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Computable general equilibrium analysis of neutral carbon trading scheme and revenue recycling impacts on income distribution in China

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Utilizing a dynamic computable general equilibrium (CGE) model, this paper critically assesses the potential distortions and efficacy of various revenue-neutral carbon emission trading schemes (ETSs) in China, through government subsidies and value-added tax (VAT) relief strategies aimed at achieving peak carbon emissions before 2030. The analysis reveals that reallocating market revenues to the production sector, either through government subsidies or VAT reductions, can feasibly attain carbon peaking before 2030, with minimal impact on GDP. Notably, both government subsidies and VAT cuts foster output growth in the oil, gas, and ETS-covered sectors. Moreover, directing carbon market revenue toward ETS-covered industries via VAT relief emerges as the most effective approach to reducing income disparities. In contrast, redistributing carbon market revenue to non-ETS-covered industries via VAT relief is found to be the least effective in promoting social equity. The study emphasizes that the reallocation of carbon market revenues to ETS-covered sectors is paramount. This strategy not only regulates the overall energy consumption effectively but also steers the nation towards a more sustainable and optimized energy consumption pattern. In light of these findings, this paper offers detailed insights and tailored policy recommendations, aiming to assist policymakers in striking a balance between environmental goals and economic and social imperatives.

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Introduction

Global warming, which has led to an increase in the Earth's temperature by more than 2.5 °C, is a significant contributor to the substantial reduction in economic output. Nations worldwide are required to swiftly mitigate their carbon dioxide (CO_2) emissions in an effort to meet the temperature regulation objectives delineated by the Paris Accord. China, as the world's largest CO_2 emitter and the largest developing country, has set the goal to achieve peak carbon emissions before 2030. It implies that China faces the dual challenge of sustaining economic growth, while concurrently reducing carbon emissions (Y. Zhang et al., 2023)

The carbon pricing mechanism, encompassing both carbon tax and carbon emission trading scheme (ETS), supports countries in transitioning towards "net-zero" carbon emissions within the next 30 years, thereby contributing to climate change mitigation (Parry et al., 2022). The main goal of the carbon ETS is to regulate market participants using the price mechanism, focusing on controlling CO2 emissions. After successfully piloting of carbon ETS in various cities and provinces, China's national carbon market was officially launched and commenced its initial trading on 16 July 2021 (Zhang, 2022). Unlike the carbon ETS, the carbon tax is levied on the carbon content or CO2 emissions derived from fossil fuels. While many studies indicate that a revenue-neutral carbon tax might worsen income inequality and potentially increase poverty rates, China has not yet adopted a carbon tax policy (Hu et al., 2021). China chose to implement a carbon ETS rather than a carbon tax because the former can better adapt to changes in carbon emissions in different domestic industries and regions, allowing for a more flexible approach to emissions reduction.

Although the ETS may lead to certain potential distortions like carbon taxes, it is worth noting that research on how to avoid or mitigate such distortions and achieve a neutral carbon ETS is still limited. The existence of a market for carbon allowance trading can escalate energy costs, particularly for energy-intensive industries. It could give rise to uncertainties regarding its environmental benefits, cost-effectiveness, and potential inequitable distortions, which could in turn undermine its acceptance and feasibility (Wang et al., 2019). One of the most crucial challenges is that the additional costs of carbon pricing inevitably have uneven impacts on the income distribution across various categories of individuals (Goulder et al., 2019; Wang et al., 2019). To minimize potential distortions, numerous ETS schemes are designed with various mechanisms to address concerns, such as the allocation of free allowances to emissions-intensive industries (Li & Jia, 2016). Given that China's CO_2 emissions predominantly emanate from industries, and the primary entities of the carbon ETS are situated in carbon-intensive industrial sectors, targeted strategies are essential. Efficient implementation of the revenue-neutral carbon ETS needs to be considered as a tool to mitigate the obstacles in achieving China's target of reaching peak carbon emissions before 2030.

Regarding fiscal policies, value-added tax (VAT) reductions and government subsidies are pivotal tools that nations employ to address distributional concerns. For example, Boeters et al. (2010) explored the rationale behind differentiated VAT in terms of its distributional implications. VAT reductions can stimulate economic activity by alleviating the tax burden on producers, potentially offsetting some of the increased costs associated with carbon pricing. In contrast, government subsidies offer direct support to industries, ensuring their competitiveness and mitigating potential job losses (Zhou & Pan, 2019).

Building on this foundation, the emphasis on these two instruments is driven by their potential to concurrently address both economic and environmental objectives, while also weighing the distributional impacts on various sectors and income groups (Jiang et al., 2022; Xu & Wei, 2022). Furthermore, examining these fiscal instruments aids policymakers in crafting pertinent regulations as highlighted by. Referring to the tax neutrality principle, channeling carbon market revenues to industries through subsidies or VAT reduction could potentially mitigate market distortions. However, the impact of different subsidies or VAT reductions combined with a carbon ETS on the economy, energy sector, and the environment remains ambiguous. Additionally, determining the most effective hybrid policy and sectors for revenue reallocation is still a subject of uncertainty.

Using a dynamic computable general equilibrium (CGE) model, this paper examines the impact of different revenue-neutral carbon ETS policies on China's economy, energy sectors, and environment, achieved through government subsidies and VAT reductions, with the overarching goal of achieving peak carbon emissions before 2030. To assess the efficacy of these policies, we devised seven scenarios, encompassing a Business-As-Usual (BAU) scenario, a standalone carbon ETS scenario, and multiple revenue-neutral carbon ETS scenarios. By analyzing the Gross Domestic Product (GDP) changes, government revenues, energy consumption, and environmental impacts across these scenarios, we aim to pinpoint the most favorable revenue-neutral carbon ETS policy for achieving China's carbon peak target.

The remainder of this paper is organized as follows: the section "Literature review" presents a discussion and review of the existing literature. In the section "Methodology", the neutral carbon ETS, accompanied by detailed fiscal policies, is incorporated into the CGE model. This section also sets up various scenarios and describes the data sources. Section "Scenario design" provides an analysis of the results. Finally, the section "Results and discussions" presents the conclusions and policy implications.

Literature review

Carbon pricing, including carbon taxes and carbon ETS, could generate substantial revenue, which could be recycled back into the economy, thereby mitigating the economic cost of GHG abatement (Zhu et al., 2018). Options for using the revenue earned from carbon taxes include ex-ante measures, such as public transport subsidies (Brännlund & Nordström, 2004), as well as ex-post measures, including lump-sum transfers to households (Brenner et al., 2007; Sajeewani et al., 2015), and alleviating existing taxes on labor, income, or revenues, which may naturally cause distortions (Pereda et al., 2019). A notable finding by Dorband et al. (2019) suggests that the benefits of carbon emission reduction might be offset by a decline in economic growth.

However, some studies demonstrate the existence of the "second dividend"—both environmental and economic—resulting from environmental taxes (Freire-González, 2018; Jia & Lin, 2020; Li et al., 2019). Scholars have explored the policy implications of carbon taxes, revealing their efficacy in reducing environmental pollution and carbon emissions (Freire-González & Ho, 2019; Jia & Lin, 2020; Sen & Vollebergh, 2018). Liu and Lu (2015) employed the CGE model to study the impact of carbon taxes and various tax revenue recycling schemes on China's economy, concluding that carbon taxes can effectively reduce emissions with a minimal macroeconomic impact. Similarly, Li et al. (2023) found that carbon tax revenue recycling schemes can mitigate the negative impact on sectoral output while promoting carbon emission reduction and sustainable industrial development. Furthermore, research has shown that redistributing carbon tax revenues to residents, households, or specific industries can alleviate the negative repercussions of the carbon tax, fostering the realization of the "double dividend" (Ahmadi et al., 2022; Bourgeois et al., 2021; Moz-Christofoletti & Pereda, 2021; Ojha et al., 2020; Wesseh, Lin, 2019).

Regarding carbon ETS, H. Wang et al. (2019) argued that China's ETS can stimulate macroeconomic transformation, leading to an economic dividend. Tang et al. (2016) developed a multi-sector dynamic CGE model with an ETS module to study the appropriate ETS policy design, including a carbon cap, permit allocation and supplementary policies (e.g., penalty policies and subsidy policies). CGE models have been instrumental in evaluating the multifaceted impacts of carbon pricing policies. These models have been utilized to understand the implications of carbon taxes on employment in specific regions, such as Shanxi province in China (Li et al., 2020), and the broader macroeconomic effects in diverse regions like Thailand (Timilsina & Shrestha, 2007), British Columbia (Beck et al., 2015), and India (Ojha et al., 2020).

Building on existing research related to carbon tax neutrality, it is a logical progression to explore the concept of carbon ETS revenue neutrality using a CGE model. However, research on carbon ETS, in contrast to carbon tax neutrality, often centers on quota allocation and carbon cap design, with an aim to identify the most effective ETS designs, especially in the context of China. For instance, Wu and Li (2020) developed seven scenarios and utilized a dynamic, recursive CGE model to simulate the carbon trading market. Their objective was to investigate the relationship between quota allocation and carbon price, along with the economic and environmental impacts of the carbon ETS. Similarly, Li and Jia (2016) simulated the carbon ETS to discern the correlation between the free quota ratio and the carbon trading price, as well as to evaluate the impact of carbon ETS on China's economy and environment. Wu et al. (2016) performed an analysis on the regional macroeconomic effects of carbon ETS in China under varying quota allocation criteria and methods.

The field of ETS revenue recycling has been explored extensively using CGE models. For instance, Garaffa et al. (2021) assessed the distributional effects of carbon ETS on households in Brazil utilizing a multi-regional CGE model. The study demonstrated that revenue recycling, either through lump-sum or targeted transfers, could significantly improve income distribution, benefiting vulnerable groups the most. Likewise, Tran et al. (2019) employed a CGE model to analyze the potential impacts of an ETS with various revenue recycling options on Australian households. In the context of China, Huang et al. (2019) investigated the economic outcomes of directly channeling the ETS revenue back to the residents. Lin and Jia (2018) established a CGE model and constructed three counter-measure scenarios (i.e., payment methods based on income, direct tax, and population, respectively), following China's pilot ETS pattern. The aim was to analyze and provide insights on the optimal method for the government to transfer ETS revenues to both rural and urban population. The aforementioned studies are primarily concerned with analyzing the effects of various ETS revenue recycling options on residents.

However, there's a significant gap in research focusing on the transfer of ETS revenues to selected industries. Tang et al. (2016) bridged this gap by developing a multi-sector dynamic CGE model with an ETS module. They proposed allocating ETS revenues to production firms to explore suitable ETS policy designs. Their findings emphasized the importance of setting a penalty price marginally above the carbon price for unauthorized emissions and highlighted the potential of subsidies, collected from ETS revenue, to counterbalance significant economic downturns.

The innovation of this study lies in its attempt to broaden the revenue recycling options for the carbon ETS, a crucial for the effective implementation of carbon pricing policies. By comparing the impacts of a neutral-revenue carbon ETS through different revenue return mechanisms, such as subsidies and VAT cuts, and directing revenue to various industries, this paper offers valuable insights to policymakers. It suggests how to optimize the distribution of carbon market income to reduce income inequality and progress towards a sustainable and inclusive low-carbon economy. Specifically, the paper's main contributions are twofold. Firstly, it provides a comparative analysis of the impacts of a neutral carbon ETS through various revenue recycling options, including VAT and subsidies, targeting diverse industries. This approach broadens the revenue recycling strategies of the carbon ETS with the goal of peaking carbon emissions by 2030. Secondly, the paper analyses the impact of the revenue-neutral carbon ETS on income distribution, illuminating potential trade-offs between environmental sustainability and social equity by revealing the distributive impacts of carbon market income across different income groups. Therefore, the innovation of this study lies in its comprehensive and multi-dimensional approach to carbon pricing policies, factoring in both environmental sustainability and social equity. This provides policymakers with a wider range of strategies to achieve carbon-peaking targets while fostering inclusive economic growth.

Methodology

CGE model. This paper presents a recursive dynamic CGE model for China, encompassing 35 sectors. The model incorporates two input factors for production within the production module—capital and labor, with labor further divided into 20 distinct categories. In addition to the production module, the model comprises standard modules for income and expenditure, trade, and neoclassical macro-closure, and recognizes two economic entities: households and governments.

Production module. We assume that a production sector produces only one product and that it experiences constant returns to scale. In this context, industries are denoted by i and commodities are represented by j. Total output for a sector is calculated through a stepwise synthesis from the base elements, utilizing the input-output relationship across four nested layers (see Fig. 1). The first layer nests labor, capital, and intermediate inputs using the CES (constant elasticity of substitution) function. The second layer includes the capital-labor synthesis, which is synthesized via the Cobb-Douglas (CD) function, and also incorporates the synthesis of energy sub-products and non-energy sub-products using the Leontief function. In the third layer, the synthesis of fossil fuels and electricity, and the synthesis of 20 different labor categories are all achieved using CES functions. The fourth layer encompasses the synthesis of coal, natural gas, and petroleum, as well as thermal power, hydropower, wind power, photovoltaic, nuclear, and biomass power, all synthesized as CES functions. We have also conducted a sensitivity analysis where production elasticities of substitution are adjusted by +20% and −20%, under the assumption that all other parameters remain constant. Relative to the Business-As-Usual (BAU) scenario, the maximum deviation rates for key indicators—GDP, carbon emissions, total energy consumption, and the Gini coefficient—do not exceed 1%. The model, and consequently its results, demonstrate robustness, as evidenced by the limited range of variation across its core variables.

Neutral carbon ETS module. In this study, we assume that the carbon market operates under perfect competition. We consider the supply of carbon allowances within the carbon trading market as given exogenously, determined by the government in

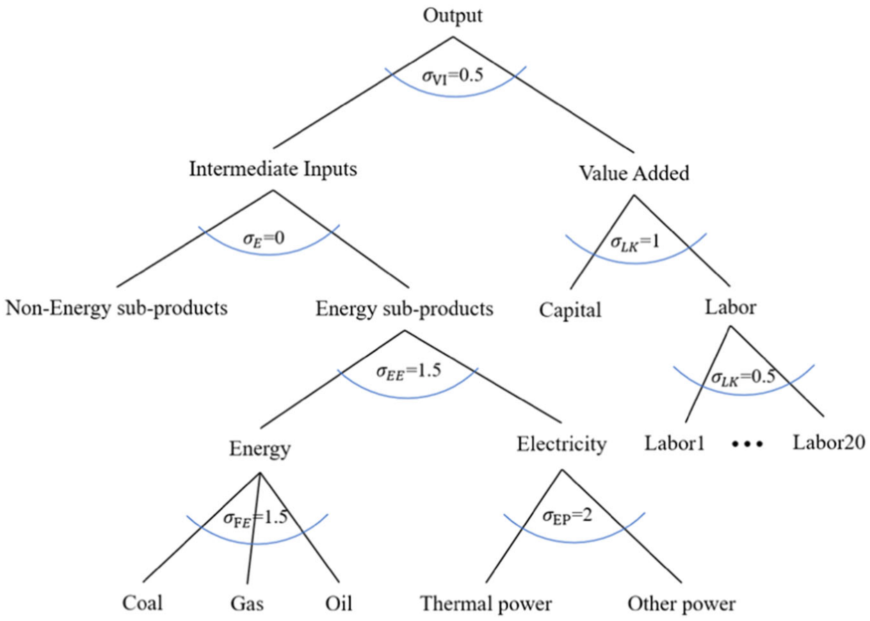

Fig. 1 The framework of the production block.

alignment with explicit emission reduction goals. The carbon market reaches equilibrium when the supply and demand of carbon allowances are equal, along with the prices of carbon allowances in various industries. The revenues derived from carbon allowances are subsequently allocated to the government. The main formulas of the carbon ETS module are below:

$$EM_{i,t} = \theta_{coal}{}^{*}D_{i,t,coal} + \theta_{oil}{}^{*}D_{i,t,oil} + \theta_{gas}{}^{*}D_{i,t,gas} \tag{1}$$

$$TCO2_t = \left(1 - tcer_t\right)CO2ref_t \tag{2}$$

$$TCO2_t = \sum_t EM_{i,t} \tag{3}$$

$$C_{i,t} = PCO2_{i,t}{}^{*}EM_{i,t} \tag{4}$$

$$\sum_i C_{i,t} = GYETS_t \tag{5}$$

$EM_{i,t}$: CO_2 emissions form sector i in period t; $D_{i,t}$.: the intermediate input of fossil energy products; θ: carbon emission coefficient of fossil energy products; $tcer_t$: the CO_2 emission reduction rate; $PCO2_{i,t}$: the equilibrium price of carbon allowances; $TCO2_t$: the total carbon emissions of all industries; $C_{i,t}$: total amount of CO_2 allowances auctioned of sector i; $GYETS_t$: the total amount of CO_2 allowances in period t.

VAT reductions and subsidies are two common forms of industrial policies. Typically, industrial policies are financed by government revenues. In this study, we assume that the government redirects the revenue to the production sector through VAT relief or government subsidies to mitigate the market distortion caused by the carbon ETS. The VAT reduction and government subsidy are set in the model as shown in the following equations, respectively.

$$rdvat0_{i,t} = DAVT_{i,t}/X_{i,t} \tag{8}$$

$$cut_{i,t} = \left(\sum_i DAVT_{i,t} - GYEST_t\right)/\sum_i DAVT_{i,t} \tag{9}$$

$$rdvat_{i,t} = cut_{i,t}{}^{*}rdvat0_{i,t} \tag{10}$$

$$rss0_{i,t} = SS_{i,t}/X_{i,t} \tag{11}$$

$$su_{i,t} = \left(\sum_i SS_{i,t} + GYEST_t\right)/\sum_i SS_{i,t} \tag{12}$$

$$rss_{i,t} = su_{i,t}{}^{*}rss0_{i,t} \tag{13}$$

$rdvat0_{i,t}$: the actual VAT rate incurred by sector i in period t under scenario BAU; $DAVT_{i,t}$: the actual VAT tax collection under scenario BAU; $cut_{i,t}$: the ratio of the actual VAT collection under the VAT relief policy to that of the BAU scenario; $rdvat_{i,t}$: the actual VAT rate of sector i in period t; $rss0_{i,t}$: the production subsidy rate of sector i in period t under scenario BAU; $SS_{i,t}$: the production subsidy obtained from the government; $su_{i,t}$: the ratio of production subsidies received to that would have been received under the BAU scenario; $rss_{i,t}$: the production subsidy rate of sector i in period t.

Data input and scenario setting. The social accounting matrix (SAM) forms the foundational data for the simulation analysis of the CGE model. We compiled the SAM table using the input-output table of 149 sectors in China for 2018. This consideration incorporated the industry structure's distinct characteristics, the electricity market segmentation, and the present and future industries within the carbon trading market's ambit. Key references for this compilation included the "National Carbon Emissions Trading Covered Industries and Codes", "National Economic Industry Classification", "China Tax Yearbook 2019", and the "China Fiscal Yearbook 2019".

We merged data from the China Taxation Yearbook 2019, the China Finance Yearbook 2019, and the China Household Income Project Survey Data 2013 (CHIP, 2013) to update and collate the SAM tables for 2018. The CHIP2013 is a representative micro-database capturing critical information such as resident location, gender, income, and employment sector on a national scale. The carbon emission coefficient of fossil energy is obtained from the International Energy Statistics 2019 Input-Output table.

In addition, we constructed a labor force matrix based on the CHIP2013 data and the 2019 China Statistical Yearbook. This matrix included 27,625 individual observations post outlier and missing value elimination. The classification of CHIP2013 participants was based on their urban or rural hukou (registered residence), income category, and gender. Furthermore, we divided the labor force employment sectors into 20 categories and consolidated different labor income types based on the remaining 19 employment sectors, excluding the international organization sector.

Scenario design

The scenario setting focuses on the design of the baseline scenario (BAU) and neutral carbon ETS implemented either through VAT relief or government subsidies. In the BAU scenario, no policies are implemented throughout the simulation period of 2018–2035. The dynamic simulation has been set to end in 2035, which allows for changes to be observed after the peak of total carbon emissions by 2030. The GDP growth rates for 2018, 2019, and 2020 are derived from the actual growth rate reported by the National Bureau of Statistics.

In 2021, China launched its national carbon emission trading market, initially encompassing the electricity sector. The market is set to expand and cover eight industries, namely power, aviation, steel, chemicals, building materials, petrochemicals, non-ferrous metals, and paper (Zhang et al., 2022). Given this roadmap, we assume that the national carbon ETS covered only the electricity sector in 2021 and 2022, and incorporated the eight sectors starting in 2023. Referring to the method of Xiao et al. (2020) and Zhang et al. (2022), we designed scenario S1 with the annual carbon intensity decline rate from 2021 to 2035 to gradually increase by 0.05%. The average annual decline rate in the carbon intensity of 4.5% is projected to reach peak emissions in 2029 after several adjustments, aligning with the predictions of some research that China would reach its carbon peak in 2030 (Cai et al., 2021; He, 2013; Mi et al., 2017) (Table 1).

Based on Scenario S1, we have designed various neutral carbon ETS scenarios using VAT reduction and government subsidies. It is worth noting that regardless of whether VAT reduction or government subsidies are used, the carbon market revenue is calculated like in Scenario S1. The only difference lies in the distribution method to the production sector, which allows us to compare the effects of different scenarios. Additionally, we have allocated the carbon market revenue to be distributed among the eight major sectors covered by the carbon ETS, non-covered industries, or all production sectors. The seven simulation scenarios are detailed in Table 2.

Table 1 20 different labor force types.

Region	Gender	Income level	Abbreviations
Urban areas		Low income	UMLI
		Low and middle income	UMLMI
	Male	Middle income	UMMI
		Middle and high income	UMMHI
		High income	UMHI
		Low income	UFLI
		Low and middle income	UFLMI
	Female	Middle income	UFMI
		Middle and high income	UFMHI
		High income	UFHI
Rural areas		Low income	RMLI
		Low and middle income	RMLMI
	Male	Middle income	RMMI
		Middle and high income	RMMHI
		High income	RMHI
		Low income	RFLI
		Low and middle income	RFLMI
	Female	Middle income	RFMI
		Middle and high income	RFMHI
		High income	RFHI

Results and discussions

Economic impact

GDP. In this study, the 2018 GDP is used as the base for real GDP. Under the BAU scenario, the GDP will be 132.51 trillion yuan in 2025, 167.89 trillion yuan in 2030, and 204.75 trillion yuan in 2035. The corresponding real GDP growth rates are 5.3%, 4.6%, and 3.8%, respectively. Compared to the BAU scenario, Fig. 2 depicts the changes in GDP under different scenarios. The implementation of the carbon ETS results in a decline in real GDP. However, when carbon market revenue is distributed to the production sector via subsidies or VAT reductions, it helps to alleviate the decline in real GDP. Economically, the decline in GDP due to the carbon ETS can be attributed to the increased costs associated with carbon emissions, which can affect the profitability and competitiveness of industries, especially those that are carbon-intensive. The additional costs can deter investments, and reduce production, which can contribute to a decline in GDP.

Specifically, when carbon revenues are returned to the production sector of high-carbon industries, the GDP loss in scenario SUB-ETS is lower than that in the VAT-ETS scenario, indicating that subsidies are more conducive to GDP growth than VAT reduction. When the carbon revenue is returned to the production sector of non-ETS-covered industries, the GDP loss in scenario SUB-NETS is greater than that in the VAT-NETS scenario, and the VAT reduction is more effective in promoting GDP growth than subsidies.

This means that government subsidies and VAT relief have different incentive effects on different industries. Subsidies may not have the same effect as those for high-carbon industries. However, VAT reduction can provide cost advantages for these industries, making them more competitive and stimulating growth. Redirecting ETS revenues through subsidies and VAT reductions to lower production costs can help mitigate these distortions. The two policies differ in their efficacy in stimulating the market and reducing distortions. Specifically, when carbon market revenues are returned to industries under the ETS, government subsidies are more conducive to GDP growth

Table 2 Simulation scenario setting.

	Scenario	Description	Decline rate of carbon intensity (%)
Single policy	S1	Carbon ETS only	4.50%
Neutral ETS	SUB-ETS	Subsidies for ETS-covered sectors	
through subsidies	SUB-NETS	Subsidies for Non-ETS covered sectors	
	SUB-ALL	Subsidies for all sectors	
Neutral ETS	VAT-ETS	VAT reduction for ETS-covered sectors	
through VAT reduction	VAT-NETS	VAT reduction for non-ETS covered sectors	
	VAT-ALL	VAT reduction for all sectors	

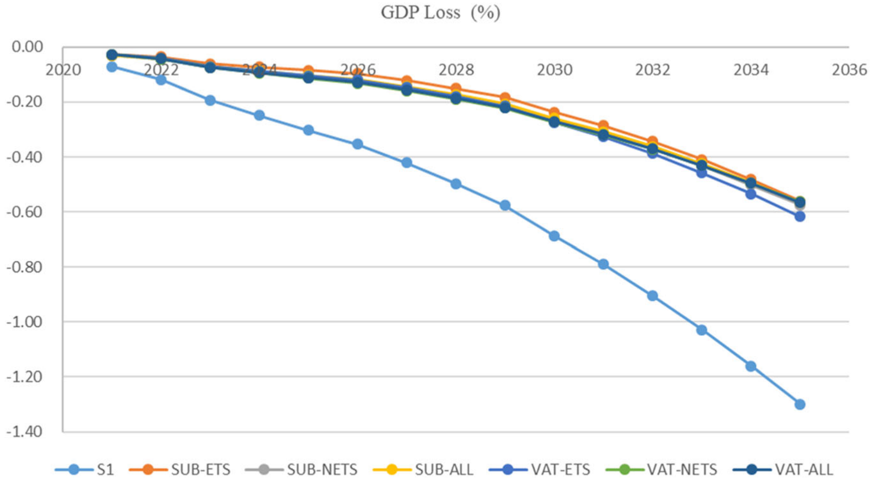

Fig. 2 the GDP loss of various scenarios compared to BAU.

Table 3 Changes in government revenue compared to the BAU Scenario.

	S1	SUB-ETS	SUB-NETS	SUB-ALL	VAT-ETS	VAT-NETS	VAT-ALL
2025	2.68%	0.34%	−0.89%	−0.67%	0.54%	−0.35%	−0.22%
2030	4.48%	0.75%	−1.32%	−0.96%	0.99%	−0.53%	−0.32%
2035	7.01%	1.40%	−1.84%	−1.27%	1.74%	−0.81%	−0.45%

compared to VAT reductions, meaning they're more effective at reducing distortions. Conversely, when the carbon market revenue is returned to industries not covered by the ETS, VAT reductions are more beneficial in mitigating market distortions. According to Liu (2016), government subsidies can be interpreted as acting as a pre-incentive, enhancing the cash flow for micro-market entities and, in turn, increasing their income and profits. The income derived from these subsidies is definite, and its allocation and application are directed by the government. In contrast, tax incentives primarily function as a post-incentive, lightening the tax load on micro-market entities. The savings from VAT reductions are considered anticipated revenue, granting businesses greater autonomy in their use.

Government revenue. The changes in government revenues relative to the BAU scenario are displayed in Table 3. Since the government receives all revenues from carbon allowance supply, the single carbon trading scenario S1 has the largest increase rate in government income, reaching 7.01% by 2035. It is because, in the scenario S1, the government obtains revenue by selling carbon allowances. Given that there are no other policy interventions in this scenario, the income the government derives from carbon trading is the highest, explaining why the increase in government revenue is the largest by 2035 under the S1 scenario.

When carbon revenues are returned to the production sectors through government subsidies or VAT reduction, government revenues fall compared to the scenario S1. The decline in government revenues caused by the government subsidy scenario is greater than that caused by the VAT cut scenario.

Government revenue decreases differently depending on which sectors are selected as beneficiary sectors. Among all the neutral carbon ETS scenarios, government revenue declines the least compared to the S1 scenario when carbon market revenues are returned to the ETS-covered industries. Government revenue increases compared to the BAU scenario since government subsidies, and VAT reductions contribute to economic growth, with VAT-ETS > SUB-ETS in government revenue. The largest decline in government revenue compared to the S1 scenario occurs when carbon market revenues are returned to the non-ETS covered sectors. The phenomenon can be explained that industries covered by the ETS are typically high-carbon-emitting sectors, where fossil fuel costs constitute a significant portion of their production expenses. Therefore, providing subsidies or VAT reductions to these industries can directly decrease their production costs, thereby stimulating their production activities and increasing the government's VAT revenue. On the other hand, non-ETS covered sectors might not be energy-intensive, with fossil fuel costs representing a smaller fraction of their expenses. The adverse impact of carbon ETS on their production costs is consequently less pronounced. Given the lower sensitivity of these non-ETS covered sectors' production costs to carbon ETS, the subsidies or VAT reductions provided to them might not yield the same economic benefits as those for ETS-covered sectors. As a result, reallocating carbon market revenues to these sectors might not produce the same economic stimulus as with ETS-covered sectors, leading to a more substantial decline in government revenue.

The change in government revenue is equal to the difference between the increase in government income resulting from GDP growth driven by the ETS revenue recycling schemes and the decrease in government income due to the GDP decline caused by the ETS. The way in which revenue recycling, as well as the sectors chosen for, have a significant impact on changes in government revenue. In terms of the method of revenue recycling, both VAT reductions and government subsidies can stimulate GDP growth, thus increasing government revenue. However, the amount of VAT reduction is directly proportional to the sectors' production values, while government subsidies are typically fixed and unrelated to the sectors' production values. From a GDP fluctuation perspective, although the GDP increase caused by VAT-ETS is slightly lower than that of SUB-ETS, the resulting government revenue is also lower than SUB-ETS. For VAT-NETS and SUB-NETS, due to the relatively lighter tax burden of non-ETS sectors (as referenced in "China Tax

Table 4 the changes in sectoral output relative to BAU by 2035.

	S1	SUB-ETS	SUB-NETS	SUB-ALL	VAT-ETS	VAT-NETS	VAT-ALL
Coal	−22.26%	−23.25%	−20.66%	−21.13%	−24.26%	−19.68%	−20.35%
Oil	1.66%	4.57%	4.50%	4.52%	5.74%	5.60%	5.64%
Gas	0.34%	3.15%	3.24%	3.23%	4.30%	4.30%	4.32%
Paper	−1.80%	1.37%	−1.28%	−0.80%	0.84%	−1.34%	−1.02%
Petrochemicals	−5.30%	0.31%	−4.20%	−3.38%	2.30%	−4.43%	−3.45%
Chemicals	−4.72%	0.04%	−3.67%	−3.00%	−0.21%	−3.89%	−3.35%
Building Materials	−5.54%	−1.99%	−2.88%	−2.70%	−2.28%	−3.26%	−3.10%
Nonferrous Metals	−5.11%	1.14%	−2.67%	−1.97%	−0.63%	−2.94%	−2.60%
Steel	−6.37%	−2.88%	−3.79%	−3.61%	−3.25%	−4.13%	−3.99%
Thermal Power	−1.06%	8.84%	0.76%	2.17%	10.58%	0.14%	1.61%
Aviation	−2.59%	0.87%	−2.80%	−2.15%	1.13%	−2.68%	−2.13%

Yearbook 2019”), these sectors contribute less to government revenue. Therefore, even though GDP has grown under these two scenarios, the increased GDP has not brought substantial revenue to the government, making it difficult to offset the distortion of ETS on government revenue (excluding revenue recycling).

Changes in sectoral output. The paper also focuses on output changes in the fossil energy sector (coal extraction, oil extraction, and gas extraction) and the eight high-carbon-intensive sectors covered by the carbon ETS. Table 4 depicts the changes in sectoral output relative to BAU by 2035 under different scenarios. In scenario S1, the coal sector’s output declines by 22.26%, whereas the oil and gas sectors’ output grow by 1.6% and 0.3%, respectively. In the context of Scenario S1, a pronounced decline in coal output and sectoral yield can be ascribed to the carbon ETS, which markedly amplifies the cost associated with fossil fuel uses. Given the high-carbon emission factor inherent to coal, its consumption costs are elevated, leading to a contraction in coal consumption and a consequent downturn in production. Although both oil and natural gas are classified as fossil fuels, their ascending trajectories indicate their prospective utility as bridge energy sources. Owing to their lower carbon emission coefficients, even as carbon ETS escalates the costs of oil and natural gas, their operational expenses remain more favorable than coal. As coal’s competitiveness diminishes due to carbon ETS, industries and consumers might gradually shift towards cleaner fossil fuel alternatives, such as natural gas.

The output of ETS-covered sectors decline, with the steel sector having the largest decrease of 6.37%. Compared to Scenario S1, government subsidies, and VAT reductions boost output growth in the high-carbon industry. Through fiscal support, subsidies can offset some of the increased costs associated with carbon pricing. Consequently, upon the implementation of such subsidies, the decline in output from high-carbon industries is less pronounced. However, subsidies might not be as effective as VAT reductions in stimulating growth, given that subsidies often proffer fixed or capped financial relief. VAT reductions provide a more dynamic form of relief proportionate to the value of goods or services produced. Such a structure not only bolsters production incentives but also enhance industry competitiveness, showing their pronounced advantages in promoting output growth in certain sectors.

Whether through subsidies or tax cuts, when carbon market revenues are transferred to the ETS-covered sector, output in the coal sector declines the most, while output in the ETS-covered sector increases the most. VAT exemptions are more advantageous than subsidies for reducing output in the coal sector and are also more effective in promoting output growth in the oil, natural gas, petrochemical, thermal power, and aviation sectors. When carbon market revenue is returned to non-ETS covered sectors, the coal sector experiences the least decline in output, and ETS-covered sectors also experience the least growth in output.

Impact on energy consumption. Figure 3 displays the change in total energy consumption relative to the BAU scenario. Under the BAU scenario, the total energy consumption increased from 4.770 billion tonnes of standard coal in 2018 to 6.69 billion tonnes of standard coal in 2035. During the simulation period, the total energy consumption of carbon ETS and neutral carbon ETS scenarios decreased compared to the BAU scenario. From an economic perspective, the introduction of carbon trading inherently raises the costs associated with carbon emissions. This cost increment is reflected in the prices of fossil energy products, making them less attractive compared to cleaner energy sources. As industries aim to optimize costs and maintain profitability, there’s a natural inclination to reduce reliance on more expensive energy sources, leading to a decrease in fossil energy consumption. Compared to the single carbon ETS scenario S1, both government subsidies and VAT cuts will to a certain extent, promote the overall growth of energy consumption, but to varying degrees. Overall, the energy consumption growth under the government subsidy scenario is more significant. It may be because the government subsidy funds come directly from the government, while tax relief is “money of their own” for production industries (Zhou & Pan, 2019). Economically, when industries perceive VAT cuts as a form of retained earnings, they are more likely to invest in efficiency improvements or alternative energy sources. This is because retaining more money within the industry provides both the means and the incentive to innovate and adapt, especially when faced with rising energy costs due to carbon trading. Conversely, direct subsidies might be seen as external financial injections, which might not always align with the industry’s long-term strategic planning or sustainability goals.

Production industries are more motivated to reduce overall energy consumption and thus lower production costs when implementing VAT cuts. In addition, in both government subsidy and VAT relief scenarios, when carbon market revenue is returned to ETS-covered sectors, the overall energy consumption decreases the most compared to the BAU scenario; when carbon market revenue is returned to non-ETS covered sectors, the overall energy consumption decreases the least; and when carbon market revenue is returned to the entire industry, the decrease in overall energy consumption is in the middle range.

The energy consumption structure from 2018 to 2035 under different scenarios is shown in Fig. 4. Simulation results show that under the BAU scenario, the proportion of non-fossil energy consumption gradually increases from 13.96% in 2018 to 15.77% in 2035, while the proportion of coal consumption gradually decreases from 58.16% in 2018 to 54.90% in 2035. In simulation

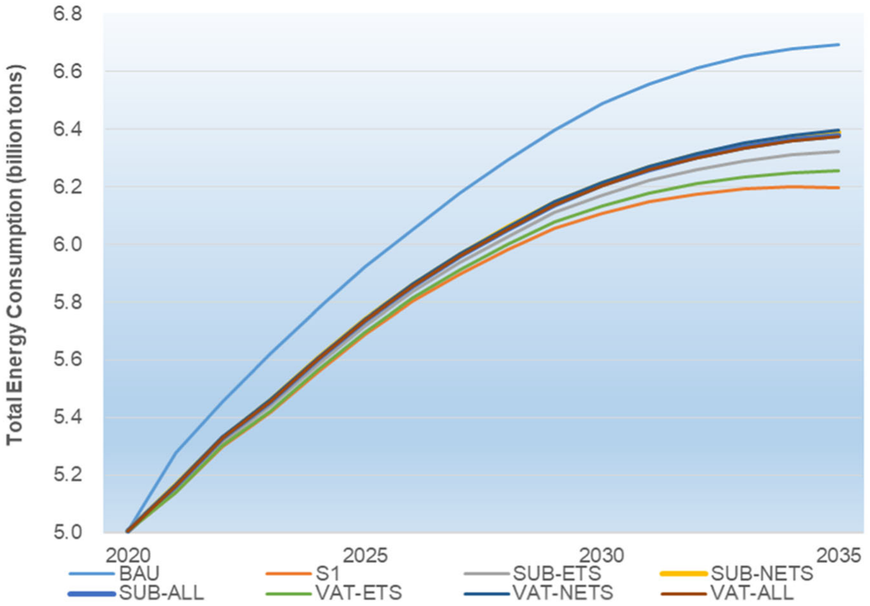

Fig. 3 Changes in total energy consumption relative to the BAU scenario.

scenarios, due to the increased cost of fossil energy use from carbon trading, non-fossil energy use has a relative cost advantage and has “crowded out” some fossil energy consumption, accelerating the optimization and upgrading of the energy consumption structure. When the cost of a particular good or service rises, both consumers and producers will seek alternatives. In this case, due to the increased costs associated with carbon trading, non-fossil energy sources become relatively more cost-effective. This substitution effect is a natural response of economic markets to price changes, leading to the optimization and upgrading of the energy consumption structure.

In scenario S1, the proportion of non-fossil energy consumption will increase to 23.30% by 2035, while coal consumption will decrease to 44.52%, petroleum consumption will increase to 22.38%, and natural gas consumption will increase to 9.80%. In the three subsidy scenarios, the proportion of non-fossil energy consumption will increase to 23.68%, 24.19%, and 24.10%, respectively, while coal consumption will decrease to 43.13%, 43.90%, and 43.76%, respectively. The proportion of petroleum consumption will increase to 23.19%, 22.07%, and 22.27%, respectively, and the proportion of natural gas consumption will increase to 9.99%, 9.84%, and 9.87%, respectively. In the three VAT reduction scenarios, the proportion of non-fossil energy consumption will increase to 23.26%, 24.08%, and 23.96%, respectively, while coal consumption will decrease to 43.03%, 44.16%, and 43.99%, respectively. The proportion of petroleum consumption will increase to 23.69%, 21.97%, and 22.21%, respectively, and the proportion of natural gas consumption will increase to 10.02%, 9.79%, and 9.83%, respectively.

Regardless of whether in the government subsidy scenario or the VAT relief scenario, when carbon market revenues are returned to ETS-covered sectors, the proportion of coal consumption decreases the most, while the proportion of petroleum and natural gas consumption increases the most. Correspondingly, the proportion of coal consumption in the VAT-ETS scenario is lower than that in the SUB-ETS scenario. On the other hand, when carbon market revenues are returned to non-ETS-covered sectors, the proportion of coal consumption decreases the least, and the proportion of petroleum and natural gas consumption increases the least. In terms of the carbon emission coefficients, petroleum and natural gas are with relatively low CO_2 emissions and lower carbon costs compared to coal. Therefore, the eight industries covered by the carbon market are more motivated to reduce the proportion of coal consumption. This change reflects the sensitivity of different industries to carbon costs. Given that coal has a higher carbon emission coefficient, its carbon cost is also relatively higher. Therefore, when carbon market revenues are returned to ETS-covered sectors, these sectors are more incentivized to reduce coal consumption and turn to petroleum and natural gas, which have lower carbon costs. This economic behavior is based on a cost-benefit analysis, where businesses will opt for more economical and efficient energy sources when faced with carbon costs.

Environmental impact. Total carbon emissions for all scenarios over the simulation period are shown in Fig. 5. Under the BAU scenario, total carbon emissions increase throughout the simulation period and fail to peak by 2030, growing from 9,820 million tons in 2018 to 12,900 million tons in 2035. The continuous rise in carbon emissions is likely correlated with economic growth. As production and consumption activities expand, the demand for energy increases, subsequently driving up carbon emissions. This trend suggests that without appropriate policy interventions, economic growth might be closely linked with the rise in carbon emissions.

In single carbon ETS scenario S1, total carbon emissions peak at 10,923 million tons in 2029. When comparing the government subsidy scenario with the corresponding VAT reduction scenario, it is found that scenario SUB-ETS and scenario VAT-ETS peak at 10,948 million tons and 10,906 million tons, respectively, in 2029. Scenario SUB-NETS and scenario VAT-NETS peak at 11,018 million tons and 11,042 million tons, respectively, in 2030. Scenario SUB-ALL and scenario VAT-ALL peak at 11,004 million tons and 11,020 million tons, respectively, in 2030. When carbon market revenues are returned to industries covered by the ETS (whether through subsidies or VAT reductions), the timing to reach peak carbon emissions remains unchanged. However, industries tend to perceive money from VAT reductions as their own, making their motivation to reduce emissions stronger than when receiving government subsidies. Furthermore, the peak carbon emissions are relatively lower compared to the SUB-NETS

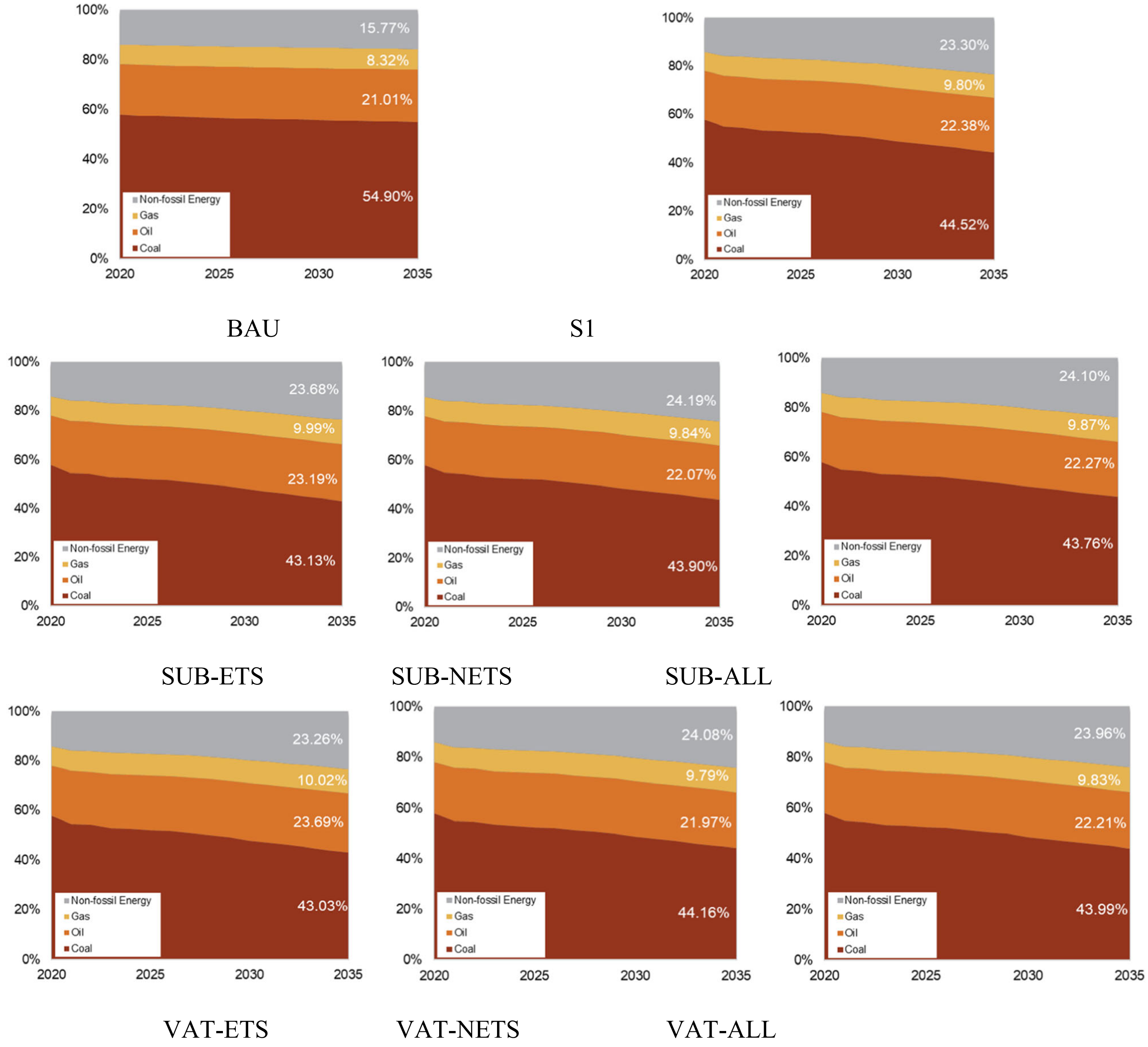

Fig. 4 Changes of the energy consumption structure under different scenarios.

and VAT-NETS scenarios. This is because, when carbon market revenues are redirected to industries not covered by the ETS, these sectors, having comparatively lower carbon emission costs, lack sufficient incentive to cut emissions. Consequently, their peak carbon emissions are higher, and the time to reach this peak is delayed by a year. However, when carbon market revenues are redistributed across all industries, the peak carbon emissions and the timing to reach this peak represent a compromise between the outcomes of the aforementioned two redistribution scenarios (subsidies and VAT reductions).

It can be observed that the carbon peak time is also different due to the different production sectors that receive carbon market revenue returns. Returning revenue to ETS-covered sectors will not affect the time of the carbon peak, and the VAT reduction is more effective in reducing carbon emissions during this time. Returning revenue to non-ETS covered or all production sectors will lead to a later carbon peak. Under these circumstances, the peak point of carbon emissions under the government subsidy scenario is observed to be even lower. When carbon market revenues are returned to non-ETS covered sectors or all production sectors, the carbon costs within the production costs of non-ETS covered sectors are relatively lower. As a result, there might not be as strong an incentive to reduce carbon emissions, leading to a later appearance of the peak in carbon emissions.

Changes in income Gini coefficient. Compared with the BAU scenario, the changes in the Gini coefficient under different scenarios are shown in Fig. 6. The research results show that in the BAU scenario, the income gap among residents is widening yearly; that is, the Gini coefficient is increasing yearly. However, when a single carbon trading scenario is adopted, the income gap among residents is reduced. This is because carbon market income belongs to the government, and low-income groups receive more government transfer payments than other groups. From an economic perspective, government transfer payments are typically aimed at redistributing income to reduce income inequality. When the revenue from the carbon market belongs to the government, it has the capacity to support low-income groups through transfer payments, thereby narrowing the income gap. The goal is to achieve a more equitable income distribution through taxation and transfer payments.

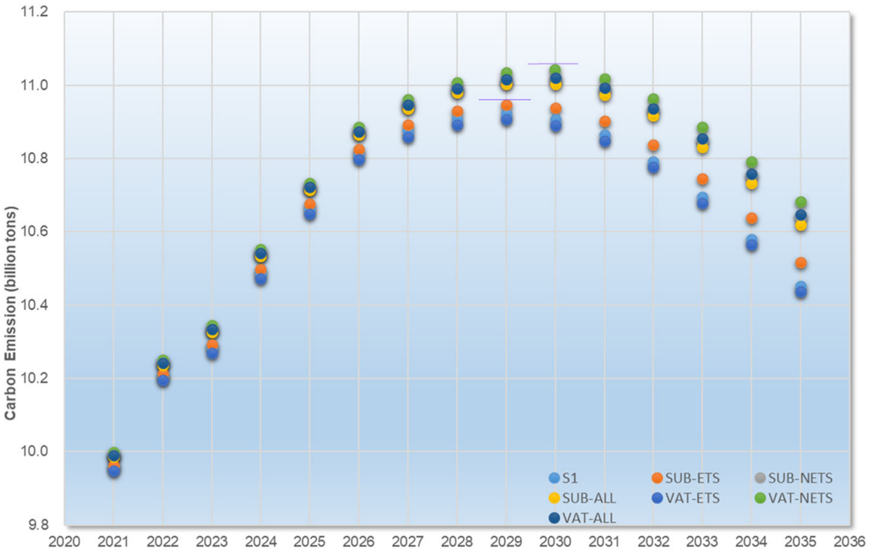

Fig. 5 Changes of total carbon emissions in different scenarios.

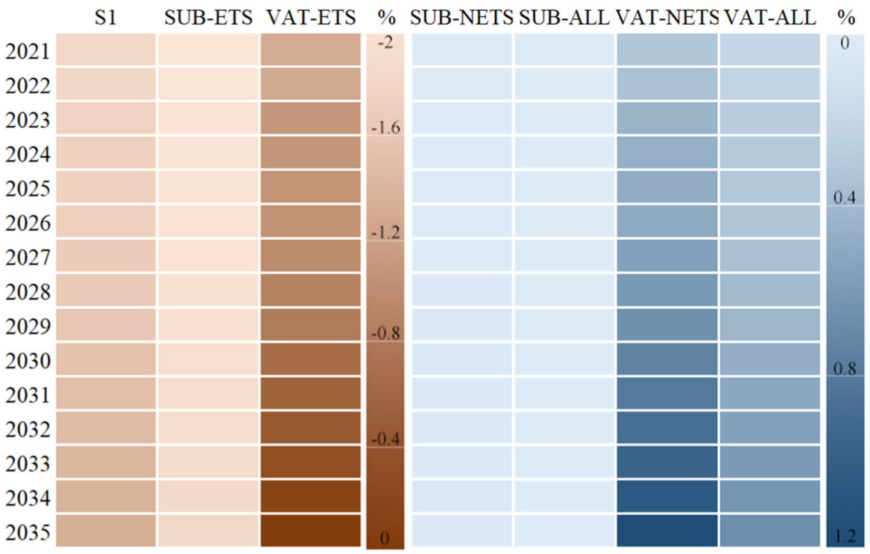

Fig. 6 Changes in the Gini coefficient under different scenarios.

In other scenarios, returning carbon market income to different industries can significantly impact income inequality and may even lead to an increase in income inequality. Specifically, returning carbon market income to ETS-covered industries through VAT relief is most conducive to narrowing income inequality, with the Gini coefficient decreasing by 1.86% in 2035. Returning carbon market revenue to non-ETS-covered industries through VAT relief is least conducive to social equity, and in this case, the Gini coefficient will increase by 1.17% in 2035.

Comparing the changes in the Gini coefficient under different ways of returning carbon market revenue, we can see that returning carbon market revenue through a VAT relief has a greater impact on income distribution while returning carbon market income through industry subsidies has a relatively smaller impact on income distribution. In addition, the study also found that, whether through subsidies or tax reductions, returning carbon market revenue to ETS-covered industries is conducive to narrowing income inequality. This result may be because there are differences in the occupational skills of different income groups, and generally, occupational skills are positively correlated with income. When companies are impacted by carbon pricing policies, high-skilled residents can smooth the adverse effects of wage decline through labor migration. In contrast, low-skilled residents in high-energy and high-emission industries must adapt to the changes in carbon market policies. Therefore, returning carbon market income to ETS-covered industries has a relatively smaller impact on low-income groups and is most conducive to narrowing income distribution. From the perspective of labor economics, high-skilled workers typically possess greater labor mobility, enabling them to more easily adapt to economic and policy changes. In contrast, low-skilled workers might find it more challenging to secure new job opportunities, especially in high-energy-consuming and high-emission industries affected by carbon pricing policies. Therefore, returning carbon market revenues to ETS-covered industries could help shield these low-skilled workers, thereby reducing income inequality. This observation aligns with the findings of Zhang et al. (2023), who emphasized the importance of targeted fiscal policies in mitigating the adverse effects of environmental regulations on vulnerable labor groups.

Conclusion and policy implications

This paper built a dynamic CGE model based on China's carbon peak target and carbon ETS, in which carbon market revenues are returned to different production sectors through government subsidies or VAT reductions.

The results of the modeling indicate that implementing carbon ETS while returning carbon market revenues to the industries through subsidies or VAT reductions has different economic, energy, and environmental effects. Firstly, China's carbon emissions could peak in 2029 at 10,923 million tons if the carbon intensity decreases at an average annual rate of 4.5% under a single carbon ETS scenario S1. While implementing carbon ETS, returning carbon market revenue to the production sector through government subsidies or VAT cuts can achieve carbon peaking before 2030 with less GDP loss. This is consistent with the research by Li et al. (2023) and further supported by studies such as Garaffa et al. (2021) and H. Wang et al. (2019), which emphasize the potential of revenue recycling in mitigating economic impacts while promoting sustainability. Specifically, compared to scenario S1, returning carbon market revenues to ETS-covered sectors still results in a peak in 2029, where the GDP loss in the government subsidy scenario is smaller than in the VAT reduction scenario. At this point, government revenues also benefit from the positive effects of subsidies or tax cuts on economic growth, with some increases compared to the BAU scenario. When returning carbon market revenues to non-ETS-covered sectors or all industries, it increases the peak emissions and delays the peak time until 2030, where the GDP loss in the VAT reduction scenario is smaller than in the government subsidy scenario.

Secondly, government subsidies and VAT cuts can stimulate output growth in the oil, gas, and ETS-covered sectors. By redirecting carbon market revenues back to these ETS-covered sectors, it provides a stronger incentive for them to adopt cleaner energy sources for production. VAT reductions can stimulate economic activity by alleviating the tax burden on producers, potentially offsetting some of the increased costs associated with carbon pricing. VAT relief is more effective than government subsidies in reducing output in the coal sector. When carbon market revenues are returned to the non-ETS-covered sectors, output in the coal sector declines the least. This is in line with the findings of Boeters et al. (2010), who found that fiscal incentives can significantly influence industries' transition to cleaner energy sources.

Furthermore, returning carbon market revenue to ETS-covered sectors has a better effect on controlling the total energy consumption, as measured by the coal consumption ratio, indicating the cleanliness and low-carbon level of the energy consumption structure. Returning carbon market revenue to ETS-covered sectors is also more conducive to optimizing and upgrading the energy consumption structure, with VAT reduction being more effective than government subsidies.

This study highlights the impact of different methods of returning carbon market revenues on various sectors, affecting GDP, peak carbon emissions, and time to peak carbon emissions under the principle of revenue neutrality. In this context, GDP losses are inversely proportional to peak carbon emissions, with lower emissions leading to higher GDP losses. Specifically, returning carbon market revenues to non-ETS sectors through VAT reductions results in the highest carbon emissions and delayed peak emissions compared to the BAU scenario, with the highest total energy consumption but minimized GDP losses. Conversely, returning revenues to ETS-covered sectors through VAT reductions leads to the lowest carbon emissions and total energy consumption, but the highest GDP losses.

To balance economic development and carbon emission goals, returning carbon market revenues to the production sector is necessary. However, no single plan can achieve lower peak carbon emissions, earlier peak carbon time, minimal GDP loss, lower energy consumption, and cleaner energy consumption structure. Therefore, the choice of return method depends on various factors and the government's policy objectives. If the aim is mainly carbon emission reduction, returning carbon market revenue to ETS-covered sectors through tax reduction is appropriate. If the focus is on economic efficiency, returning carbon market revenue to non-ETS-covered sectors through tax reduction is appropriate. If the goal is to balance emission reduction and economic efficiency, returning carbon market revenues to ETS-covered sectors through subsidies may be more appropriate.

Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

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Author contributions

LQ: data analysis, methodology, results discussion, writing—original draft. LZ: results discussion, revising draft. YZ: data collection, data analysis, methodology, results discussion, writing—original draft; funding acquisition. SJ: data analysis, results discussion—original draft. XL: data analysis, methodology, results discussion—original draft. YR: methodology, results discussion, revising draft.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study did not involve human participants.

Informed consent

Informed consent was not required as the study did not involve human participants.

Additional information

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