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Synergistic effect of carbon ETS and carbon tax under China's peak emission target: A dynamic CGE analysis

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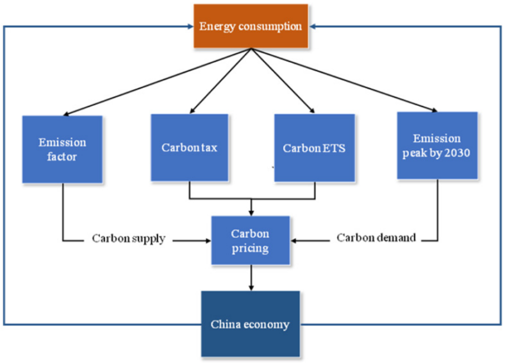
HIGHLIGHTS

- Using the dynamic CGE model, the pure carbon ETS is simulated, as well as a hybrid policy where the non-ETS sectors pay a carbon tax.
- This paper sets first the different scenarios in the context of reaching the similar carbon emissions peak as early as 2030.
- It is evident that that hybrid policy can better help reach a carbon emissions peak before 2030.

GRAPHICAL ABSTRACT



- A hybrid policy including carbon ETS and carbon tax can achieve emission peak as early as 2030 with less economic loss and lower total carbon emissions than a single ETS

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ABSTRACT

Global warming resulting from greenhouse gas emissions poses threats to humankind and has become a worldwide issue. As the top CO_2 emitter in the world, China has committed to achieving its carbon emission peak by no later than 2030; in this context, how to best use and apply carbon emission reduction policy is particularly critical. By constructing a dynamic computable general equilibrium (CGE) model, we first examine a pure ETS included only the electricity sector in 2021, and the eight sectors starting in 2022, considering a declining carbon intensity rate of 4.5% and a higher rate of 4.8%. With the carbon intensity rates of 4.3% and 4.5%, we further evaluate two-hybrid systems of the carbon tax and carbon ETS, where the carbon tax of 10 yuan per ton is the starting levied rate in 2022 and increases at 4 yuan per ton year by year. The results proved that hybrid emission reduction policy can help reach a carbon emissions peak before 2030 and do so at a lower economic cost compared to the effect of pure carbon ETS. Besides, the coordinated use of a carbon tax and a carbon ETS can promote optimization of energy consumption structures and accelerate the decline of energy intensity and carbon intensity; this can contribute to curbing the growth of total energy consumption and total carbon emissions.

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1. Introduction

Climate change is one of the primary threats to humankind and has gained considerable international attention. According to the Paris Agreement, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) is determined to control the increase of the global average temperature less than 2 °C above that of the pre-industrial level, and the UNFCCC means to limit the temperature rise to 1.5 °C above pre-industrial levels (Schleussner et al., 2016). As the top CO_2 emitter and largest energy consumer in the world, China has set aggressive targets for carbon emissions reduction by 2030, aiming to decrease CO_2 emissions per unit of GDP by more than 60–65% compared to 2005. Furthermore, in September 2020, President Xi Jinping announced at the UN General Assembly that China will endeavour to reach its peak CO_2 emissions by 2030 (Normile, 2020).

Not surprisingly, the approach to developing a series of policies to restructure the energy mix and control carbon emissions has been earnest in China. Carbon pricing, including a carbon emission trading scheme (ETS) and a carbon tax, is widely considered an effective instrument for reducing carbon emissions. On one hand, the Chinese government has adopted the carbon ETS to lessen carbon emissions; specifically, the ETS pilots were implemented in 2013, in seven provinces and cities, to reduce emissions and realize sustainable development (Zhang, 2015). Fujian and Sichuan provinces joined the ETS scheme in its second stage in 2016 and 2017. At the end of 2017, the nationwide carbon emissions trading market was proposed to begin in China. Compared with non-pilot areas, ETS industries in the pilot areas decreased energy consumption by 22.8% and CO_2 emissions by 15.5%, mainly by improving technical efficiency and changing industrial structure (Hu et al., 2020). However, many scholars still question the efficacy of a carbon ETS because of its harmful effect on economic development in China. For example, Hübler et al. (2014) used the computable general equilibrium (CGE) model to evaluate the carbon ETS in China and found that in 2020, it resulted in a GDP loss of about 1% and they assert that by 2030, it could result in a welfare loss of about 2%.

On the other hand, the National Development and Reform Commission (NDRC) and the Ministry of Finance (MOF) proposed in a joint special report that a carbon tax be levied in China by the year 2012 (Liang and Wei, 2012); however, the Chinese government did not implement the tax until 2021. The effect of an appropriate carbon tax rate on CO_2 mitigation and energy consumption reduction is attracting attention in the academic field. Lu et al. (2010) argued that had a tax rate of 300 RMB/ton been imposed in 2013, it could have cut total carbon emissions by 17.45% with a 1.1% GDP loss. Chi et al. (2014) found that carbon tax was useful for energy savings and emissions reduction but in turn posed a harmful effect on GDP under different carbon tax policy scenarios. The latest research result from Fu et al. (2021) that carbon taxes of 18.37 to 38.25 Yuan per ton are a suitable option for China. Therefore, the barriers to the implementation of a carbon pricing instrument are related to the uncertain rate and impacts of it on the economy, energy, and the environment. To alleviate the defects or controversies surrounding a carbon pricing tool, it has been suggested that a carbon ETS, a carbon tax, or multiple instruments could be combined to form a hybrid policy toward effective carbon emissions abatement (Goulder and Schein, 2013).

Economic development, environmental protection, energy transition, and the improvement of living standards are China's main priorities. However, the carbon pricing tool poses negative effects to economic growth, especially threatening the energy-intensive and trade-intensive sectors. Severe socio-economic problems will emerge if the carbon pricing tool is inappropriately designed and implemented. That said, it is critical to perform in-depth analyses on the application of carbon pricing instruments in China. With great concern for reaching the carbon emissions peak as early as 2030, this paper studies a hybrid policy that consists of the carbon ETS and carbon tax working together for China's economy, energy, and environment using a dynamic CGE model. This paper first sets the different scenarios, comparing the pure carbon ETS to the hybrid carbon policy by clarifying the quantitative gains and losses on carbon emission reduction and the macroeconomic, energy, and environmental impacts under similar carbon peak targets.

The remainder of this paper is arranged as follows: In Section 2, we review the existing literature and discuss each contribution. In Section 3, the hybrid policy and the pure ETS module will be integrated into the dynamic CGE model, and four scenarios will be set and simulated. Based on the simulation results, in Section 4 we analyze strategies for carbon emission mitigation. Finally, Section 5 puts forth several corresponding policy suggestions that will help achieve the carbon emission peak target by 2030.

2. Literature review

Much literature focuses on studies about economic and environmental effects of carbon ETS or carbon taxes in different countries. The economic and environmental effects of ETS vary depending on the participating industries and regions. For example, based on a CGE analysis of a multi-sector carbon ETS, Nong et al. (2020) analyzed the harmful impact of carbon ETS on GDP growth in Vietnam. They showed that GDP losses were 1.78% and 4.57%, respectively, caused by different sectorial coverage. Lin and Jia (2018) studied the impact of different transfer payments in ETS on the rural and urban population. They revealed that the payments based on population can also reduce by 15.09 billion tons of CO_2 emission during 2017–2030, and significantly impact commodity consumption, energy consumption, direct tax, and social welfare. Nong et al. (2017) assessed the impact of Australia's ETS on the economy and the environment there; they found that when the carbon price was AU$13.1 per ton, GDP fell by 0.85% in 2020, while carbon prices rose to AU$ 41.3 per ton, it can be achieved 28% emissions reduction in 2030 compared to 2005 with 1.6% GDP loss. Lin and Jia (2017) found that different industries coverage in China's ETS with carbon prices ranging from US$10–57 per ton by 2030 led to commodity prices increases from 0.12 to 1.64%. Studies exist as well about other countries or regions, such as EU ETS (Guo et al., 2020; Perino and Willner, 2017), and about carbon ETS links between different regions (Green, 2017; Hintermann and Gronwald, 2019).

The carbon tax, which is levied depending on the carbon content or CO_2 emissions of fossil fuels (Lin and Li, 2011), differs from the carbon ETS in mitigation effects, mitigation costs, and industries coverage (Goulder and Schein, 2013), and the subsidies tax comes in the form of an exemption—that is, a lower tax rate or rebates. In comparison, the ETS takes the form of free allowances or rebates (Haites, 2018). Liu et al. (2021) evaluated whether the carbon taxes (carbon tax rate of 20 RMB/ton-CO_2, 50 RMB/ton-CO_2, and 100 RMB/ton-CO_2) are effective for China to achieve the win-win target of carbon reduction and GDP growth based on the energy substitution theory and input-output theory. The results showed that the carbon tax policy would be effective for China and should be set at a low level to achieve the emission reduction target with the lowest economic cost. Many other studies have analyzed the performance of different tax rates on social welfare effects or dividends of different countries (Beck et al., 2015; Renner, 2018; Rosas-Flores et al., 2017; Wang et al., 2016). However, there remains controversy about which is better-the carbon ETS or the carbon tax-for emissions mitigation and economic development. Jia and Lin (2020) set the GDP as an exogenous variable to compare the difference between a carbon tax and a carbon ETS using a recursive dynamic CGE model. The results showed that in terms of mitigation effect, a carbon tax is slightly better than that of a carbon ETS in the long run. Bi et al. (2019) found that the ETS would stimulate increased energy-saving innovations, while the carbon tax would not, and thus the ETS policy presents the lowest cost in terms of GDP growth. However, the free allocation of emissions permits may hinder the potential investment of environmental technology innovations (Yang et al., 2016).

Design issues for better economic and environmental effects of the carbon tax and the carbon ETS have been discussed (Pizer, 2002; Tyler and Cloete, 2015). Chiu et al. (2015) designed the carbon tax and carbon ETS in the theoretical model and pointed out that a country that wants to reduce carbon emissions through either a carbon tax or carbon ETS needs to examine the structure of the energy market. As a popular policy simulation tool, CGE models have in recent years been widely deployed in the analysis of carbon taxes and carbon ETS (Jia and Lin, 2020; Liu et al., 2018; Tang et al., 2016). The CGE model can be used to explore the interactive effects of multiple policies and provide insights about feasible carbon-mitigation policies (Cao et al., 2021). For example, Lin and Jia (2020a) adopted a dynamic recursive CGE model to simulate different impact paths of the resource tax and carbon tax. The results showed that a carbon tax could significantly reduce the energy demand of enterprises and restrain energy imports. While resource tax may be a better policy of reducing emissions to obtain "excess profits" if reducing emissions is compulsory.

Consequently, a growing body of literature has examined hybrid policies of emissions mitigation. Fu et al. (2021) develop a factorial computable general equilibrium (FCGE) model to examine the interactive effects of a grouping of emission intensity/level and relevant tax rates. They pointed out that the stepped carbon tax (18.37 to 38.25 yuan per ton is more efficient than the conventional carbon tax policy. Besides, the positive effects for decreasing carbon emission intensity can be strengthened with an increasing step range of carbon tax. As to the combined effect of the carbon ETS and the carbon tax by the CGE model. For example, Cao et al. (2019) adopted a dynamic CGE model to simulate a hybrid ETS-carbon tax system with a carbon tax on non-ETS sectors in China. They found that the hybrid policy achieved the set target with lower carbon prices and GDP losses than that did the pure ETS. Li and Jia (2017) adopted the dynamic CGE model to integrate a carbon tax and ETS into one framework and found that the mixed policy is the most effective strategy to achieve China's carbon peak by 2030. However, unlike Cao et al. (2019)'s study, they set different carbon tax and ETS prices. In Bi et al. (2019)'s research, carbon ETS started with electricity sector, and the carbon tax was also fixed, which was at 25 yuan/ton. They asserted that the effect of the mixed policy is not a simple combination of the impacts of the carbon tax and carbon ETS but rather shows another pathway for green growth.

In summary, even though much literature has shown the effectiveness of the pure carbon ETS and the carbon tax, or compared the differences between hybrid and single-emission reduction policies, little research demonstrates how to combine a carbon ETS and a carbon tax by adjusting carbon tax and carbon intensity rate to achieve the similar carbon emission peak by around 2030. This paper hopes to contribute new perspectives on this topic from three aspects. First, we simulate, by a dynamic CGE model, a carbon ETS market and a hybrid system where the non-ETS sectors pay a carbon tax. Specifically, to achieve similar carbon peak scenarios by 2030, the carbon tax of 10 yuan per ton is the starting levied rate and increases at 4 yuan per ton year by year; carbon ETS includes only the electricity sector in 2021, and the eight sectors starting in 2022. The exogenous tax rate in our hybrid system is selected to harmonize the carbon price in ETS and non-ETS sectors by several modelling simulations, resulting in similar carbon peak scenarios. Different carbon prices on ETS versus non-ETS sectors would lead to inefficient carbon reduction and require careful adjustment. Besides, we select the year 2035 as the end year of the dynamic simulation to observe changes occurring in a few years after the total carbon emissions peak around 2030. Second, we examine a pure ETS with a declining carbon intensity rate of 4.5% and a higher rate of 4.8%. We then evaluate two-hybrid systems of the carbon tax and carbon ETS, with different declining carbon intensity rates of 4.3% and 4.8%. The setting is straightforward to compare the difference between the hybrid carbon emission reduction policy and the pure carbon ETS on the macroeconomic, energy, and environmental impacts under similar carbon emission peaks by 2030. Third, our simulations indicate that the carbon prices and GDP losses of hybrid systems and a pure ETS achieve similar CO_2 goals. However, the hybrid emission reduction policy does so at a lower economic cost compared to the effect of pure carbon ETS. Because, mixed carbon pricing in our model let all sectors pay for carbon emission, while ETS is not. Carbon leakage exists not only between regions, but also between industries. So, we usually suggest ETS together with carbon tax as a low carbon policy.

3. CGE model

CGE models stem from the general equilibrium theory (Walras, 1954). The general equilibrium theory examines changes in the prices, quantities, and market supply-and-demand relationships of all commodities and factors within an entire economic system as they relate to variations in an exogenous variable; it allows study of the impact of the transition of the economic system from one equilibrium state to another on the macroeconomic level (Sue Wing, 2011). This paper constructs a multi-sectoral recursive dynamic CGE model in China, to include production module, income and expenditure module, trade module, carbon tax and carbon trading module, dynamic module, and macro closure module. The study works across 29 sectors, two kinds of production factors (capital and labor), and two economic entities (residential and government). This section introduces the production module and the carbon tax and carbon ETS module. For other main modules, refer to the Appendix A.

3.1. Production module

The production module describes the relationship between factor input and output of the domestic production sector. In this model, we assume that the market is perfectly competitive. The output is determined by market equilibrium conditions with the principle of cost minimization. The production module uses a multi-level nested structure to reflect the complex substitution relationship between multiple inputs (see Fig. 1). The intermediate input and added value input solve the first level of nesting through the CES function. The second layer consists of two parts: The first is the compounding of the intermediate input through the LT function, and the second is the compounding of the capital-labour bundle through the CES function. The third layer describes the energy sub-products bundle formed by combining energy products and electricity products through the CES function. The fourth layer is the bundle of fossil energy products and electricity products. The energy products on the left are composed of coal, oil, and natural gas through the CES function. The electricity product on the right is a composite of thermal power and other power.

3.2. Carbon tax and carbon ETS module

This paper assumes that a carbon tax is levied on the carbon emissions of the production sector, which adopts a fixed-tax rate and is calculated based on the carbon content in fossil energy. Here we set the tax rate exogenously, and the tax revenue is collected for the government's general budget management. In addition, we do not set carbon tax incentives or tax refunds. The main formula of the carbon tax module is as follows:

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

$$CATX_{i,t} = CT_t * EM_{i,t} \tag{2}$$

$$GYCATX_t = \Sigma_t CATX_{i,t} \tag{3}$$

where $CATX_{i,\ t}$ represents the carbon tax levied by sector i in period t, CT_t represents the carbon tax rate in period t; $EM_{i,\ t}$ means CO_2 emissions form sector i in period t; $D_{i,\ t}$means the intermediate input of fossil energy products in period t; θ is the carbon emission coefficient of fossil energy products in period t; and $GYCATX_t$ denotes the government's carbon tax revenue in period t.

As for the carbon ETS, the model assumes that the carbon market is perfectly competitive. Besides, it also assumes that all allowances needed to be auctioned because of two reasons. First, based on the practical experience of the first to fourth stages of the EU carbon market, the auction ratio of carbon allowances gradually increased, and even 100% was auctioned in the power sector,[1] with the stricter emission reduction targets. Second, the initial allocation of emissions allowances is usually considered independent of

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[1] International Carbon Action Partnership (ICAP) Status Report 2021.

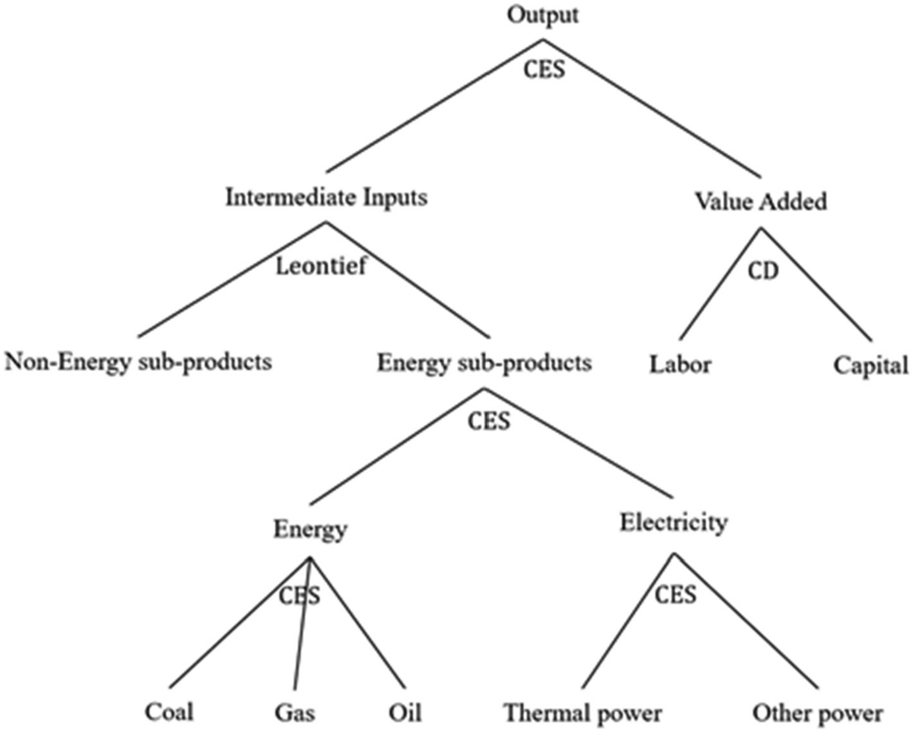

Fig. 1. The framework of production module.

the emissions reduction, free allocation can affect the performance and fairness of allowance trading (Burtraw and McCormack, 2017). Therefore, we assume that 100% of carbon allowances are auctioned in order to study the emission reduction potential of the carbon market and ignore the impact of free allocation on the performance and fairness of allowance trading.

When carbon supply and carbon demand are equal, the carbon market reaches equilibrium status, and the carbon allowance prices of all participating carbon trading industries reach the same level. The government exogenously sets the supply of carbon allowances in the carbon trading market in the model, according to specific emission reduction targets, to set the total emission cap. Just as with the carbon tax revenue, the carbon allowance revenue is collected and uniformly distributed by the government. The main formula of the carbon trading module is as follows:

$$TCO2_t = (1 - tcer_t)CO2ref_t \tag{4}$$

$$TCO2_t = \Sigma_i EM_{i,t} \tag{5}$$

$$C_{i,t} = PCO2_{i,t} * EM_{i,t} \tag{6}$$

$$GYETS_t = \Sigma_i C_{i,t} \tag{7}$$

where $CO2ref_t$ is the total carbon emissions in period t under BAU scenario. $tcer_t$ is the carbon emission reduction rate of sectors covered by ETS set by the government according to the emission reduction target. The left side of Eq. (4) represents the demand for carbon allowances and the right side means the supply of carbon allowances, which determines $PCO2_{i,\ t}$. $PCO2_{i,\ t}$ denotes the unit price of carbon allowances for each sector in period t. $TCO2_t$ represents the total carbon emissions of all industries in period t, and $C_{i,\ t}$ means the total value of carbon allowances auctions by each sector in period t, and $GYETS_t$ represents the total value of carbon allowances auctions in period t. From the perspective of production costs, carbon trading and carbon taxes increase the price of fossil energy products. The formula is as follows:

$$X_{i,t} * PX_{i,t} = OC_{i,t} + CATX_{i,t} + C_{i,t} \tag{8}$$

where $X_{i,\ t}$ represents the domestic output of each sector in period t, $PX_{i,\ t}$ means the price of domestic output of each sector in period t, $OC_{i,\ t}$ denotes original production cost of each sector in period t. The operating mechanism of the hybrid policy is shown in Fig. 2 below.

3.3. Scenario setting

The first compliance period (1 January 2021–31 December 2021) of the national carbon emissions trading market was launched in China. The carbon market started with the electricity sector included in 2021. Later, carbon ETS is proposed to cover eight industries: power, aviation, steel, chemical, building material, petrochemical, nonferrous metals, and paper. China committed to achieving the CO_2 emissions peak by 2030, and in fact endeavored to realize the peak before 2030.[2] In this paper, we assume that the national carbon ETS included only the electricity sector in 2021, and the eight sectors starting in 2022 as well as carbon tax implemented. According to China's policies and actions in response to climate change 2018 annual report,[3] and Li and Jia (2016)'s study, the year 2035 is selected as the end year of the dynamic simulation to observe changes occurring in a few years after the total carbon emissions peak.

This paper refers to the method of Xiao et al. (2020). The annual carbon intensity decline rate from 2021 to 2035 is gradually increased by 0.05% based on the dynamic baseline scenario. After several adjustments, the average annual carbon intensity decline rate of 4.5% and 4.8% can reach their peaks in 2029 and 2027, respectively, which is consistent with some studies' predictions for China to achieve carbon peaks in 2030 (Cai et al., 2021; He, 2013; Mi et al., 2017). Besides, in order to design a series of similar carbon peak scenarios, we conducted several model simulation tests on the carbon tax rate. Based on the starting carbon tax of 10 yuan per ton, we gradually increased the carbon tax rate from 1 yuan per ton every year. After many tests, it was finally found that our research purpose can be realized when the carbon tax rate increases at 4 yuan/ton year by year. It aligns with Su et al. (2009)'s and Liu and Zhang (2019)'s findings that if China

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[2] China-U.S. Joint Statement on Climate Change can be viewed (in Chinese) at http://www.gov.cn/xinwen/2014-11/13/content_2777663.htm

[3] "China's policies and actions in response to climate change 2018 annual report" https://www.mee.gov.cn/ywgz/ydqhbh/qhbhlf/201811/P020181129539211385741.pdf

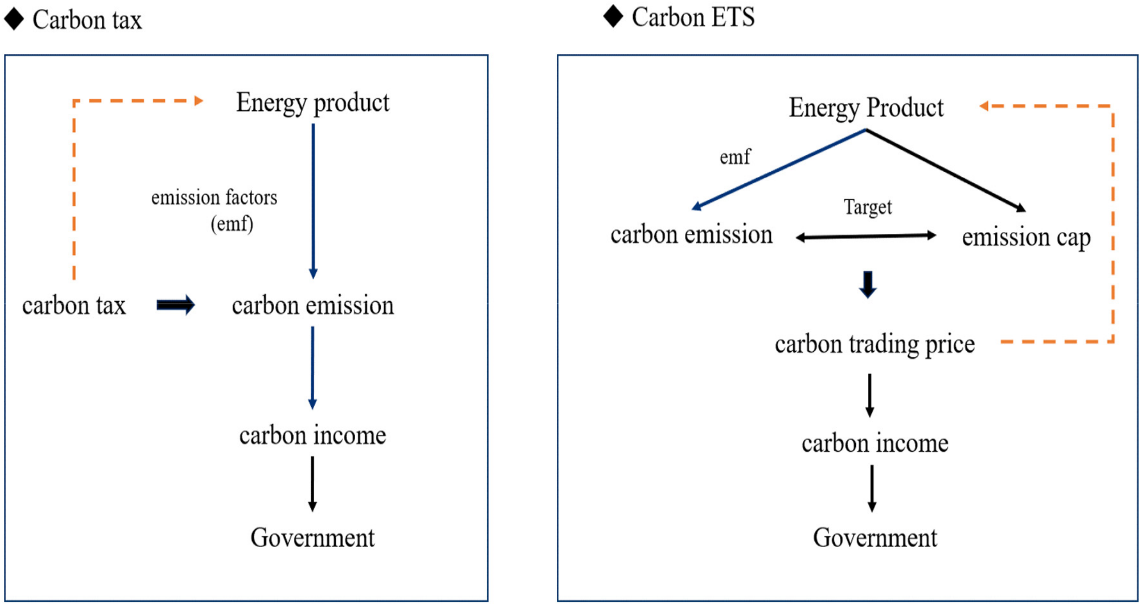

Fig. 2. The operating mechanism of the hybrid policy.

levies a carbon tax, it should start with a low tax rate and gradually increase, which will have a negligible impact on the economy.

As shown in Table 1 and the BAU scenario, we set up four different emission reduction scenarios. The first scenario, S1, only includes the single carbon trading scheme with the annual average decline rate of the carbon intensity of 4.5%. The second scenario, S2, is also the single carbon trading scheme with the annual average decline rate of the carbon intensity of 4.8%. The third scenario, M1, mixes carbon trading scheme and carbon tax with the average annual decline rate of the carbon intensity of 4.3%. The fourth scenario, M2, is also the mixed policy with an average annual decline rate of the carbon intensity of 4.5%. In these two mixed scenarios, the carbon tax of 10 yuan/ton is levied on industries covered by the non-carbon market from 2021 and will increase by 4 yuan/ton annually.

4. Results and discussion

4.1. Environmental impact

Fig. 3 shows the total peak carbon amount from 2021 to 2035 under each scenario. Under the BAU scenario, the total amount of carbon emissions gradually rises but could not reach the emission peak before 2030, while in scenarios S1, S2, M1, and M2 the total carbon emissions gradually increase first and then gradually decrease after reaching a peak at a certain point in time. The total carbon emissions of the S1 scenario peak at 10.93 billion tons in 2029 and then gradually decrease to 10.60 billion tons by 2035; the total carbon emissions of the S2 scenario will reach 10.68 billion tons in 2027. After the peak, emissions will gradually decrease to be reduced to 10.11 billion tons by 2035. In Scenario M1, the total carbon emissions will peak at 10.98 billion tons in 2029, gradually declining to 10.56 billion tons by 2035; in scenario M2, the total carbon emissions peak at 10.57 billion tons in 2027 and then gradually decline to 10.03 billion tons in 2035. It is evident that the higher the average annual decline rate of carbon intensity, the earlier the carbon peak is reached and the lower the total carbon emissions.

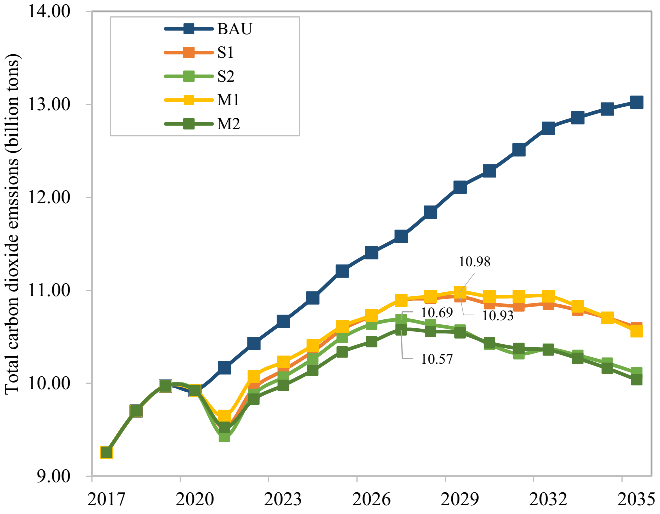

Fig. 3. Total carbon emissions from 2017 to 2035 in each scenario (million tons).

It was found that the S1, S2, M1, and M2 scenarios have all achieved China's goal of peaking carbon emissions by 2030, and the total emission peaks and the timing of scenarios S1 and M1 are similar. In scenarios S2

Table 1
Scenarios setting.

Scenarios	Carbon ETS		Carbon tax	
	Coverage	Decline rate of carbon intensity (%)	Coverage	Tax rate (Yuan/ton)
S1		4.50%	–	–
S2		4.80%	–	–
M1	Power, aviation, steel, chemical,	4.30%	Non-carbon market	10 + (Year-2021) *4
M2	building material, petrochemical, nonferrous metals, and paper industries	4.50%	industries	10 + (Year-2021) *4

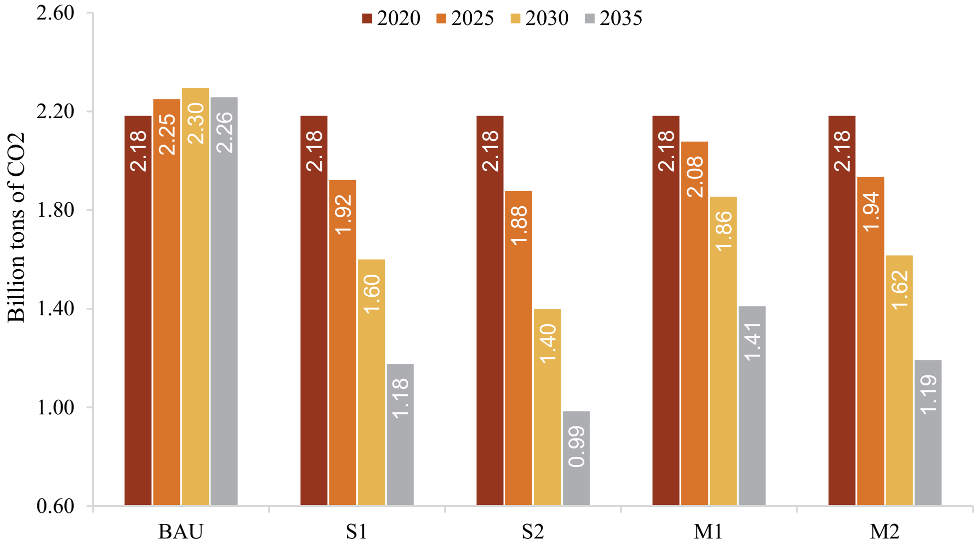

Fig. 4. Carbon emissions of the thermal power industry.

and M2, the total carbon peak amount and time are similar; therefore, based on the research goal of this paper, the subsequent analysis is mainly to compare the results of S1 and M1 and of S2 and M2. During the entire simulation period, the total emission reduction of scenario M1 is similar to that of S1. However, the total emission reduction ratio of scenario M2 is higher than that of S2.

Under the BAU scenario, the carbon emissions of the thermal power industry increase first and then decrease, while in the other scenarios the carbon emissions of the thermal power industry kept declining over time (see Fig. 4). In contrast, in the BAU scenario the carbon emissions of the steel industry show an increasing trend over time, while in the other scenarios, the steel industry experienced a slight fluctuation and a downward trend (see Fig. 5). At the same time, it was found that the higher the average annual decline rate of carbon intensity, the more the carbon emissions of thermal power and steel industries will decrease.

Regarding carbon intensity, Table 2 reveals that under the BAU scenario, carbon intensity declines year by year, from 112.45 tons/million yuan in 2017 to 63.02 tons/million yuan in 2035. However, China's 2030 carbon intensity target has not been achieved in BAU. In other scenarios, the total carbon emissions have decreased, and the decline of carbon intensity has accelerated, all of which help to achieve China's 2030 carbon intensity target. The carbon intensity of S1, S2, M1, and M2 will decrease from 112.45 tons/million yuan in 2017 to 51.85 tons/million yuan, 49.66 tons/million yuan, 51.54 tons/million yuan, 49.16 tons/million yuan in 2035, respectively. By 2035, the carbon intensity of scenarios M1 and M2 is smaller than that of S1 and S2, respectively.

Table 3 shows the price of carbon allowance and carbon tax rate in each scenario. Compared with the single carbon trading market scenarios S1 and S2, the mixed policy of carbon trading and carbon tax can reduce the price of carbon allowances and the scale of the carbon market. The decline in the price of carbon allowances and the scale of the carbon market are mainly due to the introduction of carbon tax policies. Industries covered by the non-carbon trading market have undertaken certain emission reduction obligations to reduce the pressure of emissions in the carbon market. The price of carbon allowances and the scale of the carbon market have also declined correspondingly. Furthermore, the higher the annual average decline rate of carbon intensity, the higher the price of carbon allowances.

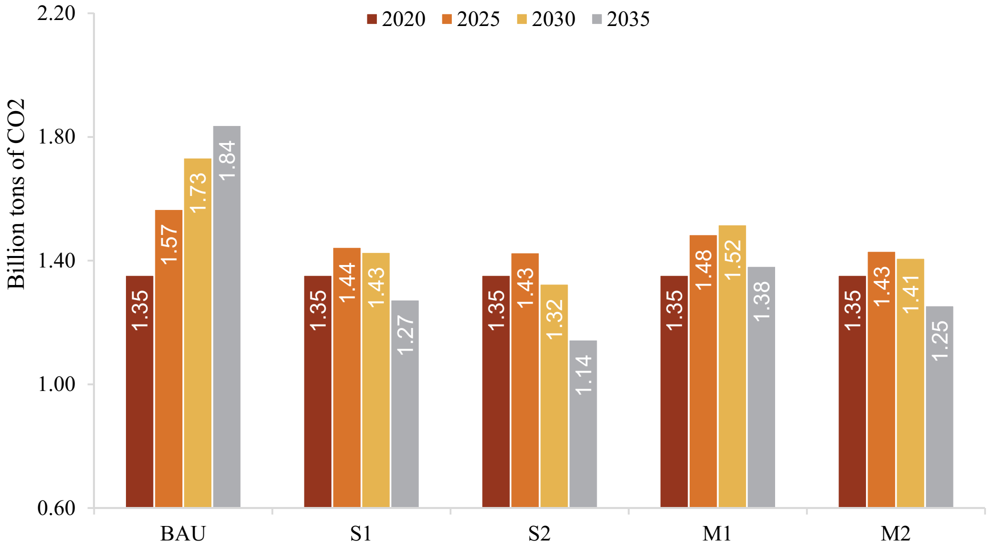

Fig. 5. Carbon emissions of the steel industry.

Table 2
Carbon intensity under different scenarios from 2017 to 2035 (Tons/million yuan).

Year	BAU	S1	S2	M1	M2
2017	112.45	–	–	–	–
2018	110.57	–	–	–	–
2019	106.96	–	–	–	–
2020	104.12	–	–	–	–
2021	100.84	94.62	93.67	95.80	94.62
2022	97.53	93.14	92.53	94.27	92.04
2023	94.30	89.78	89.15	90.53	88.35
2024	91.42	86.74	86.10	87.22	85.07
2025	88.45	83.66	83.00	83.88	81.77
2026	85.50	80.60	79.94	80.59	78.53
2027	82.61	77.87	76.46	77.84	75.65
2028	80.06	74.01	72.18	74.11	71.65
2029	77.72	70.45	68.24	70.68	67.98
2030	74.95	66.58	64.03	66.96	64.04
2031	72.68	63.31	60.47	63.80	60.69
2032	70.57	60.53	58.00	60.89	57.84
2033	68.00	57.53	55.11	57.63	54.82
2034	65.48	54.64	52.33	54.52	51.92
2035	63.02	51.85	49.66	51.54	49.16

4.2. Impact on energy consumption and energy intensity

The total energy consumption from 2017 to 2035 under each scenario is shown in Fig. 6. The results show that carbon trading and carbon taxes are conducive to restraining the growth of total energy consumption and accelerating the decline in energy intensity. The reason is that carbon trading and carbon taxes increase the price of fossil energy products, which will inevitably lead to a decrease in demand and ultimately to a significant reduction in total energy consumption. In particular, there is a great decline in the proportion of fossil energy consumption alongside a rise in the proportion of non-fossil energy consumption. In addition, it is found that under the similar carbon peaking scenario, the mixed carbon emission reduction policy has a better energy control effect than the single carbon trading policy.

In all scenarios, the total energy consumption has increased year by year from 4.56 billion tons of coal equivalent (btce) in 2017. By 2035, the total energy consumption of BAU will increase to 6.91 btce. In scenario S1, the increase in the total energy consumption is 6.59 btce. In scenario S2, the increase in the total energy consumption is 6.50btce. In scenario M1, the increase in the total energy consumption is 6.42 btce. In scenario M2, the increase in the total energy consumption is 6.37 btce. During the entire simulation period, the total reduction in total energy consumption in scenario M1 is 1.05 btce more than that in S1, and the total decline in total energy consumption in scenario M2 is 1.32 btce more than that in scenario S3.

The energy consumption structure from 2021 to 2035 in each scenario is shown in Figs. 7A & 7B. The simulation results show that carbon trading can promote the development and consumption of non-fossil energy and accelerate the optimization and upgrading of the energy structure by restraining the consumption of fossil energy. In the BAU scenario, the proportion of coal in total energy consumption is gradually decreasing over time, and the proportion of non-fossil energy is gradually increasing; however, carbon trading and carbon taxes have accelerated the decline in the proportion of coal and an increase in the proportion of non-fossil energy, the higher the average annual decline rate in carbon intensity, the higher the proportion of non-fossil energy consumption. The reason is that carbon trading and carbon taxes have increased the cost of using fossil energy, and non-fossil energy has a relative cost advantage, “squeezing out” part of the share of fossil energy in energy consumption.

In the BAU scenario, the energy consumption structure is continuously optimized. The proportion of coal consumption drops from 60.60% in 2017 to 42.74% in 2035, and the proportion of non-fossil energy consumption increases from 13.60% in 2017 to 22.02% in 2035. Correspondingly, in scenarios S1, S2, M1, and M2, the proportion of coal consumption drops in 2035 to 34.02%, 32.13%, 34.18%, and 32.16%, respectively, from 60.60% in 2017, while the proportion of non-fossil energy consumption increases in 2035 to 31.01%, 33.54%, 29.97%, and 32.41%, respectively, from 13.60% in 2017. This is because the carbon ETS and carbon tax increase the cost of fossil energy use, which consequently inhibits fossil energy consumption

Table 3
Carbon allowance price and carbon tax under each scenario in 2021–2035(Yuan).

	S1	S2	M1		M2	
Year	Carbon price	Carbon price	Carbon price	Tax rate	Carbon price	Tax rate
2021	78.04	92.24	61.39		78.04	
2022	56.20	65.06	24.62	10.00	54.63	10.00
2023	62.20	72.02	28.25	14.00	59.97	14.00
2024	70.16	81.29	32.98	18.00	67.31	18.00
2025	77.25	89.53	37.37	22.00	73.73	22.00
2026	84.52	98.01	41.92	26.00	80.32	26.00
2027	87.21	118.35	39.04	30.00	82.30	30.00
2028	125.33	174.01	63.33	34.00	119.81	34.00
2029	169.81	241.12	91.19	38.00	163.78	38.00
2030	220.46	320.58	122.15	42.00	213.81	42.00
2031	279.42	416.66	157.52	46.00	272.30	46.00
2032	336.76	479.92	197.71	50.00	329.26	50.00
2033	391.47	550.77	242.68	54.00	383.43	54.00
2034	453.00	630.74	293.67	58.00	444.43	58.00
2035	523.84	722.21	351.59	62.00	513.27	62.00

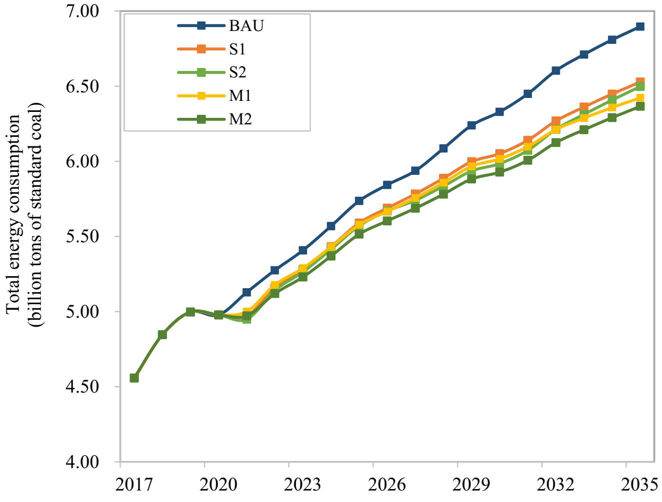

Fig. 6. Total energy consumption in each scenario from 2017 to 2035.

and promotes the consumption of non-fossil energy to accelerate the optimization of energy consumption structure.

The energy intensity from 2017 to 2035 in each scenario is shown in Table 4. Energy intensity is calculated by dividing total energy consumption by GDP. Under BAU, the energy intensity will reduce from 55.37 tons of standard coal per million yuan in 2017 to 33.37 tons of standard coal per million yuan in 2035. In the carbon peak scenario, the rate of decline in energy intensity accelerates. The energy intensity in scenario S1 will reduce from 55.37 tce (ton of coal equivalent) per million yuan in 2017 to 31.93 tce per million yuan in 2035; the energy intensity in scenario S2 will drop from 55.37 tce per million yuan in 2017 to 31.90 tce per million yuan in 2035; the energy intensity in scenario M1 will reduce from 55.37 tce per million yuan in 2017 to 31.34 tce per million yuan in 2035, and the energy intensity in the M2 scenario will drop from 55.37 tce per million yuan in 2017 to 31.17 tce per million yuan in 2035. Moreover, by 2035 the energy intensity in scenario M1 will be less than that of S1, and the energy intensity in scenario M2 will be less than scenario S2, which is consistent with the previous comparison of carbon intensity and total energy consumption.

4.3. Economic impact

Compared with the BAU scenario, consumption, investment, and net exports in different scenarios are shown in Table 5. Carbon ETS and carbon taxes have a negative impact on consumption, investment, and net exports, and the stricter the carbon emission reduction policy target is, the greater the negative impact will be. The results show that the increase in the cost of fossil energy use caused by carbon trading and carbon tax has reduced the total consumption and total investment of residents and government departments. At the same time, the external competitive advantage has become smaller and the total net export volume has decreased. Carbon trading raises the price of fossil energy products, leading to higher production costs and lower output in related industries. The decline in household income influenced by industry further results in a reduction of household consumption and savings, which leads to a decline in investment. In addition, and similar to the energy and environmental results, the hybrid carbon emission reduction policy can achieve similar carbon peak targets with less consumption, investment, and net export losses.

Compared with the BAU scenario, the actual GDP change rates in different scenarios are shown in Fig. 8. Carbon trading and carbon taxes will have a negative impact on real GDP, and the reduction in real GDP can be attributed to the decline in consumption, investment, and net exports. Fig. 8 and Table 5 show that compared to a single carbon emission reduction policy, a mixed carbon emission reduction policy can achieve a similar carbon peak target with less GDP loss. In the long run, the organic combination of carbon tax policy and the carbon trading market can achieve a carbon emission control effect similar to that of the single carbon trading market scenario with a small actual GDP loss. The reason is that because of the mixed policy of carbon trading and carbon tax, the industries covered by the non-carbon trading market have undertaken certain obligations of emission reduction, and the emission reduction cost of the carbon trading market has decreased compared with a single carbon trading scenario.

5. Conclusion and policy suggestions

This paper simultaneously introduces carbon ETS and carbon tax modules by the multi-sectoral recursive dynamic CGE model. It analyzes the different effects between hybrid policy and a pure ETS in similar carbon peak targets on total carbon emissions, carbon intensity, carbon quota prices, total energy consumption, energy intensity, energy consumption structure, consumption, investment, net exports, and real GDP. The main conclusions are outlined below.

Both a pure ETS and a hybrid policy can reduce energy consumption and increase the proportion of renewable energy consumption, which helps optimize the energy consumption structure to achieve China's carbon peak before 2030. However, they also increase the price of fossil energy use and the production costs of various industries, which leads to a decline in consumption, investment, net exports, and real GDP. A hybrid policy

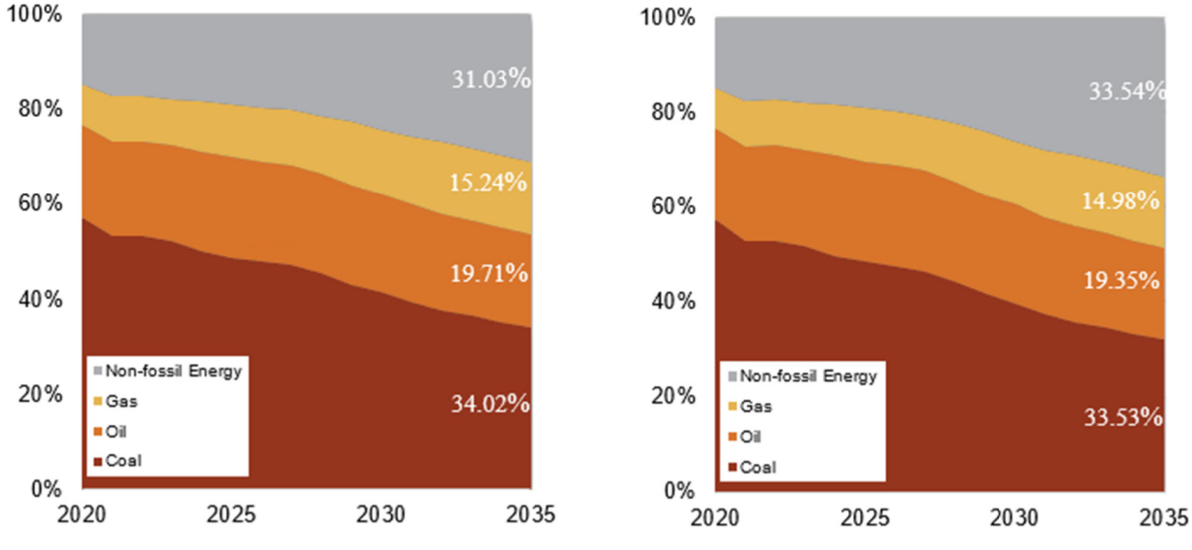

Fig. 7A. The energy consumption structure of scenario S1 and S2 in 2017–2035.

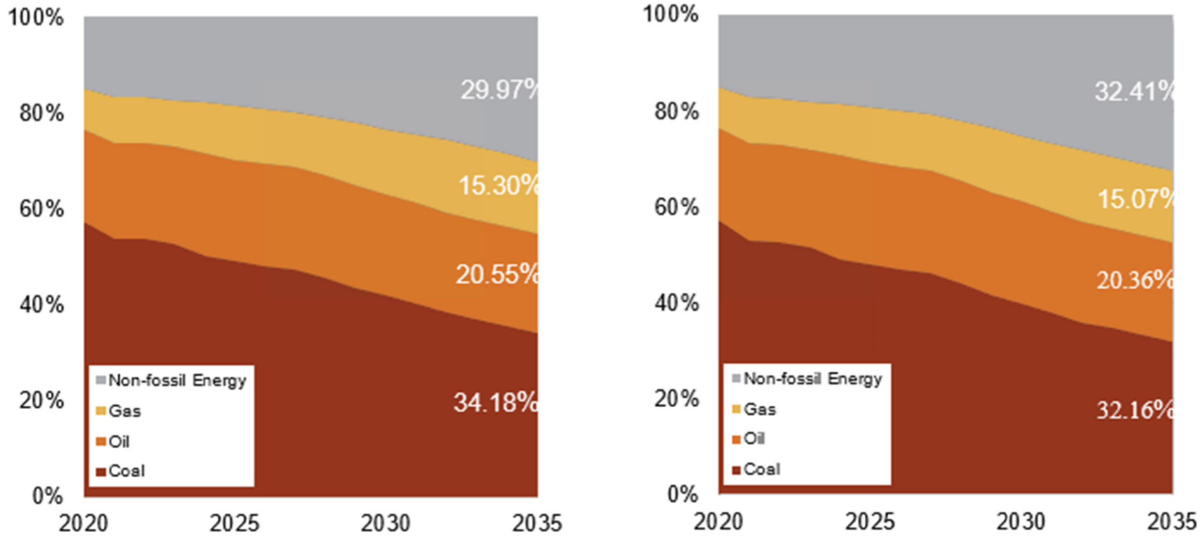

Fig. 7B. The energy consumption structure of scenario M1 and M2 in 2017–2035.

including carbon trading and carbon tax can achieve carbon peaks before 2030 with less economic loss and lower total carbon emissions than a single ETS. It is in line with that of Cao et al. (2019), who found that hybrid policy achieved the set target with lower carbon prices and GDP losses than the ETS in China. The reason behind this phenomenon is that when the hybrid policy is implemented, industries not covered by the ETS undertake certain emission reduction obligations, which can lessen the pressure on the carbon market to reduce emissions and lower the price of carbon allowances. Besides, the carbon constraint of full coverage caliber is certainly better than that of specific coverage (Lin and Jia, 2020b). At the same time, the cumulative role of carbon price in the industrial chain should be considered. However, the cost of MRV is another important topic of coverage in carbon pricing (Lin and Jia, 2018). Specific speaking, mixed carbon pricing in the model let all sectors pay for carbon emission, while ETS is not. Because carbon leakage exists not only between regions, but also between industries. Therefore, full coverage of carbon emission constraints combined with carbon tariffs may be the most efficient way to reduce emissions for an economy.

China has, however, made it clear that the carbon peak will reach before 2030 and that the carbon intensity in 2030 will show a reduction by more than 65% compared to 2005. The study of Cao et al. (2019) is set against this background. In this paper, we simulated specific carbon peak emissions according to the method of Xiao et al. (2020). In reality, the specific value when the total carbon emissions peak is achieved has not yet been determined, which is not conducive to the control of the total carbon emissions. Hence, when the government wants to set the specific value of the total carbon emissions peak, it should take into consideration China's potential economic growth and carbon intensity reduction targets across the next ten years. Moreover, once the total target is clarified, it should be broken down and assigned to all provinces, cities, and industries according to relevant data such as historical output and historical emissions. Then, the carbon ETS and carbon tax can be better used to ensure that all provinces, cities, and industries reach their peak carbon as early as 2030.

In addition, when the carbon emission target is stricter and the annual average decline rate of carbon intensity is higher, the carbon peak can be achieved sooner and the total carbon peak emissions be lower. In the

Table 5
The total loss of consumption, investment, and net exports (100 million yuan).

Scenarios	S1	S2	M1	M2
Consumption	56,798.27	74,412.37	44,626.09	65,731.19
Investment	149,722.81	194,955.29	121,260.22	174,681.65
Net exports	14,364.77	18,765.99	10,888.17	15,951.49

Table 4
Energy intensity under each scenario (tce/million yuan).

Year	BAU	S1	S2	M1	M2
2017	55.37	–	–	–	–
2018	55.22	–	–	–	–
2019	53.61	–	–	–	–
2020	52.23	–	–	–	–
2021	50.87	49.38	49.17	49.65	49.38
2022	49.33	48.29	48.15	48.46	47.94
2023	47.81	46.76	46.62	46.81	46.31
2024	46.63	45.57	45.43	45.53	45.05
2025	45.27	44.21	44.07	44.08	43.63
2026	43.81	42.75	42.61	42.55	42.12
2027	42.35	41.35	41.08	41.14	40.69
2028	41.15	39.94	39.62	39.70	39.24
2029	40.05	38.66	38.31	38.41	37.93
2030	38.62	37.11	36.78	36.85	36.38
2031	37.46	35.89	35.59	35.58	35.14
2032	36.57	34.98	34.76	34.58	34.20
2033	35.49	33.93	33.78	33.46	33.15
2034	34.43	32.92	32.82	32.38	32.15
2035	33.37	31.93	31.90	31.34	31.17

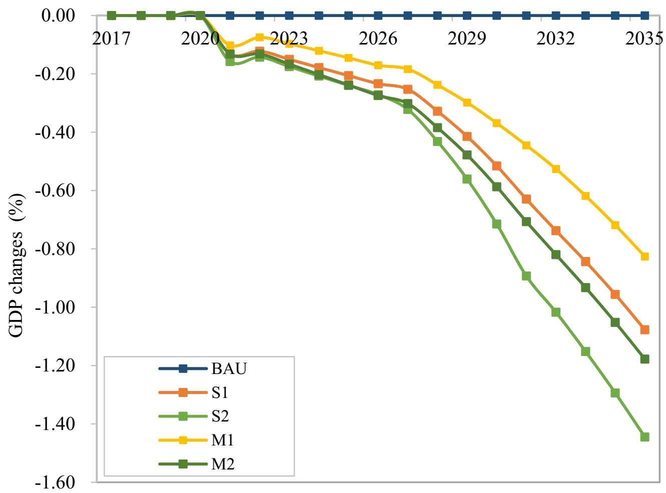

Fig. 8. GDP change rate of each scenario compared with BAU.

meantime, the energy consumption structure is more optimized because the ETS can increase energy-saving innovation and impose the lowest cost in terms of GDP growth (Bi et al., 2019). China's carbon ETS officially launched its first compliance cycle on 1 January 2021, marking that the country's carbon market had entered a new stage of development; however, the current carbon market is only dominated by the power generation industry, and the effect of reducing emissions is limited. It is recommended to accelerate the construction and operation of the national carbon market, and to expand the coverage of the carbon market industry and the scope of trading entities toward ensuring the smooth and effective operation of the carbon market.

This paper presents scenarios that include a carbon tax levied in China, although the tax has been postponed in reality because of its uncertain effects. However, we find that the coordinated use of a carbon tax and a carbon ETS can promote optimization of energy consumption structures and accelerate the decline of energy intensity and carbon intensity; this can contribute to curbing the growth of total energy consumption and total carbon emissions and also to achieving the peak of carbon by 2030 with less actual GDP loss. Considering the current carbon market's limited role in reducing emissions, it is recommended that China impose a carbon tax at a suitable time. To be more specific, China can levy carbon taxes on industries not covered by the carbon ETS starting with a low tax rate, adopting a dynamic and flexible mechanism, and gradually increasing the tax rate level; policy makers should scientifically align a carbon tax and a carbon ETS to make best use of the economic and environmental synergies to help achieve the goal of carbon peaking.

CRediT authorship contribution statement

Yongqiang Zhang: Data collection, Data analysis, Methodology, results discussion, Writing - Original draft; **Lingli Qi:** Data analysis, Methodology, results discussion, Writing - Original draft; **Xinyue Lin:** Data analysis, Methodology, results discussion, Writing - Original draft; **Haoran Pan:** Supervision; Writing- Reviewing and Editing; **Basil Sharp:** Supervision; Writing- Reviewing and Editing.

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 A. CGE Model equations

A.1. Production block

Production function for goods

$$PX_{i,t} * X_{i,t} = PV_{i,t} * V_{i,t} + PU_{i,t} * U_{i,t} \tag{A.1}$$

$$\frac{PV_{i,t}}{PU_{i,t}} = \frac{\delta_v}{\delta_u} * \left(\frac{U_{i,t}}{V_{i,t}}\right)^{1-\rho_i^Q} \tag{A.2}$$

$$X_{i,t} = \left(\delta_v V_{i,t}^{\rho_i^Q} + \delta_u U_{i,t}^{\rho_i^Q}\right)^{\frac{1}{\rho_i^Q}} \tag{A.3}$$

$$PV_{i,t} * V_{i,t} = R_t * K_{i,t} + W_t * L_{i,t} \tag{A.4}$$

$$L_{i,t} = \frac{\gamma_{li,t} * PV_{i,t} * V_{i,t}}{W_t} \tag{A.5}$$

$$W_{i,t} = \frac{\gamma_{ki,t} * PV_{i,t} * V_{i,t}}{R_t} \tag{A.6}$$

$$NE_{i,t} = \mu_{i,t}^{NE} * U_{i,t} \tag{A.7}$$

$$E_{i,t} = \mu_{i,t}^{E} * U_{i,t} \tag{A.8}$$

$$PE_{i,t} * E_{i,t} = PFE_{i,t} * FE_{i,t} + PEP_{i,t} * EP_{i,t} \tag{A.9}$$

$$\frac{PFE_{i,t}}{PEP_{i,t}} = \frac{\delta_{fe}}{\delta_{ep}} * \left(\frac{EP_{i,t}}{FE_{i,t}}\right)^{1-\rho_i^E} \tag{A.10}$$

$$E_{i,t} = \lambda_i^E \left(\delta_{fe} FE_{i,t}^{\rho_i^E} + \delta_{ep} EP_{i,t}^{\rho_i^E}\right)^{\frac{1}{\rho_i^E}} \tag{A.11}$$

$$PFE_{i,t} * FE_{i,t} = \Sigma_{fe}\left(PQ_{i,t}^{fe} * QFE_{i,t}^{fe}\right) \tag{A.12}$$

$$QFE_{i,t}^{fe} = \frac{FE_{i,t}}{\alpha_i^{fe}} * \left(\frac{\delta_i^{fe}}{PQ_{i,t}^{fe}}\right)^{\frac{1}{1-\rho_i^{fe}}} * \left[\sum_{fe} \delta_i^{fe\left(\frac{1}{1-\rho_i^{fe}}\right)} * PQ_{i,t}^{fe\left(\frac{\rho_i^{fe}}{\rho_i^{fe}-1}\right)}\right)]^{\frac{-1}{\rho_i^{fe}}} \tag{A.13}$$

$$PEP_{i,t} * EP_{i,t} = \Sigma_{ep}\left(PQ_{i,t}^{ep} * QEP_{i,t}^{ep}\right) \tag{A.14}$$

$$QEP_{i,t}^{ep} = \frac{EP_{i,t}}{\alpha_i^{ep}} * \left(\frac{\delta_i^{ep}}{PQ_{i,t}^{ep}}\right)^{\frac{1}{1-\rho_i^{ep}}} * \left[\Sigma_{ep} \delta_i^{ep\left(\frac{1}{1-\rho_i^{ep}}\right)} * PQ_{i,t}^{ep\left(\frac{\rho_i^{ep}}{\rho_i^{ep}-1}\right)}\right)]^{\frac{-1}{\rho_i^{ep}}} \tag{A.15}$$

A.2. Income and expenditure module

$$HY_t = W_t * LS_t + R_t * KS_t + GT_t \tag{A.16}$$

$$HE_t = \Sigma_j\left(PC_{j,t} * HC_{j,t}\right) + DT_t + HS_t \tag{A.17}$$

$$\begin{aligned} GY_t = {} & PT_t + DVAT_t + TARF_t + IMCF_t + IMVAT_t + DCT_t + DT_t \\ & + GYCATX_t + GYETS_t \end{aligned} \tag{A.18}$$

$$GE_t = \Sigma_j\left(PC_{j,t} * GC_{j,t}\right) + GYSS_t + GS_t + GT_t \tag{A.19}$$

A.3. Trade Module

$$QC_{j,t} = AA_{j,t} * \left[\delta_{j,t} * QD_{j,t}^{\rho_{j,t}} + \left(1-\delta_{j,t}^{q}\right) \cdot IMP_{jt}^{\rho_{j,t}}\right]^{\frac{1}{\rho_{j,t}}} \tag{A.20}$$

$$Q_{j,t} = AT_{j,t} * \left[\varepsilon_{j,t} * QD_{j,t}^{\rho_{j,t}} + \left(1-\varepsilon_{j,t}^{p}\right) * EXP_{jt}^{\rho_{j,t}}\right]^{\frac{1}{\rho_{j,t}}} \tag{A.21}$$

A.4. Carbon tax and carbon trading block

$$EM_{i,t} = \theta_{coal} * D_{i,t,coal} + \theta_{oil} * D_{i,t,oil} + \theta_{gas} * D_{i,t,gas} \tag{A.22}$$

$$TCO2_t = \Sigma_i EM_{i,t} \tag{A.23}$$

$$TCO2_t = (1-tcer_t)CO2ref_t \tag{A.24}$$

$$C_{i,t} = PCO2_{i,t} * EM_{i,t} \tag{A.25}$$

$$CI_t \;=\; TCO2_t/\Sigma_j\left(HC_{j,t} + GC_{j,t} + INV_{j,t} + SC_{j,t} + EXP_{j,t} - IMP_{j,t}\right) \tag{A.26}$$

$$GYETS_t = \Sigma_i C_{i,t} \tag{A.27}$$

$$CATX_{i,t} = CT_t * EM_{i,t} \tag{A.28}$$

$$GYCATX_t = \Sigma_i CATX_{i,t} \tag{A.29}$$

$$X_{i,t} * PX_{i,t} = OC_{i,t} + CATX_{i,t} + C_{i,t} \tag{A.30}$$

A.5. Dynamic module

$$KS_{t+1} = (1+g_{kt}) * (1-dep_t) * KS_t + INVPS_t \tag{A.31}$$

$$LS_{t+1} = (1+gpop_t) * LS_t \tag{A.32}$$

A.6. Close module

$$Q_{j,t} = XX_{j,t} + HC_{j,t} + GC_{j,t} + INV_{j,t} + SC_{j,t} \tag{A.33}$$

$$\overline{LS}_t = \Sigma_{i,t} L_{i,t} \tag{A.34}$$

$$\overline{KS}_t = \Sigma_{i,t} K_{i,t} \tag{A.35}$$

$$TSAV_t = HSAV_t + GSAV_t \tag{A.36}$$

Appendix B. Descriptions of variables and parameters

There are many endogenous, exogenous variables and parameters in the CGE model. The key variables are shown in Table B.1. The key parameters are shown in Table B.2.

Table B.1
Descriptions of key variables.

Variables	Descriptions	Type
$X_{i,t}$	Domestic output	Endogenous
$V_{i,t}$	Capital and labor input	Endogenous
$U_{i,t}$	Energy and non-energy input	Endogenous
$K_{i,t}$	Capital input	Endogenous
$L_{i,t}$	Labor input	Endogenous
$NE_{i,t}$	Non-energy input	Endogenous
$E_{i,t}$	Energy input	Endogenous
$FE_{i,t}$	Fossil energy input	Endogenous
$EP_{i,t}$	Power energy input	Endogenous
$QFE_{i,t}^{fe}$	Coal/oil/gas input	Endogenous
$QEP_{i,t}^{ep}$	Thermal power/clean power input	Endogenous
$PX_{i,t}$	Price of domestic output	Endogenous
$PV_{i,t}$	Price of capital and labor input	Endogenous
$PU_{i,t}$	Price of energy and non-energy input	Endogenous
R_t	Price of capital input	Endogenous
W_t	Price of labor input	Endogenous
$PE_{i,t}$	Price of energy input	Endogenous
$PFE_{i,t}$	Price of fossil energy input	Endogenous
$PEP_{i,t}$	Price of power energy input	Endogenous
$PQ_{i,t}^{fe}$	Price of coal/oil/gas input	Endogenous
$PQ_{i,t}^{ep}$	Price of thermal power/clean power input	Endogenous
HY_t	Income of residents	Endogenous
GY_t	Income of the government	Endogenous
HE_t	Expenditure of residents	Endogenous
GE_t	Expenditure of the government	Endogenous
HS_t	Savings of residents	Endogenous
GS_t	Savings of the government	Endogenous
$HC_{j,t}$	Consumption of residents	Endogenous
$GC_{j,t}$	Consumption of the government	Endogenous
LS_t	Total labor input	Exogenous
KS_t	Total capital input	Exogenous
GT_t	Expenditure of the government transfers	Endogenous
DT_t	Expenditure of individual income tax	Endogenous
PT_t	Income from production tax	Endogenous
$DVAT_t$	Income from domestic VAT	Endogenous
$TRAF_t$	Income from import duties	Endogenous
$IMCF_t$	Income from consumption tax on imported commodities	Endogenous
$IMVAF_t$	Income from VAT on imported goods	Endogenous
DCT_t	Income from consumption tax on domestic goods	Endogenous
$GYCATX_t$	Income from carbon tax	Endogenous
$GYETS_t$	Income from ETS	Endogenous
$GYSS_t$	Expenditure of the government subsidies	Endogenous
$Q_{j,t}$	Domestic output	Endogenous
$QD_{j,t}$	Armington commodity	Endogenous
$EM_{i,t}$	Carbon emissions from the sector	Endogenous
$D_{i,t}$	Carbon emissions of the sector come from coal/oil/gas	Endogenous
$TCO2_t$	Total carbon emissions	Endogenous
$CO2ref_t$	Total carbon emissions under BAU scenario	Exogenous
$C_{i,t}$	Revenue from the sector carbon allowances auction	Endogenous
$CATX_{i,t}$	Carbon tax from the sector	Endogenous
$OC_{i,t}$	Original production cost of the sector	Endogenous
$PCO2_{i,t}$	Price of the carbon allowance	Endogenous
CT_t	Carbon tax rate	Exogenous
$INVPS_t$	Investment in fixed assets	Endogenous
$XX_{j,t}$	Intermediate commodity demand	Endogenous
$INV_{j,t}$	Investment in commodities	Endogenous
$SC_{j,t}$	Commodities in stock	Endogenous
$TSAV_t$	Total savings	Endogenous
$HSAV_t$	Total household savings	Endogenous
$GSAV_t$	Total government savings	Endogenous
EXP_t	Export	Endogenous
IMP_t	Import	Endogenous
$INVF_t$	Domestic investment overseas	Endogenous
$PEXP_t$	Price of the export	Endogenous
$PIMP_t$	Price of the import	Endogenous

Table B.2
Descriptions of key parameters.

Parameters	Descriptions	Type
δ_v	Scaling parameter of CES production function for factor input	Exogenous
δ_u	Scaling parameter of CES production function for intermediate input	Exogenous
ρ_i^Q	Substitution rate of power energy input	Exogenous
$\gamma_{li,t}$	Coefficient of labor input	Exogenous

(continued on next page)

Table B.2 (*continued*)

Parameters	Descriptions	Type
$\gamma_{ki,\ t}$	Coefficient of capital input	Exogenous
$\mu_{i,\ t}^{E}$	Coefficient of energy input	Exogenous
$\mu_{i,\ t}^{NE}$	Coefficient of non-energy input	Exogenous
δ_{fe}	Scaling parameter of CES production function for fossil energy input	Exogenous
δ_{ep}	Scaling parameter of CES production function for power energy input	Exogenous
ρ_i^E	Substitution rate of fossil energy and power energy input	Exogenous
ρ_i^{fe}	Substitution rate of fossil energy input	Exogenous
ρ_i^{ep}	Substitution rate of power energy input	Exogenous
$AA_{j,\ t}$	Scaling parameter of Armington function	Exogenous
$\delta_{j,\ t}$	Substitution rate of Armington assumption	Exogenous
$AT_{j,\ t}$	Scaling parameter of Transformation function	Exogenous
$\varepsilon_{j,\ t}$	Substitution rate of transformation assumption	Exogenous
θ	The carbon emission coefficient of fossil energy products	Exogenous
$tcer_t$	Carbon emission reduction rate	Exogenous
g_{kt}	Capital growth rate	Exogenous
dep_t	Capital depreciation	Exogenous
$gpop_t$	Population growth rate	Exogenous

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