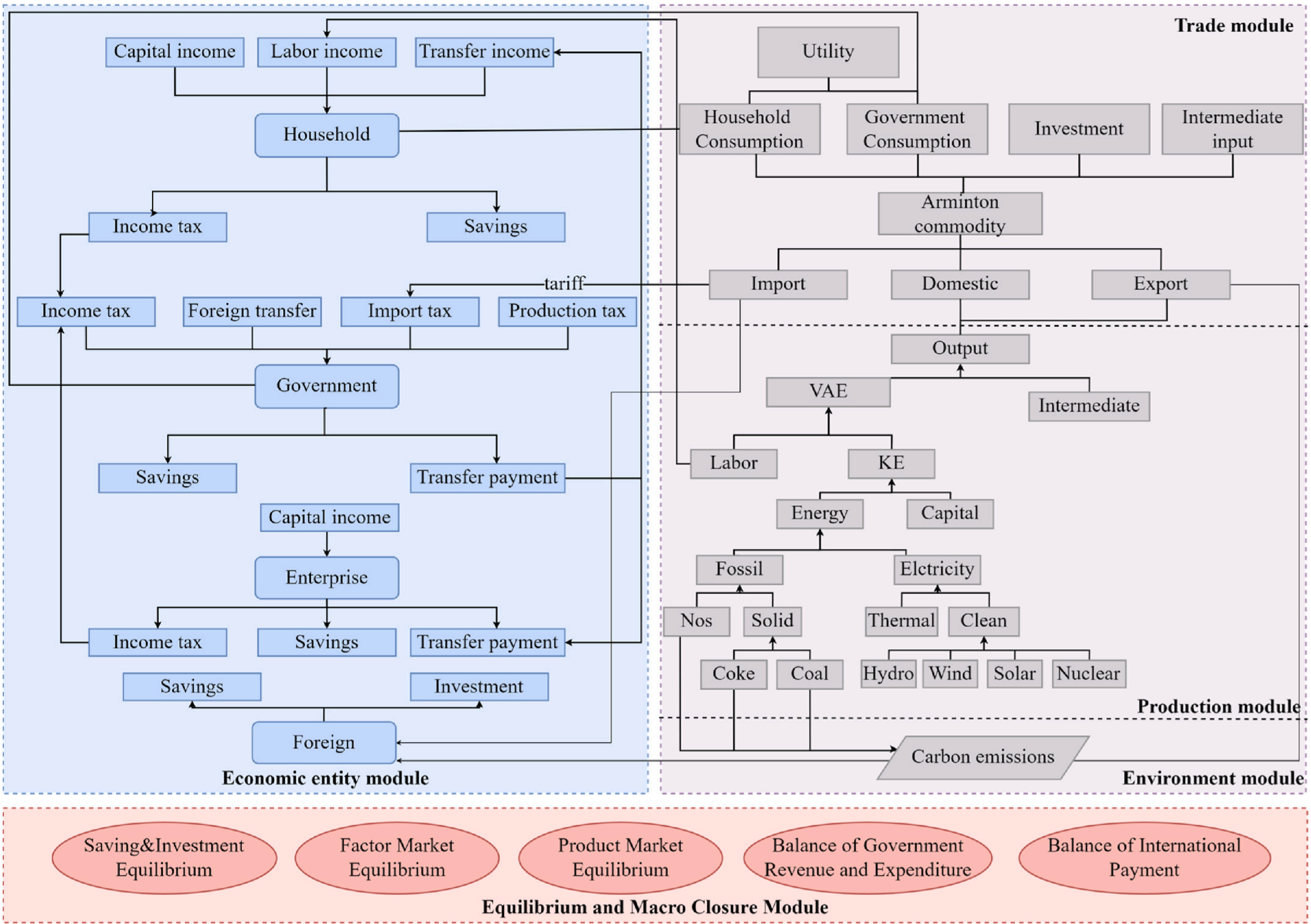


Fig. 1. Graphical representation of the CGE model.

effects, this paper employs the Linear Expenditure System (LES) as the household demand function. Unlike the Cobb-Douglas (CD) and Constant Elasticity of Substitution (CES) production functions, the LES function can simulate Engel's curve over the long term, where the proportion of food consumption decreases as household income increases. As a result, applying the LES function is more effective for modeling long-term scenarios.

$$Xp_{i,l} = Sub_{i,l}^{LES} + \frac{\beta_{i,l}^{LES}}{p_i^q}\left(\sum\nolimits_{h,j} p_{h,j}^f F_j rff_{l,h} - Sp_l - Td_l - \sum\nolimits_j p_j^q Sub_{i,l}^{LES}\right) \tag{17}$$

Among them, l represents the residents, including urban and rural residents; h means the input factors, including labor and capital; $Xp_{i,l}$ is the household consumption of urban and rural residents; $Sub_{i,l}^{LES}$ denotes the Survival consumption of consumption function, necessitating the minimum consumption to meet living needs; $\beta_{i,l}^{LES}$ indexes the marginal consumption share, $p_{h,j}^f$ means the input price of factor h in industry j; F_j represents the factor input of industry j; $rff_{l,h}$ is factor input rate.

We hypothesize that all economic agents were price takers in the trade block. The domestic market encompasses both domestically produced goods and imported products, which are regarded as imperfect substitutes, in accordance with the Armington assumption. Specifically, the Armington assumption pertains to the degree of substitution between domestic and imported goods. To minimize the cost of domestic demand, a CES function was employed, and the details are presented as follows:

$$Q_i = \gamma_i\left(\delta m_i M_i^{\eta i} + \delta d_i D_i^{\eta i}\right)^{1/\eta i} \tag{18}$$

$$M_i = \left[\frac{\gamma_i^{\eta i}\delta m_i p_i^q}{(1+\tau_i^m)p_i^m}\right]^{1/1-\eta i} Q_i \tag{19}$$

$$D_i = \left[\frac{\gamma_i^{\eta i}\delta d_i p_i^q}{p_i^d}\right]^{1/1-\eta i} Q_i \tag{20}$$

where Q_i and p_i^q are the quantity and market price of Armington commodity i in the domestic market. D_i and p_i^d are the quantity and price of domestic commodity i. M_i and p_i^m regulate the quantity and price of import commodity i. γ_i is a scale parameter, δm_i and δd_i show the share parameter of the Armington production function, η_i denotes the elasticity parameter, and τ_i^m means the import tariff.

Further, domestic production is allocated between domestic consumption and exports, using a constant elasticity of transformation (CET) function to maximize the revenues of the domestic output, expressed as below:

$$Z_i = \theta_i\left(\xi e_i E_i^{\phi i} + \xi d_i D_i^{\phi i}\right)^{1/\phi i} \tag{21}$$

$$E_i = \left[\frac{\phi_i^{\phi i}\xi e_i \frac{p_i^z}{1+\tau_i^z}}{p_i^e}\right]^{1/1-\phi i} Z_i \tag{22}$$

$$D_i = \left[\frac{\phi_i^{\phi i} \xi d_i \frac{p_i^z}{1+\tau_i^z}}{p_i^d} \right]^{1/1-\phi i} Z_i \tag{23}$$

where Z_i and p_i^z are the quantity and market price of domestic output in sector *i*. E_i and p_i^e are the quantity and cost of export commodity *i*. θ_i represents a scale parameter, ξe_i and ξd_i present domestic share parameter, η_i denotes the elasticity parameter, and τ_i^z presents the rate of added-value tax in sector *i*. ϕ_i is a conversion parameter related to the conversion elasticity.

There are three principles for macroeconomic closures: the government budget balance, the savings-investment balance, and the foreign trade balance. This study employs a neoclassical closure to investigate the long-term effects of the rebound effect. It assumes that the labor and capital markets are perfectly competitive, with no unemployment or capital redundancy. Armington goods are allocated for investment, household and government consumption, and intermediate inputs.

The backfire effect in the clean energy sector facilitates the advancement of clean production and the optimization of the energy structure. To further enhance this effect, we assume the imposition of a carbon tax on fossil fuels used as intermediate inputs. The relevant formulas for the carbon tax policy are integrated into the production, income and expenditure, and energy modules. We thus extend the carbon tax scenario under the carbon peak constraints by Jia and Lin (2022b) by removing carbon emission constraints and applying a fixed exogenous carbon tax rate on fossil fuels.

$$PLC_i = ctr \cdot EM_i \cdot Dummy^{cf} \tag{24}$$

$$p_j^{fossil} Fossil_j = p_j^{solid} Solid_j + p_j^{nos} Nos_j + PLC_j \tag{25}$$

$$Xg_i = \mu_i \frac{\sum_l Td_l + \sum_i (Tz_i + Tm_i + PLC_i) - Sg}{p_i^q} \tag{26}$$

$$Sg = ssg \left[\sum_l Td_l + \sum_i (Tz_i + Tm_i + PLC_i) \right] \tag{27}$$

Here, PLC_i represents the cost of the carbon tax policy; *ctr* is the carbon tax rate; EM_i the carbon dioxide emissions of different industries; $Dummy^{cf}$ is a counterfactual dummy variable (1 when the carbon tax policy is implemented); $Fossil_j$, $Solid_j$, and Nos_j represent the input of fossil energy, solid fossil energy and non-fossil energy respectively; Xg_i means the government consumption; μ_i is share of government consumption; Td_l, Tz_i and Tm_i represent direct taxes, indirect taxes and tariffs respectively; *Sg* means government saving, and *ssg* means the average propensity for government saving.

Regarding the dynamic aspects, the model is dynamized by assuming population and fixed asset growth. Exogenously given parameters for GDP, carbon emissions, and power efficiency are used to construct dynamic parameters for Total Factor Productivity (TFP), Autonomous Energy Efficiency Improvements (AEEI), and efficiency parameters to simulate technological progress over different periods.

The model has been validated through correctness test with detailed results provided in Appendix 2.

3.2.2. *Data and scenarios*

We use the 2018 Social Accounting Matrix (SAM) data, compiled based on China's national input-output tables published by the National Bureau of Statistics for 2018. Initially detailing 153 sectors, the input-output tables were reclassified and consolidated into 21 sectors. Given, the primary objective of our analysis, we follow Du et al. (2020) and Lu et al. (2017) and choose 5 % and 10 % energy efficiency improvement as the simulation scenarios. These values advocate that the energy efficiency of clean energy sources – solar, wind, hydro, and nuclear power – will be boosted by 5 % and 10 %, respectively. Four simulation rounds are conducted under each scenario, and the outcomes are compared with baseline scenario results across three dimensions: economic, energy, and environmental. Furthermore, if a backfire effect is observed in the clean energy sector, it would be conducive to promoting cleaner production and optimizing energy structure. To further enhance the role of the backfire effect in fostering cleaner production and optimizing energy structure, a policy scenario involving the imposition of a carbon tax on fossil fuels has been added. According to previous research, such as Wang et al. (2012), a carbon tax of 50 RMB per ton is levied based on improved energy efficiency. Table 3 provides the description of the scenarios setting.

Table 3
Scenarios setting.

Scenarios	Description
BAU	The benchmark scenario setting
S1-S4	Scenarios where the energy efficiency of hydropower (S1), wind power (S2), solar power (S3), and nuclear power (S4) is increased by 5 %
S5-S8	Scenarios where the energy efficiency of hydropower (S5), wind power (S6), solar power (S7), and nuclear power (S8) is increased by 10 %
S1CT-S4CT	Scenarios where energy efficiency in each sector is increased by 5 %, with an additional carbon tax of 50 RMB/ton
S5CT-S8CT	Scenarios where energy efficiency in each sector is increased by 10 %, with an additional carbon tax of 50 RMB/ton

4. Results and discussion

4.1. *Analysis of rebound effects*

We address the rebound effects of efficiency improvements in the clean energy sector from short-term, medium-to-long-term, and long-term perspectives. The short-term analysis involves the simulation results of a static model following efficiency improvements in each clean energy sector. The medium-to-long-term and long-term effects are examined using dynamic model outputs for 2030 and 2060, respectively. Additionally, by incorporating both production and consumption perspectives, the rebound effects are dissected into four components for detailed analysis: intra-sectoral rebound, macroeconomic rebound, rebound in other production sectors, and consumption-side rebound.

Table 4 reveals that all clean energy sectors exhibit a backfire effect after clean energy efficiency improvements, which amplifies clean energy usage. Specifically, regarding the *sector-level rebound effects*, when energy efficiency improves by 5 %, the short-term backfire effect is most pronounced in the nuclear power sector, with a rebound effect of 3.148. The rebound effects for hydropower, wind, and solar power are approximately 2.05. In the long term, while some scholars argue that the long-term rebound is smaller than the short-term rebound (Turner, 2009, 2013), others believe that the long-term offers greater flexibility, increasing the energy rebound effect (Stern, 2020). We show that the rebound effect from improvements in clean energy efficiency persists over the medium and long term, with a backfire effect present. However, the extent of the rebound decreases. In the long term, the rebound effect for hydropower, wind power, and solar power decreases to below 1.4, while the nuclear power sector continues to have the highest rebound effect at 1.819. When energy efficiency improves by 10 %, the rebound effect shows a noticeable increase across all sectors and periods compared to the 5 % improvement scenario. This is consistent with the findings of Li et al. (2017), although the growth rate of the rebound effect is lower than the growth rate of energy efficiency. The nuclear power sector remains the highest, with a maximum rebound effect of 5.877, while the rebound effects for hydropower, wind power, and solar power are similar across different periods.

Macroeconomic rebound effects. Substantial backfire effects are observed when energy efficiency improvements are set at 5 % and 10 % across different clean energy sectors. The rebound effects for the

Table 4
Simulation outcomes of energy rebound effect in each period under different scenarios.

	5 %			10 %		
	short-term	medium-to-long-term	long-term	short-term	medium-to-long-term	long-term
HYP	**2.074**	**1.836**	**1.395**	**3.258**	**2.740**	**1.805**
Economic-wide	4.281	3.749	2.840	7.980	6.601	4.107
Other production	2.226	1.936	1.481	4.757	3.903	2.371
Consumption	−0.019	−0.022	−0.037	−0.035	−0.042	−0.069
WDP	**2.076**	**1.872**	**1.381**	**3.274**	**2.828**	**1.773**
Economic-wide	4.357	3.721	2.584	8.028	6.651	4.183
Other production	2.275	1.844	1.199	4.741	3.814	2.402
Consumption	0.006	0.004	0.004	0.013	0.009	0.008
SOP	**2.041**	**1.844**	**1.378**	**3.197**	**2.771**	**1.769**
Economic-wide	4.273	3.674	2.607	7.848	6.561	4.239
Other production	2.226	1.826	1.226	4.637	3.783	2.465
Consumption	0.006	0.004	0.003	0.014	0.007	0.005
NCP	**3.148**	**2.664**	**1.819**	**5.877**	**4.676**	**2.734**
Economic-wide	7.705	6.582	5.146	16.078	13.202	9.672
Other production	4.553	3.914	3.319	10.192	8.519	6.921
Consumption	0.004	0.004	0.008	0.009	0.007	0.017

hydropower, wind, and solar power sectors are relatively consistent. For a 5 % improvement in energy efficiency, the rebound effects range from 2.584 to 4.357, while a 10 % improvement yields rebound effects ranging from 4.107 to 8.028, with the most pronounced effects in the short term and a decline in the medium to long term. The nuclear power sector exhibits the highest rebound effects for 5 % and 10 % energy efficiency improvements across all periods. In the scenario of a 10 % improvement, the short-term rebound effect in the nuclear power sector reaches a peak of 16.078.

Fundamentally, Lu et al. (2017) noted that the rebound effect operates through three mechanisms: the substitution effect, the income effect, and the economic growth effect, each playing a role at different levels. The substitution effect is observed as increased energy efficiency reduces energy prices, leading to a rise in energy consumption as it substitutes other factor inputs. The income effect is particularly relevant for producers, especially energy-intensive ones, where lower energy prices reduce production costs, enabling the production of more goods. The economic growth effect illustrates that energy is a key driver of economic growth; improvements in energy efficiency can spur economic development, resulting in higher energy consumption at the new equilibrium level.

Regarding decomposing the rebound effect, the energy rebound effects in various sectors are predominantly observed on the production side, with negligible impact on the consumption side. From the perspective of production sectors, short-term improvements in energy efficiency across all clean energy sectors result in significant backfire effects. This is because increased energy efficiency effectively lowers energy prices, leading to a substitution effect as energy becomes cheaper relative to other inputs, thereby increasing energy demand. Additionally, lower production costs in energy-demanding industries lead to increased output. On the consumption side, except for the hydropower sector, energy demand from households and exports exceeds the baseline scenario. The increase in household energy consumption can be attributed to higher household incomes and enhanced purchasing power, generating an income effect. Overall household consumption rises, leading to increased direct and indirect energy consumption. Similarly, exports benefit from lower prices due to improved energy efficiency, enhancing export competitiveness.

Table 5 illustrates the impact of a 5 % and 10 % improvement in energy efficiency in different clean energy sectors on the market price and demand for electricity. The results indicate that enhancements in energy efficiency within the clean energy sector significantly reduce electricity prices, with a 10 % improvement having a more pronounced effect on electricity prices than a 5 % improvement. Among the sectors, improvements in hydropower efficiency have the most considerable impact on electricity prices.

Table 5
Changes in electricity price and electricity consumption in different scenarios.

	5 %		10 %	
	Pelc (%)	Electricity (%)	Pelc (%)	Electricity (%)
HYP	−0.821	0.095	−1.714	0.165
WDP	−0.266	0.012	−0.559	0.009
SOP	−0.126	−0.002	−0.264	−0.013
NCP	−0.386	0.284	−0.865	0.631

Furthermore, improvements in energy efficiency also affect electricity demand. Energy efficiency enhancements in the hydropower, wind power, and nuclear power sectors lead to increased electricity demand across various industries, resulting in higher electricity consumption. Conversely, improvements in solar power efficiency cause a slight decrease in total electricity consumption. Additionally, the impact of energy efficiency improvements in the nuclear power sector on electricity consumption is the most significant, with a 5 % improvement increasing electricity consumption by 0.284 % and a 10 % improvement increasing it by 0.631 %. This also confirms that the rebound effect in the nuclear power sector is the most pronounced among clean energy sectors.

The particularly pronounced rebound effect observed in the nuclear power sector can be attributed to its distinct economic characteristics and cost structure as follows: First, nuclear power exhibits a strong investment-led income effect. Compared to renewable sources such as wind, solar, and hydropower, nuclear power requires significantly higher capital expenditures, with a substantial proportion of investment absorbed domestically. This stimulates indirect output growth in related upstream sectors such as steel and cement and generates a larger investment multiplier effect than that observed in wind and solar development. As a result, the expansion of GDP leads to higher overall income levels, which in turn increases electricity demand from the consumption side and amplifies the rebound effect in the nuclear power sector.

Second, nuclear power entails much lower system costs compared to other renewable energy technologies (World Nuclear Association, 2023). Its lower system cost structure translates into reduced marginal costs and falling nuclear electricity prices. The subsequent result confirms that improvements in nuclear energy efficiency yield a more pronounced decline in average electricity prices than in wind and solar scenarios (see Table 5). The price reduction further stimulates electricity consumption, thereby amplifying the rebound effect in the nuclear sector.

Energy efficiency improvements can reduce energy costs, influencing various production industries' input. Fig. 2 visualizes the Pareto results of the production sector rebound effects under a 5 % energy efficiency

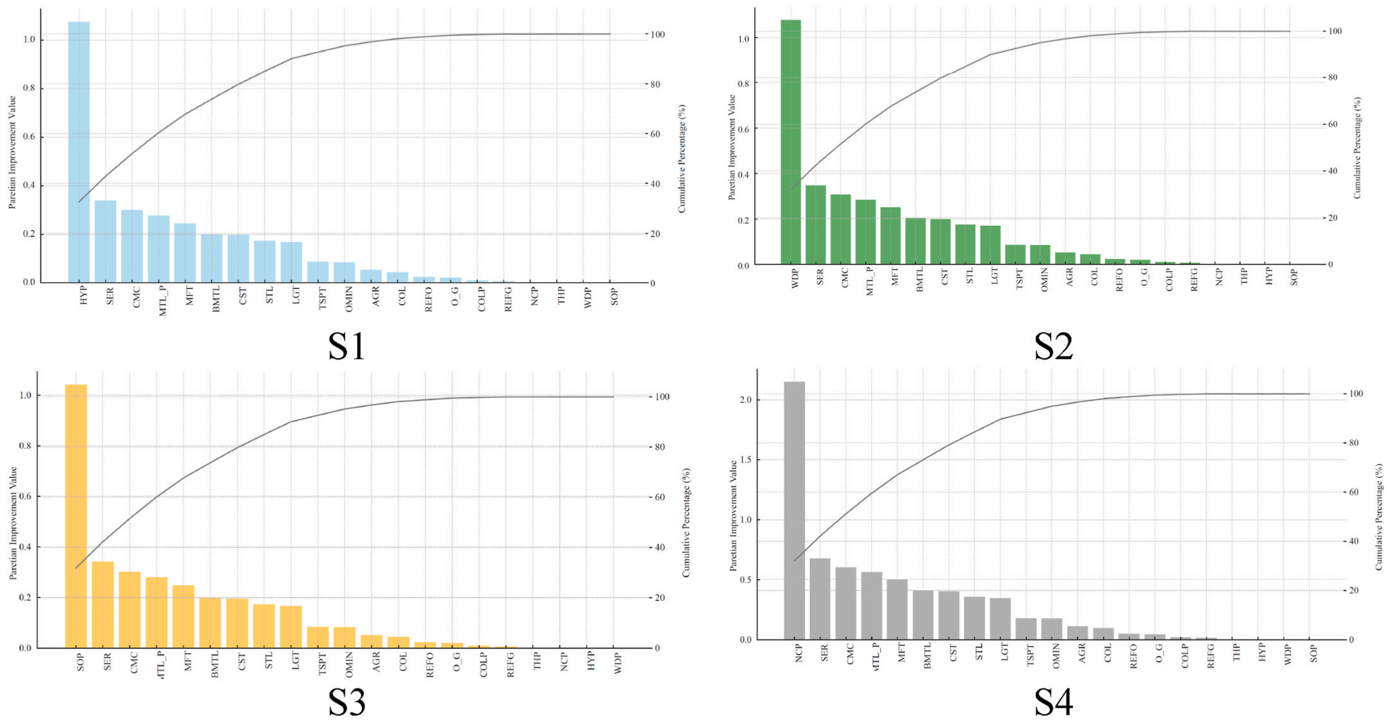


Fig. 2. The pareto chart of the production sector rebound effects (5 % improvement).

improvement scenario. The Pareto distribution of rebound effects across different scenarios is similar, with the sector-specific rebound effect accounting for approximately 32 % of the total production-side rebound. The cumulative rebound effects of the SER (Services), CMC (Chemicals), MTL_P (Metal Products), MFT (Manufacturing), BMTL (Basic Metals), and CST (Construction) sectors account for 80 % of the production-side rebound effects. This is because the manufacturing of metals and chemical products and the construction industry are energy-intensive. In these sectors, energy costs constitute a significant portion of production costs. Thus, they benefit more from reduced production costs due to lower energy prices, which, coupled with increased output, leads to a further increase in energy demand and a pronounced rebound effect.

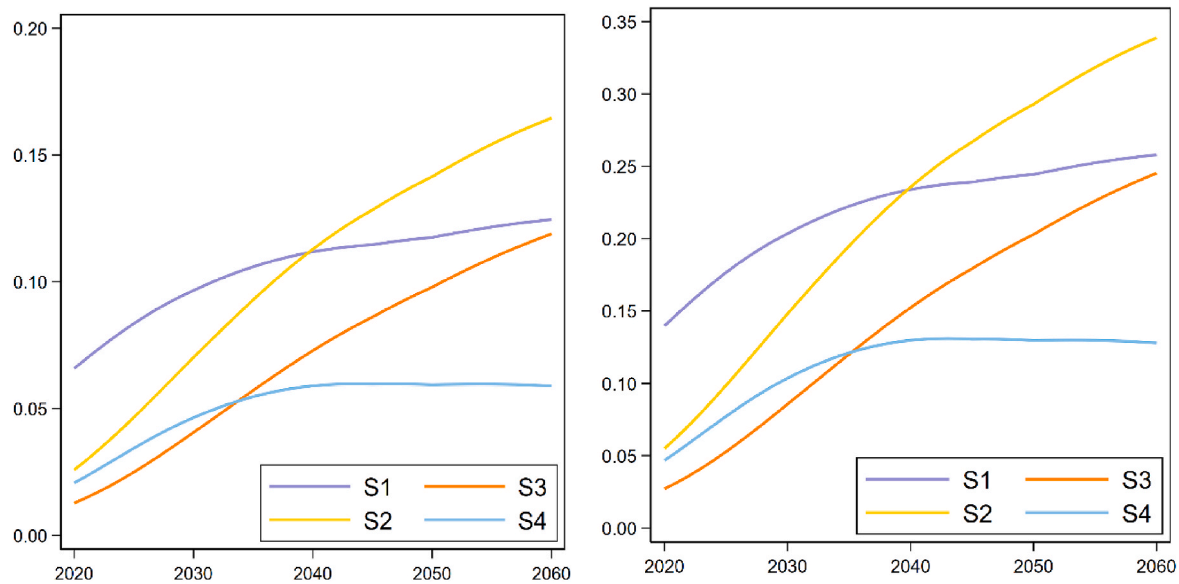
4.2. Economic analysis

At the macroeconomic level, short-term and long-term simulation results of improved energy efficiency in various clean energy sectors in the macroeconomy are shown in Table 6. Clean energy efficiency enhancement drives economic growth (Liang et al., 2009), evidenced by positive effects on GDP, household consumption, investment, and trade. Increased energy efficiency reduces production costs for energy-demanding sectors, stimulating output, consumption, and exports, and boosting aggregate output. Two primary reasons for this effect are: a) Improved energy efficiency enhances cost-effectiveness, creating a competitive export advantage and bolstering export levels; b) Increased energy efficiency leads to higher sectoral output, which, in turn, raises demand for inputs such as labor and capital, leading to higher wages and stimulating increased household consumption (Liang et al., 2009). Notably, the impact of improved efficiency in the hydropower sector is significantly greater than in the other three clean energy sectors. A 5 % improvement in hydropower efficiency results in a short-term GDP increase of 0.057 %, more than three times that of other clean energy sectors, with a more pronounced effect on consumption and investment. In the long term, improvements in wind power efficiency result in the most significant GDP growth, reaching 0.165 %, and also exhibit a more substantial boost to consumption, investment, and trade.

Fig. 3 presents the long-term impact of a 5 % and 10 % improvement in energy efficiency on GDP. In the 5 % energy efficiency improvement scenario, compared to the Business-As-Usual (BAU) scenario, the following trends are observed: 1) Hydropower efficiency improvement results in a GDP growth rate increase of approximately 0.057 %, with rates reaching 0.096 % in 2030 and 0.125 % in 2060. 2) Solar power efficiency improvement leads to a steady increase in GDP growth rate

Table 6
The impact of improved energy efficiency in various clean energy sectors.

Variable		5 %				10 %			
		S1	S2	S3	S4	S5	S6	S7	S8
GDP (%)	short-term	0.057	0.019	0.009	0.016	0.122	0.041	0.020	0.037
	long-term	0.125	0.165	0.119	0.059	0.258	0.339	0.245	0.128
Household consumption (%)	short-term	0.050	0.017	0.008	0.015	0.107	0.036	0.018	0.033
	long-term	0.110	0.148	0.107	0.051	0.229	0.304	0.221	0.110
Investment (%)	short-term	0.083	0.028	0.014	0.026	0.177	0.059	0.029	0.060
	long-term	0.148	0.195	0.142	0.073	0.305	0.402	0.292	0.158
Export (%)	short-term	0.041	0.013	0.006	0.011	0.089	0.028	0.013	0.026
	long-term	0.122	0.156	0.11	0.058	0.253	0.323	0.229	0.126
Import (%)	short-term	0.043	0.014	0.006	0.011	0.092	0.029	0.014	0.027
	long-term	0.123	0.158	0.111	0.058	0.255	0.325	0.230	0.127



(a) GDP growth trends under 5% energy efficiency improvements

(b) GDP growth trends under 10% energy efficiency improvements

Fig. 3. GDP growth trends across different scenarios.

over time, peaking at 0.118 %. 3)Nuclear power efficiency improvement yields the highest GDP growth rate of 0.059 % throughout the period, with growth rates below 0.06 %. 4)Wind power efficiency improvement continuously boosts GDP growth, peaking at 0.165 %. These results indicate that any improvement in energy efficiency positively impacts GDP growth, with wind power efficiency improvements providing the most significant GDP growth rate.

When the energy efficiency improvement is increased to 10 %, the GDP growth trends across different scenarios are similar to those observed with a 5 % improvement. Still, the GDP growth rates are significantly higher: 1) Hydropower efficiency improvement has the most substantial impact on GDP growth in the medium to long term, although the growth rate eventually stabilizes, peaking at 0.258 %. 2) Short-term GDP growth rates for wind and nuclear power improvements are 0.040 % and 0.036 %, respectively. Wind power efficiency improvements show a steady increase in GDP growth in the medium to long term, reaching 0.339 % by 2060, while nuclear power's impact stabilizes with a GDP growth rate of 0.128 % by 2060. 3)Solar power efficiency improvements have the smallest short-term impact on GDP, at just 0.020 %, but the impact steadily increases over time, reaching 0.245 % by 2060. These findings highlight that increasing energy efficiency significantly enhances GDP growth, with wind power improvements showing the most considerable long-term benefits.

4.3. Environmental analysis

Advancing energy efficiency in the clean energy sector aims not only to optimize the energy structure and promote clean production but also to enhance long-term energy security by reducing dependence on fossil fuel imports. In this context, the backfire effect in clean energy sectors can play a constructive role by expanding the clean energy ratio. This section analyzes the impact of 5 % and 10 % improvements in energy efficiency and corresponding carbon tax scenarios from three perspectives: the share of clean energy in primary energy use (clean energy ratio), the share of electricity in total energy input (electricity rate), and carbon dioxide emissions (emissions), which together reflect both decarbonization progress and energy security enhancement.

Table 7 presents the short-term simulation results for the growth rates of clean energy share, electricity share, and CO_2 emissions following 5 % and 10 % improvements in energy efficiency across different clean energy sectors. The findings indicate that energy efficiency improvements in all sectors contribute to optimizing the energy structure and reducing carbon dioxide emissions, with the positive effects correlated with the intensity of the efficiency improvements. The hydropower sector shows the most significant impact on optimizing the energy structure and promoting clean production, with a 10 % efficiency improvement, increasing the clean energy share by 1.506 % and reducing carbon dioxide emissions by 1.756 %.

Table 8 shows simulated results for clean energy share and CO_2 emissions across different scenarios and periods.[5] The findings indicate that merely enhancing the energy efficiency of clean energy sectors does not significantly optimize the energy structure in the long term, with the clean energy share increasing only from 57.037 % in the baseline scenario to a maximum of 57.774 %. In contrast, the carbon tax policy has a notably positive effect on optimizing the energy structure, increasing the long-term clean energy share to 59.698 % and 60.238 %. This structural shift not only facilitates climate mitigation but also reduces exposure to external fossil fuel risks, thereby improving the sustainability dimension of energy security. The combined effect of a 10 % improvement in wind power efficiency and the carbon tax policy yields the most significant improvement in the energy structure.

Regarding carbon dioxide emissions, similarly, improving clean energy sectors' energy efficiency does not significantly reduce emissions, which aligns with the findings of Jia and Lin (2022a). The likely reason is the relatively small proportion of clean energy in China, resulting in limited impact through the factor market, thus leading to minimal emission reduction. However, with the addition of the carbon tax policy, long-term carbon dioxide emissions significantly decrease, dropping from 84,910 tons in the baseline scenario to a minimum of 74,240 tons. Further supporting both climate goals and fossil-fuel risk reduction. These findings demonstrate that long-term enhancements to energy security require coordinated policy instruments that both promote clean

[5] We assume the implementation of a carbon tax policy starting in 2021, so the short-term refers to 2021 in Table 7.

Table 7
Short-term simulation results on energy structure and carbon emissions.

	5 %				10 %			
	S1	S2	S3	S4	S5	S6	S7	S8
Clean energy ratio (%)	0.726	0.230	0.107	0.420	1.506	0.480	0.222	0.939
Electricity rate (%)	0.126	0.038	0.016	0.104	0.258	0.076	0.033	0.234
Emissions (%)	−0.841	−0.275	−0.131	−0.388	−1.756	−0.581	−0.277	−0.873

Table 8
Results for clean energy ratio and CO_2 emissions across different scenarios and periods.

	Clean energy ratio (%)			Emissions (ten thousand tons)		
	short-term	medium-to-long-term	long-term	short-term	medium-to-long-term	long-term
BAU	13.238 %	22.212 %	57.037 %	11.366	12.418	8.491
S1	13.967 %	22.836 %	57.221 %	11.267	12.318	8.468
S1CT	15.183 %	24.441 %	59.698 %	10.156	11.206	7.455
S5	14.744 %	23.490 %	57.403 %	11.161	12.212	8.446
S5CT	16.000 %	25.119 %	59.871 %	10.062	11.112	7.439
S2	13.541 %	22.727 %	57.408 %	11.325	12.343	8.458
S2CT	14.734 %	24.331 %	59.883 %	10.207	11.228	7.448
S6	13.868 %	23.275 %	57.774 %	11.279	12.261	8.426
S6CT	15.079 %	24.901 %	60.238 %	10.167	11.155	7.424
S3	13.384 %	22.506 %	57.320 %	11.345	12.374	8.465
S3CT	14.569 %	24.100 %	59.799 %	10.226	11.256	7.453
S7	13.541 %	22.819 %	57.601 %	11.323	12.326	8.439
S7CT	14.734 %	24.427 %	60.073 %	10.206	11.213	7.434
S4	13.763 %	22.952 %	57.316 %	11.310	12.332	8.471
S4CT	14.969 %	24.553 %	59.772 %	10.195	11.221	7.459
S8	14.404 %	23.816 %	57.616 %	11.242	12.232	8.450
S8CT	15.642 %	25.438 %	60.041 %	10.135	11.133	7.445

energy expansion and constrain fossil energy dependence.

Fig. 4 portrays long-term simulation results for clean energy share under different scenarios. The carbon tax policy significantly and sustainably optimizes energy structure adjustments. As shown in the figure, in the wind, hydropower, and nuclear power sectors, a 10 % improvement in energy efficiency initially has a stronger effect on optimizing the energy structure compared to a 5 % improvement. However, the long-term improvement is not significantly greater. Additionally, varying intensities of energy efficiency improvements in the solar power sector do not produce heterogeneous results in terms of energy structure optimization. With the implementation of the carbon tax policy, there has been a noticeable increase in the clean energy share, which also addresses the issue of insufficient sustainability in the long-term effects of energy efficiency improvements. This ensures that the clean energy share maintains consistent growth over time.

Fig. 5 presents simulation results of the impact of clean energy sector energy efficiency improvements on CO_2 growth rates. It demonstrates that enhancing energy efficiency in the clean energy sector helps reduce carbon dioxide emissions and achieve cleaner production. The impact of different intensities of energy efficiency improvements on carbon dioxide reduction varies. The findings indicate that hydropower has the most significant short-term effect on carbon reduction, followed by nuclear power, although the long-term reduction effects of wind and nuclear power diminish. Wind power shows the most notable long-term impact on carbon reduction. In contrast, the short-term effect of solar power efficiency improvements on carbon reduction is less pronounced than other clean energy sources. Even with a 10 % improvement in solar power efficiency, the results are still lower than those of a 5 % efficiency improvement in the hydropower and nuclear sectors. However, in the long term, the carbon reduction effect of the solar power sector is more favorable.

The timing of carbon peaking and the carbon emissions at the peak are also key areas of our focus. Table 9 presents the simulation results for the timing of carbon peaks and the emission levels at those peaks across different scenarios. The study indicates that improvements in energy efficiency within the clean energy sectors and a moderate carbon tax policy do not significantly impact the timing of carbon peaking. The baseline scenario projects a carbon peak in 2036, while the combined policy scenario mostly advances the peak to 2035. Additionally, although the solar power sector can advance the peak to 2035 solely through energy efficiency policies, its overall carbon emission levels remain relatively high. This suggests that while energy efficiency improvements can help achieve earlier carbon peaking, additional measures might be necessary to reduce emission levels substantially.

4.4. Sensitivity analysis

To assess the robustness of the model, sensitivity analysis was conducted by adjusting key parameters(Du et al., 2020). The selected parameters for sensitivity analysis are as follows: (1) Changing elasticity of substitution between capital and energy σ^{ke}; (2) Changing elasticity of substitution for clean energy demand σ^{clean}; (3) Changing Armington elasticity of substitution σ^{c}. Specifically, we conduct the sensitivity test under the scenario of a 5 % improvement in energy efficiency, simulating the effects of increasing and decreasing the above elasticity parameters by 10 %. The analysis focused on short-term GDP growth rates, household consumption, investment, exports, imports, and the sector-specific rebound effects.

Appendix 3 shows that improvements in energy efficiency across all clean energy sectors continue to exhibit a pronounced backfire effect. Except for the nuclear power sector, which indicates relatively higher sensitivity to changes in elasticity parameters, other sectors do not display significant deviations. The results for GDP, household consumption, investment, and trade variables also remain stable, suggesting that the study's conclusions are robust.

5. Conclusions

5.1. Research findings

Energy efficiency improvement is a crucial strategy for optimizing the energy structure and reducing carbon emissions, especially under China's dual carbon goals. Enhancing energy efficiency is a vital means to achieve carbon neutrality, and understanding the energy rebound effect is essential for formulating effective energy efficiency policies. This study establishes scenarios for clean energy efficiency improvements, calculates the rebound effects at the macroeconomic, production, and consumption levels, and analyzes the impacts from an energy-economy-environment perspective. Additionally, it examines the role of combined carbon tax policies in optimizing the energy structure and promoting clean production. Key findings include:

First, significant backfire effects exist across different clean energy sectors following efficiency improvements, with the intensity of the backfire effect increasing with the extent of efficiency enhancement(Li et al., 2017). The nuclear power sector exhibits the strongest backfire effect, while the rebound effects in hydropower, wind power, and solar power sectors are similar across different periods. The rebound effect persists over the medium to long term, although the degree decreases (Turner, 2009, 2013). Decomposition analysis shows that the rebound effect is primarily observed in the production sectors, particularly in

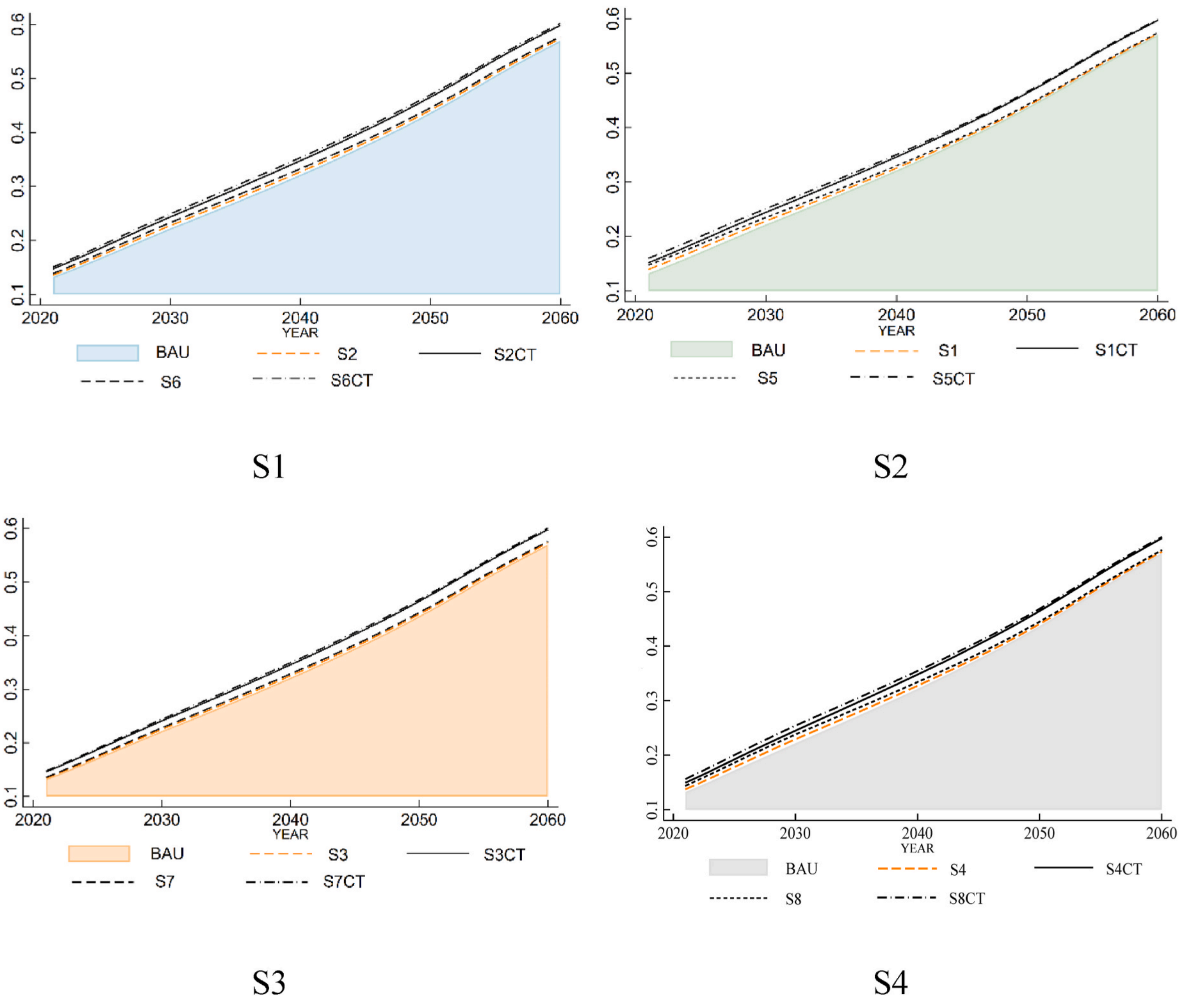


Fig. 4. Long-term simulation results for clean energy share under different scenarios.

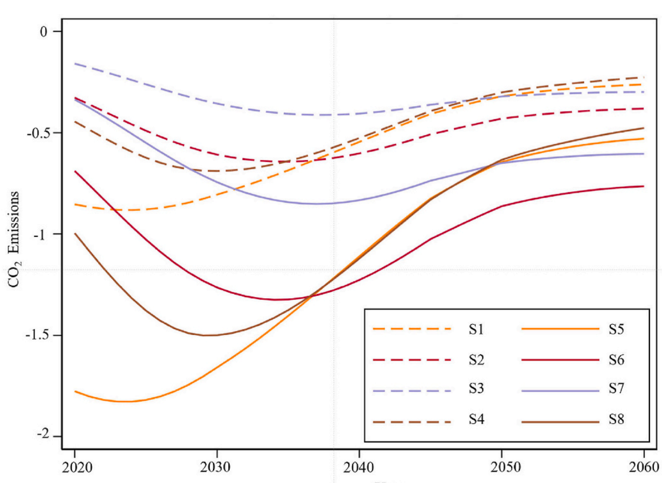


Fig. 5. The impact of clean energy sector energy efficiency improvements on CO_2 growth rates.

Table 9
The timing of carbon peaks and the emission levels across different scenarios.

Scenarios	Timing of carbon peaks	Emissions (ten thousand tons)
BAU	2036	12.700
S1	2036	12.616
S1CT	**2035**	11.482
S2	2036	12.619
S2CT	**2035**	11.486
S3	**2035**	12.648
S3CT	**2035**	11.513
S4	2036	12.621
S4CT	**2035**	11.489
S5	2036	12.529
S5CT	2036	11.404
S6	2036	12.533
S6CT	**2035**	11.409
S7	**2035**	12.593
S7CT	**2035**	11.463
S8	2036	12.531
S8CT	2036	11.410

energy-intensive industries like metal manufacturing.

Second, energy efficiency improvements effectively reduce electricity prices and increase electricity consumption. The most significant price reduction is observed in the hydropower sector. Lower electricity prices lead to a substitution effect in energy-demanding industries, increasing energy demand and stimulating electricity consumption. Increased output, along with higher household income and purchasing power, generates an income effect, resulting in increased overall household consumption and, consequently, higher direct and indirect electricity consumption(Liang et al., 2009; Lu et al., 2017).

Third, clean energy efficiency improvements positively impact GDP, household consumption, investment, and trade(Liang et al., 2009). In the short term, the hydropower sector has the most significant positive impact on macroeconomic indicators, while in the long term, the wind power sector's influence is more pronounced. The long-term effects of efficiency improvements are more substantial than the short-term effects across all clean energy sectors.

Fourth, energy efficiency improvements in all sectors contribute to optimizing the energy structure and reducing carbon dioxide emissions, with positive effects correlated with the intensity of efficiency improvements. The hydropower sector shows the most significant impact on optimizing the energy structure and reducing carbon emissions. However, solely improving energy efficiency in clean energy sectors does not significantly enhance the clean energy share or reduce carbon emissions in the long term (Jia and Lin, 2022a). Introducing a moderate carbon tax scenario reveals that the carbon tax policy strongly and sustainably optimizes the energy structure and promotes carbon reduction. The study also focused on the timing of carbon peaking and the emission levels at the peak, finding that solely improving clean energy efficiency and imposing a moderate carbon tax on fossil fuels does not significantly alter the timing of carbon peaking.

The economic implications of this study are particularly relevant in the context of the low-carbon transition. Unlike traditional rebound effects, where increased energy use may undermine environmental goals, the rebound effects observed in clean energy sectors reflect higher usage of renewable resources—such as wind, solar, hydro, and nuclear—which are aligned with decarbonization targets. These efficiency-driven rebounds reduce electricity prices, stimulate production across energy-intensive sectors, and raise household consumption by lowering energy costs. As a result, clean energy backfire effects not only expand renewable energy use but also contribute to GDP growth and employment, creating a virtuous cycle of clean energy-led development.

From a policy perspective, understanding these technology-specific rebound mechanisms enables more accurate forecasting of economic outcomes and improves the precision of energy efficiency strategies. Moreover, the findings underscore the importance of coupling energy efficiency improvements with well-calibrated policy instruments, such as carbon taxes or renewable subsidies, to ensure that economic growth and environmental sustainability progress in tandem. Overall, this study offers concrete economic insights that can support the formulation of integrated policies aimed at advancing green growth while safeguarding long-term energy and climate goals.

5.2. Policy implications

To encourage cleaner production, policies should be enacted that increase the cost of fossil fuel usage, thereby incentivizing a shift towards cleaner energy sources. This approach will help sustain the long-term positive impacts of energy efficiency improvements on carbon emission reduction and energy structure optimization. Unlike the rebound effects of fossil fuels, the backfire effect in clean energy sectors is advantageous, as it promotes the use of clean energy. Therefore, comprehensive strategies are crucial to address both short-term and long-term impacts of energy efficiency improvements, with particular attention to leveraging the backfire effect in clean energy sectors.

In the case of nuclear power, where the rebound effect is particularly pronounced, a dual control strategy that combines price regulation and demand-side management is recommended. Policymakers may consider introducing a minimum electricity price or placing caps on capacity-based subsidies to prevent excessive demand growth driven by persistently low electricity prices resulting from efficiency-induced cost reductions. For wind and solar energy, which display more moderate rebound effects, policy interventions should focus on enhancing system flexibility. This includes increasing investment in high-penetration energy storage and demand response systems, which can complement the baseload characteristics of nuclear power and help mitigate the risk of negative marginal pricing. In addition, time-of-use pricing schemes could be adopted to better align electricity consumption with the variable output of renewable generation. Regarding hydropower, policy efforts may prioritize ecological conservation at the watershed level and emphasize improving the efficiency of existing infrastructure rather than expanding large-scale dam construction. This approach balances environmental protection with the continued contribution of hydropower to the clean energy transition.

However, given the heterogeneous nature of rebound effects across clean energy sectors, it is vital to implement sector-specific energy efficiency standards. In this regard, more robust coordination between energy policy and industrial policy is necessary. Policies should aim to align energy efficiency improvements with broader economic and industrial objectives. For example, incentivizing energy-intensive industries (e.g., metal manufacturing) to adopt cleaner production processes can help mitigate rebound effects.

Moreover, promoting technological advancements is essential for achieving significant gains in energy efficiency. This can be accomplished by increasing funding for research and development in renewable energy technologies such as wind, solar, hydroelectric, and nuclear power. Fostering public-private partnerships will further accelerate technological innovations through collaborations among government bodies, research institutions, and private companies. Additionally, providing tax credits or subsidies for businesses and households that adopt advanced energy-efficient technologies—or imposing higher carbon taxes on industries with high fossil fuel usage—will facilitate broader adoption. Prioritizing energy efficiency improvements within clean energy sectors, and setting clear efficiency targets for hydropower, wind, solar, and nuclear power, will ensure these sectors contribute effectively to overall energy efficiency goals.

The carbon tax should be introduced gradually and tiered, encouraging energy-intensive industries to reduce carbon emissions while promoting cleaner energy production without placing undue burdens on emerging technologies. Such a policy would help optimize the energy structure by making fossil fuels comparatively less attractive. Another key concern is the allocation of carbon tax revenues, which can be directed towards research and development in clean energy technologies. By channeling carbon tax revenues into innovations for wind, solar, nuclear, and hydropower, policymakers can ensure that advancements in clean energy technologies continue. These revenues can also support subsidies for clean energy installations, increasing their accessibility and affordability for both the public and industry.

Strengthening policy integration is imperative to ensure that energy efficiency strategies align with broader environmental and economic objectives. Cross-sector coordination can create synergies among energy, industrial, transportation, and urban planning policies. A holistic approach that accounts for the impacts of energy efficiency on economic growth, environmental sustainability, and social well-being is paramount. Finally, establishing robust mechanisms to monitor and evaluate integrated policies will enable continuous improvement and necessary adjustments.

5.3. Research limitations and further research directions

Despite the novelty of our simulation analysis, this study holds several limitations. One study limitation is that the analysis focuses primarily on the macroeconomic, production, and consumption-level rebound effects in four clean energy sectors (hydropower, wind, solar, and nuclear). While the study provides valuable insights into these sectors, it does not account for potential rebound effects in other emerging clean energy technologies, such as geothermal or biomass.

Future research could expand the scope by including a broader range of clean energy technologies and region-specific factors that may influence rebound effects. Second, another limitation arises from the assumptions made about the carbon tax rate. The study does not explore how varying carbon tax rates or different carbon tax structures (i.e., border carbon adjustments or carbon dividends) might affect the rebound effects or the effectiveness of clean energy policies.

In addition, future research could further examine the implications of clean energy rebound effects for national energy security. While this study focuses on the Acceptability (sustainability) dimension, subsequent work could adopt a more comprehensive framework by integrating all four dimensions of energy security—Availability, Affordability, Acceptability, and Adaptability. For instance, distinguishing between domestic and imported energy sources would help assess how rebound effects interact with energy import dependency and supply vulnerability. Moreover, evaluating how efficiency-driven demand shifts influence system flexibility and long-term infrastructure resilience could offer valuable insights into the Adaptability dimension. Such extensions would provide a more complete understanding of how rebound effects shape not only economic and environmental outcomes but also energy system stability.

CRediT authorship contribution statement

Jing Yu: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Lingli Qi:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Miaomiao Tao:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **David Roubaud:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of competing 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.

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Appendix 1

Table A1
Code of sectors

Abbr.	Re-classified sector in SAM	Sector in IOT
AGR	Agriculture related sectors	Agriculture products; forest product; livestock products; fishery products; agricultural, forestry, animal husbandry and fishery service products
COL	Coal production	Coal mining and washing products
COLP	Coal processing	Coal processing products
O_G	Oil and gas production	Oil and gas production products
REFO	Refined oil	Refined petroleum and nuclear fuel processing products
REFG	Refined gas	Gas production and supply
OMIN	Other mining products	Ferrous metal ore mining and beneficiation products; Nonferrous metal ore mining and beneficiation products; Nonmetallic ore mining and beneficiation products; Mining ancillary activities and other mining products
LGT	Light industry	Grain grinding products; Feed processing products; Vegetable oil processed products; Sugar and sugar products; Slaughtering and meat processing products; fishery product; Vegetables, fruits, nuts and other processed agricultural and sideline foods; instant food; dairy; Condiments, fermented products; Other food; Alcohol and wine; Drinks; Refined tea; Tobacco products; Cotton, chemical fiber textile and printing and dyeing finishing products; Wool textile and dyeing and finishing products; Hemp, silk and silk textiles and processed products; Knitted or crocheted articles; textile made-up article; Textile clothing; Leather, fur, feather and their products; shoes; Wood processing and wood, bamboo, rattan, palm and grass products; furniture; Paper and paper products; Reproduction of printing and recording media; Handicraft Article; Cultural, educational, sports and entertainment supplies
CMC	Chemicals	Basic chemical raw materials; fertilizer; pesticides; Coatings, inks, pigments and similar products; synthetic material; Special chemical products and explosives, pyrotechnics and fireworks products; Daily chemical products; Pharmaceutical products; Chemical fiber products; Rubber products; plastic
BMTL	Building materials	Cement, lime and gypsum; Gypsum, cement products and similar products; Brick, tile, stone and other building materials; Glass and glass products; Ceramic products; Refractory products; Graphite and other nonmetallic products
STL	Steelmaking	Steel; Steel calendaring products
MTL&P	Metal and the products	Iron and ferroalloy products; Nonferrous metals and their alloys; Nonferrous metal calendaring products; Metalware
MFT	Manufacturing	Boiler and prime mover; Metal processing machinery; Material Handling Equipment; Pumps, valves, compressors and similar machinery; Oven, fan, packaging and other equipment; Cultural and office machinery; Other general equipment; Special equipment for mining, metallurgy and construction; Special equipment for chemical, wood and nonmetallic processing; Special machinery for agriculture, forestry, animal husbandry and fishery; Medical instruments and apparatus; Other special equipment; Complete vehicle; Auto parts and accessories; Railway transportation and urban rail transit equipment; Ships and related installations; Other transportation equipment; electric machinery; Power transmission and distribution and control equipment; Wires, cables, optical cables and electrical equipment; Battery; Household appliances; Other electrical machinery and equipment; computer; Communication equipment; Radio and television equipment, radar and supporting equipment; Audio visual equipment; Electronic components; Other electronic equipment; Instruments and Apparatuses; Other manufactured products; Water production and supply; Waste resources and waste materials recycling and processing products; Metal products, machinery and equipment repair services
THP	Thermal power	Power and heat production and supply
HYP	Hydropower	Power and heat production and supply
WDP	Wind power	Power and heat production and supply
NCP	Nuclear power	Power and heat production and supply
SOP	Solar power	Power and heat production and supply
CST	Construction	Residential building; Sports venues and other buildings; Railway, road, tunnel and bridge engineering construction; Other civil engineering buildings; Building installation; Architectural decoration, decoration and other architectural services
TSPT	Transportation	Railway passenger transport; Railway freight transportation and auxiliary activities; Urban public transport and highway passenger transport; Road freight transportation and transportation auxiliary activities; Water passenger transport; Water cargo transportation and transportation auxiliary activities; carriage of passengers by air; Air cargo transport and transport ancillary activities; Pipeline transportation; Multimodal transport and transportation agency; Handling and storage

(*continued on next page*)

Table A1 (*continued*)

Abbr.	Re-classified sector in SAM	Sector in IOT
SER	Service	Wholesale; retail; Post Office; get accommodation; Restaurant; telecom; Radio, television and satellite transmission services; Internet and related services; Software services; Information technology services; Monetary and other financial services; Capital market services; Insurance; real estate; lease; Business services; Research and experimental development; Professional technical services; Technology promotion and application services; Water conservancy management; Ecological protection and environmental governance; Public facilities and land management; Resident services; Other services; education; hygiene; Social work; Press and publication; Radio, television, film and television recording production; Culture and art; Sports; entertainment; social security; Public administration and social organizations

Appendix 2

Figure A1 is Walras dummy variable (WALRAS1 and WALRAS2) under the BAU scenario from 2020 to 2060. Both residual series remain close to zero throughout the simulation horizon, indicating that the model satisfies the general equilibrium condition and achieves market-clearing. This confirms the internal consistency and numerical robustness of the CGE model.

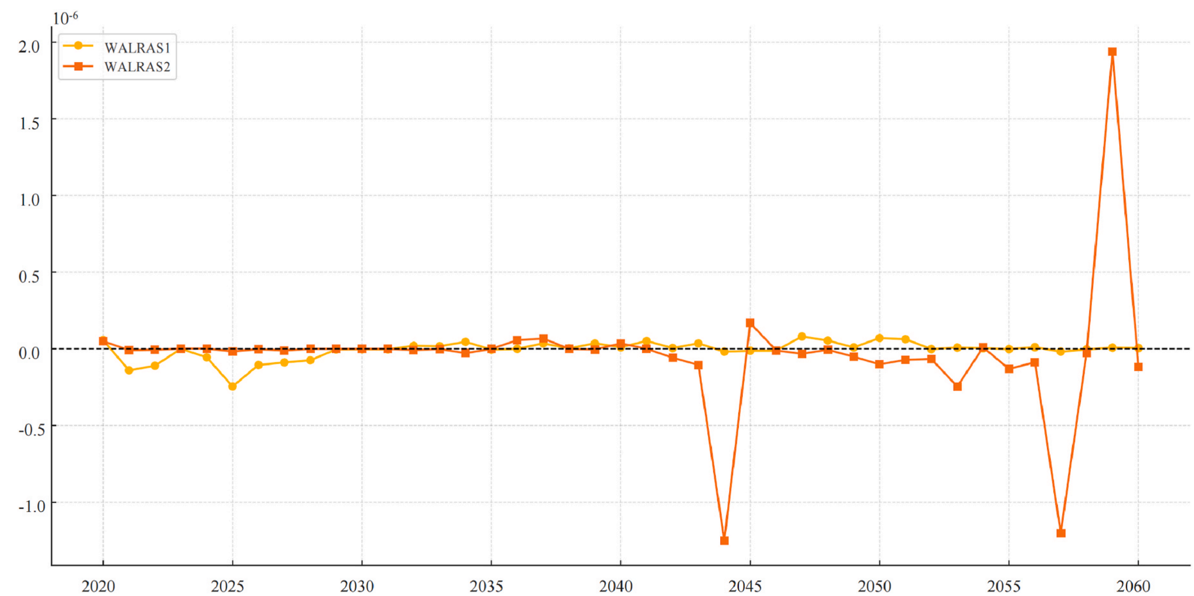

Fig. A1. The Walras dummy variable value across BAU scenario during 2020–2060.

Figure A2 presents the distribution of GDPCHEK values, the residuals between GDP calculated via the expenditure and income approaches, across all policy scenarios over the simulation period. The results show that these residuals remain extremely close to zero. This indicates a high degree of numerical consistency and convergence throughout the simulations. Accordingly, the CGE model employed in this study can be considered both robust and computationally stable.

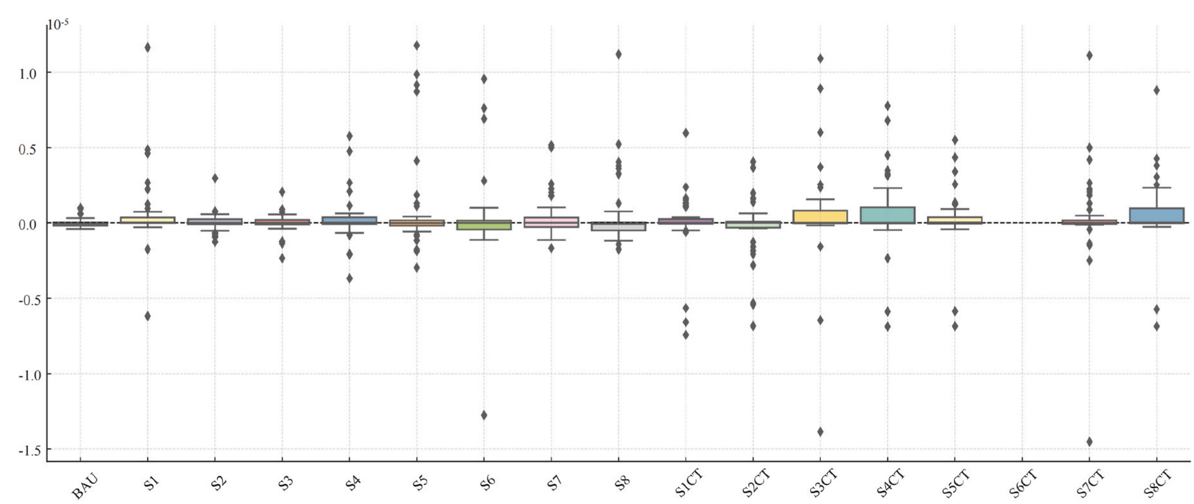

Fig. A2. The GDPCHEK variable value across all policy scenarios during 2020–2060.

Appendix 3

Table A2
Sensitivity analysis results.

elasticity parameter	selected indicators	HYP			WDP			SOP			NCP		
		low	actual	high	low	actual	high	low	actual	high	low	actual	high
σ^{ke}	GDP(%)	0.058	**0.057**	0.056	0.019	**0.019**	0.019	0.009	**0.009**	0.009	0.017	**0.016**	0.016
	household consumption(%)	0.050	**0.050**	0.050	0.017	**0.017**	0.017	0.008	**0.008**	0.008	0.014	**0.015**	0.015
	investment(%)	0.084	**0.083**	0.083	0.028	**0.028**	0.028	0.014	**0.014**	0.013	0.027	**0.026**	0.026
	export(%)	0.048	**0.041**	0.035	0.015	**0.013**	0.011	0.007	**0.006**	0.005	0.014	**0.011**	0.009
	import(%)	0.050	**0.043**	0.037	0.016	**0.014**	0.012	0.007	**0.006**	0.005	0.014	**0.011**	0.009
	energy rebound	2.202	**2.074**	1.971	2.205	**2.076**	1.972	2.166	**2.041**	1.940	3.347	**2.664**	2.982
σ^{re}	GDP(%)	0.057	**0.057**	0.057	0.019	**0.019**	0.019	0.009	**0.009**	0.009	0.016	**0.016**	0.016
	household consumption(%)	0.050	**0.050**	0.050	0.017	**0.017**	0.017	0.008	**0.008**	0.008	0.015	**0.015**	0.014
	investment(%)	0.083	**0.083**	0.083	0.028	**0.028**	0.028	0.014	**0.014**	0.014	0.027	**0.026**	0.026
	export(%)	0.041	**0.041**	0.041	0.013	**0.013**	0.013	0.006	**0.006**	0.006	0.011	**0.011**	0.011
	import(%)	0.043	**0.043**	0.043	0.014	**0.014**	0.014	0.006	**0.006**	0.006	0.012	**0.011**	0.011
	energy rebound	2.087	**2.074**	2.062	2.098	**2.076**	2.055	2.064	**2.041**	2.019	3.245	**2.664**	3.059
σ^{c}	GDP(%)	0.057	**0.057**	0.057	0.019	**0.019**	0.019	0.009	**0.009**	0.009	0.016	**0.016**	0.016
	household consumption(%)	0.050	**0.050**	0.050	0.017	**0.017**	0.017	0.008	**0.008**	0.008	0.015	**0.015**	0.015
	investment(%)	0.084	**0.083**	0.083	0.028	**0.028**	0.028	0.014	**0.014**	0.014	0.026	**0.026**	0.026
	export(%)	0.041	**0.041**	0.041	0.013	**0.013**	0.013	0.006	**0.006**	0.006	0.011	**0.011**	0.011
	import(%)	0.042	**0.043**	0.043	0.013	**0.014**	0.014	0.006	**0.006**	0.006	0.011	**0.011**	0.012
	energy rebound	2.074	**2.074**	2.074	2.076	**2.076**	2.076	2.041	**2.041**	2.041	3.148	**2.664**	3.148

Data availability

Data will be made available on request.

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