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Research article

Exploring a pathway to optimise the carbon tax policy in terms of the economy, the environment and health: A scenario-based system dynamics approach

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ABSTRACT

The carbon tax, a pivotal policy instrument in tackling climate change, holds the potential to significantly influence the development of society. To comprehensively analyse the effectiveness of the policy on carbon taxation and explore its possible optimisation path, this study utilizes system dynamics theory to establish a simulation model. A detailed analysis and evaluation of this policy is then conducted from the perspectives of the economy, the environment, and health. To guarantee the precision of the simulation model, a new, comprehensive evaluation method is proposed, which can test the degree of fit of the relative trend and absolute data of the simulation model with reality. The findings reveal that, despite its negative economic implications, a carbon tax policy has positive ramifications for the environment, energy, health, industrial structure, and carbon intensity targets. Furthermore, the synergistic reinforcement effect of R&D and new energy support policies on carbon taxation surpasses the impact of any individual policy alone. Notably, the influence of auxiliary policies has a temporal difference on this policy. Based on these insights, the study concludes with practical policy recommendations.

1. Introduction

With increasing global warming, reducing greenhouse gas emissions has gained unanimous global recognition [1]. Of the world's 15 climate tipping points, 9 have already been activated [2]. Furthermore, projections by the Intergovernmental Panel on Climate Change suggest that the atmospheric concentration of carbon dioxide (CO_2) is poised to surge from approximately 400 ppm to either 670 ppm or 936 ppm by the century's end [3]. To mitigate the impact of climate change, nearly 200 countries to the United Nations Framework Convention on Climate Change gathered in Paris, France, aiming to reach a new climate accord [4]. The Agreement underscores the necessity to intensify the response to the looming threat of climate change, aiming to cap the global temperature rise to well below 2 °C, and endeavoring to restrict it to 1.5 °C [5].

As the world's foremost carbon emitter, China has responded to the declaration of the Convention by announcing a commitment: by 2030, it aims to reduce carbon intensity by a margin of 60 %–65 % relative to the 2005 levels [6]. In addition, the President of China pledged during the General Assembly of the United Nations to attain a carbon peak by 2030 and accomplish carbon neutrality by 2060 [7]. The realisation of China's emission reduction targets will play a pivotal role in mitigating the global greenhouse effect. To respond

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and implement emission reduction targets in a timely manner, China has introduced a comprehensive set of policies and measures aimed at significantly reducing CO_2 emissions, such as introducing renewable energy subsidies [8], carbon trading [9] and carbon capture and storage [10]. China also aims to introduce carbon taxation measures to accelerate the achievement of its emission reduction targets. The policy on carbon taxation can significantly contribute to promoting a low-carbon economy [11] and improving social welfare [12]. Furthermore, the concurrent formulation of additional energy-saving and emission-reduction policies alongside the carbon tax can potentiate its effectiveness even further [13,14]. Nevertheless, it is important to acknowledge that the policy on carbon taxation may also exert a negative influence on economic development [15–19], potentially resulting in economic growth stagnation or regression. To alleviate the adverse effects of the policy on sustainable economic development, a majority of countries incorporate carbon tax revenue in the general budget and use tax revenue for rebates to maintain carbon tax neutrality [20]. Therefore, this study devotes attention to the system of carbon taxation as the primary research object, specifically examining its implementation under the mode of tax collection and rebate.

The system of carbon taxation implemented under the mode of tax collection and refund, can realize a double dividend for the environment and economy at the same time [12,21]. The environmental dividend refers to the mitigation of pollutant emissions and the attainment of environmental goals through the imposition of emission taxes on carbon-containing energy sources. Economic dividend means that the tax rebate can alleviate the distorting effect of the existing tax, to promote the realisation of non-environmental goals such as social employment and economic growth. However, some scholars [19,22,23] believe that even if the carbon tax revenue is refunded, it will not fully offset the economic side effects caused by the tax collection. To this end, this study attempts to introduce a technology research and development support (RDS) policy and a new energy support (NES) policy to enhance the favorable impact of the taxation mechanism for carbon emissions while mitigating its adverse effects. Among them, the RDS policy is conducive to the innovation and development of science and technology, thereby improving efficient energy use and facilitating the transition to environmentally friendly energy consumption [24,25]. The NES policies contribute to the energy transition and can promote economic development without compromising environmental sustainability [26].

Therefore, to explore the action mechanism and optimisation path of this policy within the social system, this study establishes a system dynamics (SD) simulation model encompassing four crucial aspects: economy, environment, energy, and health. To make the simulation model consistent with reality, we consider the delay in the carbon tax collection and refund process. In addition, the policy mainly affects consumers' judgment behaviour through price signals, aiming to achieve greenhouse gas mitigation. The simulation model established herein also addresses the characteristics of consumers' loss aversion, thereby enhancing the model's scientificity and credibility. To assess the model's accuracy and robustness accuracy and robustness, a new, comprehensive evaluation model is proposed to verify the error between the simulation model and reality in terms of relative trends and absolute data. In the process of simulation model construction, the study also introduces the RDS policy and the NES policy to explore the possible optimisation path from the viewpoint of input–output constraints and provide scientific guidance to improve the favorable impacts of this policy and alleviate its adverse effects.

The contribution of this paper is that the research offers a new path to strengthen the benefits of the policy on carbon taxation. Although the synergistic effect of multiple policies is higher than that of a single measure, scholars have scantily focused on the concurrent implementation costs of multiple policies and measures, as well as the influence of existing systems on new carbon reduction policies and measures [27]. Our research results confirm that there exist temporal disparities in the strengthening effects of RDS and NES policies on taxation measures for carbon emissions and adopting different supporting policies in different periods can reduce policy costs and strengthen the efficacy of this policy.

The organization of the remainder proceeds as follows. Section 2 offers a review of the existing research. Section 3 describes the framework and foundation of the simulation model in detail. Section 4 presents the outcomes of our simulations and subsequent analysis. Section 5 is a discussion of the results. Section 6 summarizes our conclusions and outlines potential policy implications.

2. Literature review

The carbon tax, first introduced in the 1990s, is imposed on the production, distribution, or consumption of fossil fuels [18]. As a carbon emission pricing strategy, this policy is relatively easy to implement [28], and compared with another carbon pricing mechanism, the carbon trading system, its prolonged emission decrease effect stands out as more significant [29]. Moreover, the policy possesses a legal binding force. Consequently, numerous researchers advocate the policy on carbon taxation to decelerate the rise in CO_2 emissions [30]. According to the World Bank's report titled 'State and Trends of Carbon Pricing 2022', as of April 2022, a total of 68 carbon pricing systems have been executed globally, encompassing approximately 23 % of the global greenhouse gas emissions. Notably, 37 of these mechanisms are carbon tax systems [31]. In addition, there is a vast amount of research on this policy. From the standpoint of the research process, the existing literature can be categorized into three distinct groups: energy conservation and emission reduction efficiency assessment, comprehensive benefit assessment and combined policy benefit research.

In terms of the efficiency assessment of energy conservation, scholars have accorded greater attention to the emission reduction benefits arising from the policy on carbon taxation [32–34]. In general, the policy serves as a market-oriented tool for emission reduction, effectively elevating the cost of fossil energy utilization and subsequently motivating the public to transition towards a cleaner and more sustainable energy consumption model [32–34]. Some countries have also achieved considerable results in greenhouse gas mitigation. For instance, Denmark's carbon tax reduced corporate energy consumption by 10 %, while Sweden reduced carbon emissions by 13 % from 1987 to 1994 [35]. Nong found that South Africa could achieve a 12.25%–15.6 % reduction in carbon emissions at the cost of a 1.17%–1.59 % reduction in GDP at a tax rate of $9.15 [36]. Furthermore, the carbon tax policy can not only mitigate greenhouse gas emissions but also effectively decrease the associated pollutants, such as sulfur dioxide, nitrogen oxides, etc [23]. However, some researchers [37,38] have contended that the environmental effect of this policy is not especially significant. There are three reasons for the insignificant benefits of greenhouse gas mitigation. First, to safeguard the competitiveness of energy-intensive industries, the tax rate is set at a comparatively lower level, coupled with the implementation of generous tax incentives and rebate systems [39]. Second, the price elasticity of energy commodities is low [40] and energy consumption tends to be rigid, both of which weaken the price signal. Third, the tax rate remains constant over a certain period. In the case of inflation or rapid economic growth, the impact of the policy on the actual tax rate will thereby be weakened, resulting in an offset of the effective tax rate [23,41].

In conducting a comprehensive benefit evaluation, scholars have delved into the influence of carbon tax policy on both economic development and social welfare, beyond mere emission reduction benefits [15–19,28,39,42–47]. Most researchers [15–19,28,39,45–47] have argued that while carbon tax policy effectively promotes greenhouse gas mitigation, it simultaneously carries significant adverse implications for economic and social welfare. For example, Lin and Li [18] employed the difference-in-difference method to assess the emission reduction impact on five Nordic countries and found that the carbon tax effectively curbs energy consumption, enhances energy efficiency, and promotes the use of renewable energy but simultaneously slows economic development and diminishes social welfare. Similarly, Wesseh Jr et al. [19] showed that a carbon tax reduces environmental damage but makes people in the low-earning areas poorer. However, some scholars observe a certain positive impact of the policy on economic development and social welfare [48,49]. For example, from the perspective of the internal optimisation of the system, Yao [48] analyzed the economic impact of the policy on carbon taxation across various regions in China under different tax rates and found that a moderate tax rate positively regulates the balanced development of China's regional economy. Furthermore, Qu and Wu [49] established a partial equilibrium model to investigate the consequences of carbon tariffs on import and export countries, revealing that carbon tariffs imposed by import countries can improve the welfare of their own citizens.

Investigations on the benefits of combination policy showed that with further research, scholars gradually realised the limitations of a single policy and the inherent complementarity between multiple policies, consequently paying greater attention to the comparison and formulation of hybrid policies [14,50–55]. For example, Eichner and Pethig [54] found that as long as the coverage of the carbon tax and carbon trading system didn't overlap, and the tax rate was set equal to the carbon emission right price, energy conservation and emission reduction efficiency could be maximised. Shi et al. [51] demonstrated that a balanced combination of the policy on carbon taxation and a carbon trading system can achieve emission reduction targets at moderate cost. From the standpoint of combination policies, Brink et al. [55] found that the EU's simultaneous introduction of a carbon tax policy and carbon trading system can increase the welfare of quota buyers. Furthermore, Xia et al. [14] argued that the use of mixed policies is the more efficient, less costly, fairer and more sustainable emission reduction model.

The above review indicates that the existing literature still has two limitations. First, few scholars have investigated the influence of the carbon tax on public health. While reducing greenhouse gas emissions, a carbon tax policy can concurrently mitigate the emissions of pollutants associated with greenhouse gases [23], thereby indirectly promoting public health. Second, most investigations on mixed policies focus on the assessment of synergies, and few studies explore the temporal effects of other policies or measures on carbon tax policy. To some extent, this study compensates for these limitations of the existing research.

3. Method

Forrester proposed system dynamics in 1956 [56]. SD is a quantitative method based on computer technology, cybernetics and systems theory [57] that pays attention to the characteristics and rules of interaction between system components to solve practical problems. SD has been extensively employed to tackle decision-making challenges across diverse industries, encompassing the building sector [58], transportation [59], agriculture [60], energy [61] and electricity [62]. These studies provide references for the establishment of the policy effect model and a valuable theoretical reference for the establishment of this research model. The research logic of SD follows this path: problem analysis–framework setting–data collection and analysis–simulation model construction–model verification and simulation. Among these, problem analysis acts to clarify the scientific problem of research. The framework setting is established to define the scope of the problem and the correlation of variables within the system. Data collection and analysis are based on the research framework, collecting the real data of each variable within the research framework and the equality relationship between the variables. Simulation model construction helps input the variables and realistic data or rules inside the framework into the simulation software. The purpose of model verification and simulation is to test the rationality and scientificity of the previous steps and, finally, demonstrate and analyse the evolutionary principle of the system.

3.1. Research framework

Based on the research logic of SD and the research purpose, it is necessary to further address the research framework herein. First, the policy on carbon taxation is designed to promote greenhouse gas mitigation by raising the relative cost of acquiring carbon-based energy sources. Therefore, the enactment of the policy on carbon taxation will exert a significant influence on both economic development and energy consumption. Second, changes in energy consumption are further fed back into the environmental system. In addition, other harmful substances produced during energy use can affect public health levels. Finally, under the influence of this policy, the environmental cost will again affect economic development. Thus, the study divides those variables directly or indirectly influenced by the policy into four subsystems: economic, energy, environment and health. The specific subsystem division and research framework are clearly presented in Fig. 1.

Fig. 1 reveals a complex, coupled closed-loop system. The economic subsystem encompasses the gross domestic product (GDP) and the recirculation of tax revenue. GDP is categorized based on the three major industries. The economic output of each industry is sustained by a specific quantity of energy, and the amount of energy required for each unit of economic output subsequently has a direct effect on the overall level of energy usage. The pollutants produced by energy usage are affected by the resource structure characteristics of a given country or region, that is, when the proportion of new energy is high, the proportion of other types of energy deployed will be reduced, and the emission of pollutants will be less and vice versa. The pollutants generated during energy usage can significantly impact both the environment and public health. When it comes to environmental assessment, the policy on carbon taxation leverages tax revenue to measure the environmental cost. Specifically, this cost is calculated as the product of the tax rate and carbon emissions, representing the environmental expenditure. To alleviate the adverse effects, the tax revenue will flow back to the economic market as subsidies after a delay.

3.2. Data collection and analysis

In Fig. 1, the datasets pertaining to GDP, energy, and population are sourced from the China Statistical Yearbook (https://www.stats.gov.cn/sj/ndsj/), the China Energy Statistical Yearbook (http://www.shujuku.org/china-energy-statistical-yearbook.html) and the China Population Census Yearbook (https://www.stats.gov.cn/sj/pcsj/rkpc/7rp/zk/indexce.htm), respectively. The population data include the total population, birth rate and death rate. GDP includes the output of the primary, secondary and tertiary sectors. As for the energy data, it comprises not only the consumption across the primary, secondary, and tertiary sectors but also the respective market shares of coal, oil, gas, and new energy sources. Additionally, the unit energy consumption figures for each industry are meticulously calculated, taking into account both the GDP and energy data.

The primary objective of the carbon tax policy lies in reducing CO_2 emissions. Therefore, the study chooses CO_2 emissions as the environmental assessment index. Given that coal, oil and natural gas contribute to 99 % of CO_2 emissions [63], these three energy sources are specifically chosen to calculate CO_2 emissions. To reduce the error of environmental assessment, the study analyzed the CO_2 emission coefficient and carbonisation rate of each energy source in detail. Among them, the emission coefficient is based on the standard coal equivalent of each energy source. In addition, the conversion coefficient of CO_2 to carbon is 44/12 [64]. While a high concentration of CO_2 can indeed have adverse effects on human health, the current level of CO_2 in the air doesn't pose a significant threat to human health at this time [65]. Considering the repeatability of different pollutants to the same health subject, the study only selected sulfur dioxide (SO_2), a companion of CO_2 as the pollutant to assess the health risk. The coefficients related to SO_2 and CO_2 emissions are shown in Table 1.

Most countries have chosen to increase tax rates to mitigate the effect of economic development on the policy's effectiveness [66]. Therefore, to enhance the simulation model's alignment with reality, a dynamic tax rate was introduced into each industry subsystem. Currently, China hasn't yet implemented a carbon tax, but it has established a national carbon trading system. Therefore, this study refers to these carbon trading prices to set the carbon tax rate. On June 18, 2013, China's first city-level emissions trading system was implemented in Shenzhen, with the average trading price reaching 29 CNY/tCO_2 on the opening day [67]. Since 2022, the national carbon market has seen its daily closing price range from 56 to 62 CNY per tonne [68]. Thus, we set the initial price of the tax rate at 30 CNY/t, with an annual increase of 3 CNY/t.

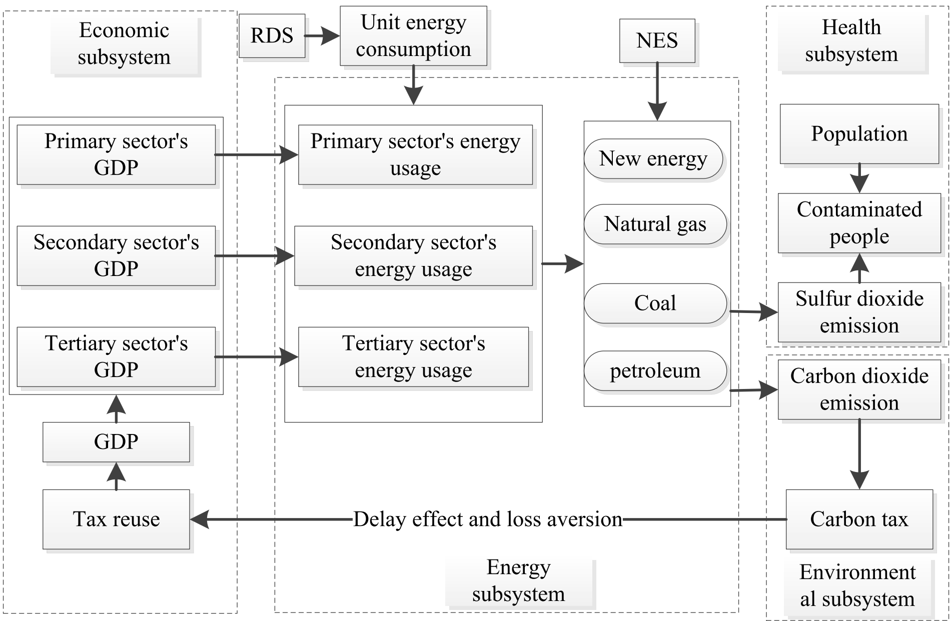


Fig. 1. Subsystem classification and research framework.

Table 1
Pollutant emission coefficients of various energies.

Category	Carbon emission coefficient (tons C/tons standard coal) [63]	Carbonisation ratio [63]	Conversion coefficient between other energies and standard coal	SO_2 emission coefficient (kg/ton, kg/10^3 m^3)
Coal	0.7329	0.916	0.7143	33.6
Oil	0.5574	0.987	1.4286	5.25
Natural gas	0.4426	0.990	1.3300	0.63

3.3. Model construction

Drawing upon the core variables in the research framework, we further add auxiliary variables related to the core variables and construct a flowchart for simulating the carbon tax policy. The flow diagram comprises four distinct modules: primary sector (Fig. 2(a)), secondary sector (Fig. 2(b)), tertiary sector (Fig. 2(c)) and others (Fig. 2(d)), as shown in Fig. 2. Using this flowchart as a basis, we embedded the obtained data and equations into the simulation flow diagram and then obtained a simulation model that can reproduce reality. The simulation model's essential variables and equations are detailed in Appendix A (some of the equations in Appendix A are derived from other studies [69–71]). The model's simulation period spans from 2010 to 2030, with one year simulation step length.

3.4. Scenario settings

To investigate the optimisation path of the policy on carbon taxation, it is postulated that upon the enactment of this policy, the government will encourage market capital or excess financial funds to flow into the two fields of R&D and new energy. Therefore, Fig. 2 contains three alterable variables, namely, the RDS coefficient (R1), the NES coefficient (R2) and the tax coefficient (R3). By adjusting the values of the three coefficients, different simulation scenarios are established respectively, as shown in Table 2.

Over the past decade, China's annual growth rate in research and development expenditure across society has exceeded 10 % (as calculated using data from the China Statistical Yearbook). Similarly, the average annual growth rate of investment in new energy stands at approximately 8.5 % [72], and there is still a lot of growth potential. To ensure the consistency of R&D and new energy investment growth and negate disparities in the optimisation level of the carbon tax policy caused by inconsistent growth rates, it is assumed that when the government departments introduce policies to support R&D and new energy, the investment quota will

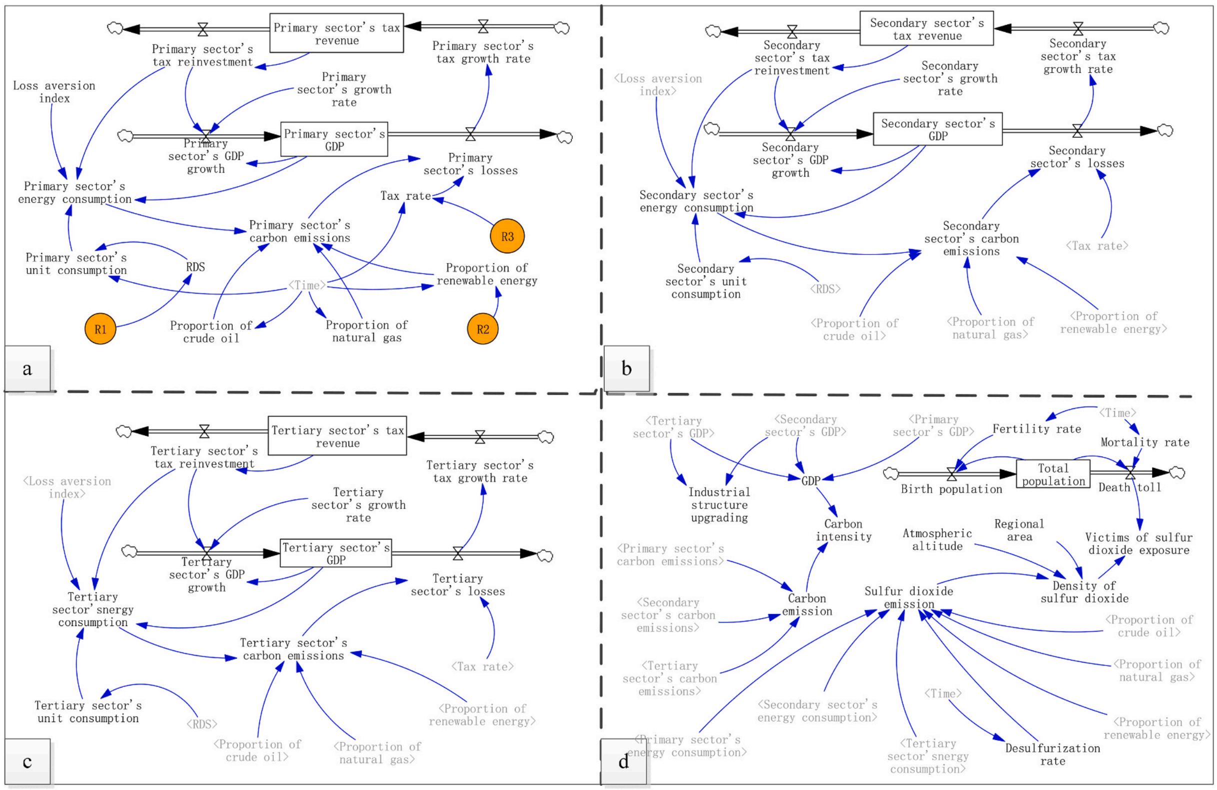


Fig. 2. Carbon tax policy simulation model (a: primary sector, b: secondary sector, c: tertiary sector, d: other).

Table 2
Scenario settings.

Scenario	Coefficient	Description
1	R1 = 0, R2 = 0, R3 = 0	This scenario fulfills two main purposes. First, it is used to validate the model's accuracy and robustness. Second, it is compared with other scenarios to measure their benefits and risk values.
2	R1 = 0, R2 = 0, R3 = 1	This scenario presages the enforcement of a carbon tax. Within this context, a comprehensive analysis is conducted to assess and contrast the economic, environmental, and health risks and benefits associated with the policy on taxation. Furthermore, the exploration of the optimal implementation path for the policy is undertaken.
3	R1 = 0.1, R2 = 0, R3 = 1	In this scenario, upon the imposition of the tax, the RDS policy serves as a supplementary measure and is subjected to a comparative analysis with other scenarios. Through this comparison, the degree of optimisation achieved by the RDS policy to this policy is revealed.
4	R1 = 0, R2 = 0.1, R3 = 1	This scenario indicates that during the imposition of the tax, the NES policy serves as a supporting measure. Additionally, the extent of optimisation achieved by the NES policy to this policy is thoroughly examined.
5	R1 = 0.1, R2 = 0.1, R3 = 1	In this scenario, both the RDS and NES policies are employed as auxiliary measures. Furthermore, the exploration is conducted to assess the degree of optimisation achieved by these auxiliary policies to the policy on carbon taxation.

increase by 10 %.

When the R1 is 0.1, it means that the capital investment of energy efficiency in research and development increases by 10 %. When the R2 is 0.1, it means that the support for new energy has increased the proportion of renewable energy by 10 %. When the tax adjustment coefficient (R3) is 0, it signifies the absence of the policy on carbon taxation; otherwise, any value other than 0 indicates the implementation of the policy on carbon taxation.

4. Simulation results

4.1. Model testing

To ascertain the accuracy and stability of the simulation model, a comprehensive evaluation method is established to verify the coincidence between the relative trend and the absolute data of the core variables and reality. The detailed analysis process of the evaluation method is as follows.

Stage 1. Obtain simulation and actual data within the verification period, and establish a comparison sequence.

Step 1. Derive the simulation data of the variables in the verification period from the simulation model, and set the simulation data as X_0, $X_0 = (x_0(1), x_0(2), x_0(3), \cdots, x_0(n))$. Let the original data be sequence X_1, $X_1 = (x_1(1), x_1(2), x_1(3), \cdots, x_1(n))$.

Stage 2. Calculate the coincidence degree of the relative trend.

Step 2. Calculate the starting point zero images $X_0^{'}$ and $X_1^{'}$ of the sequences X_0 and X_1.

$$X_0^{'} = (x_0(2) - x_0(1), x_0(3) - x_0(1), \cdots, x_0(n) - x_0(1)) = \left(x_0^{'}(1), x_0^{'}(2), x_0^{'}(3), \cdots, x_0^{'}(n-1)\right)$$

$$X_1^{'} = (x_1(2) - x_1(1), x_1(3) - x_1(1), \cdots, x_1(n) - x_1(1)) = \left(x_1^{'}(1), x_1^{'}(2), x_1^{'}(3), \cdots, x_1^{'}(n-1)\right)$$

Step 3. Let $s_0 = \sum_{k=1}^{n-2} x_0^{'}(k) + \frac{1}{2} x_0^{'}(n-1)$ and $s_1 = \sum_{k=1}^{n-2} x_1^{'}(k) + \frac{1}{2} x_1^{'}(n-1)$; then, $s_0 - s_1 = \sum_{k=1}^{n-2}\left(x_0^{'}(k) - x_1^{'}(k)\right) + \frac{1}{2}\left(x_0^{'}(n-1) - x_1^{'}(n-1)\right)$.

Step 4. Calculate the absolute degree of incidence α of sequences X_0 and X_1.

$$\alpha = \frac{1 + |s_0| + |s_1|}{1 + |s_0| + |s_1| + |s_0 - s_1|}$$

Step 5. Calculate the initial images $X_0^{''}$ and $X_1^{''}$ of the sequences X_0 and X_1.

$$X_0^{''} = \left(\frac{x_0(1)}{x_0(1)}, \frac{x_0(2)}{x_0(1)}, \frac{x_0(3)}{x_0(1)}, \cdots, \frac{x_0(n)}{x_0(1)}\right) = \left(x_0^{''}(1), x_0^{''}(2), x_0^{''}(3), \cdots, x_0^{''}(n)\right)$$

$$X_0^{''} = \left(\frac{x_1(1)}{x_1(1)}, \frac{x_1(2)}{x_1(1)}, \frac{x_1(3)}{x_1(1)}, \cdots, \frac{x_1(n)}{x_1(1)}\right) = \left(x_1^{''}(1), x_1^{''}(2), x_1^{''}(3), \cdots, x_1^{''}(n)\right)$$

Step 6. Let $s_0^{'} = \sum_{k=1}^{n-1} x_0^{''}(k) + \frac{1}{2} x_0^{''}(n)$ and $s_1^{'} = \sum_{k=1}^{n-1} x_1^{''}(k) + \frac{1}{2} x_1^{''}(n)$; then, $s_0^{'} - s_1^{'} = \sum_{k=1}^{n-1}\left(x_0^{''}(k) - x_1^{''}(k)\right) + \frac{1}{2}\left(x_0^{''}(n) - x_1^{''}(n)\right)$.

Step 7. Calculate the relative degree of incidence β of the sequences X_0 and X_1.

$$\beta = \frac{1 + |s_0'| + |s_1'|}{1 + |s_0'| + |s_1'| + |s_0' - s_1'|}$$

Step 8. Calculate the degree of grey incidence ρ.

$$\rho = \theta\alpha + (1 - \theta)\beta, \theta = 0.5$$

Stage 3. Calculate the coincidence degree of the absolute data.

Step 9. Calculate the difference image X_i of the sequences X_0 and X_1.

$$X_i = (x_1(1) - x_0(1), x_1(2) - x_0(2), \cdots, x_1(n) - x_0(n)) = (x_i(1), x_i(2), \cdots, x_i(n))$$

Step 10. Calculate the mean absolute ratio σ of the difference image X_i to the sequence X_1.

$$\sigma = \frac{1}{n}\sum \frac{|X_i|}{X_1} = \frac{1}{n}\left(\frac{|x_i(1)|}{x_0(1)} + \frac{|x_i(2)|}{x_0(2)} + \frac{|x_i(3)|}{x_0(3)} + \cdots + \frac{|x_i(n)|}{x_0(n)}\right)$$

Stage 4. Evaluate the accuracy.

Step 11. Calculate the ratio ε between the mean absolute ratio σ and the coincidence degree ρ.

$$\varepsilon = \frac{\sigma}{\rho}$$

Step 12. sEvaluate the results under qualified conditions to determine the accuracy of the simulation model.

When $\rho \geq 0.7$, the simulation model is regarded as preliminarily qualified. In the case of $\rho \geq 0.7$, when $\varepsilon \leq 0.2142$, it is considered that the accuracy is general, it can reflect the changes of the real system and the model can be used. When $\varepsilon \leq 0.1250$, the accuracy of the model is considered to be good. When $\varepsilon \leq 0.0555$, the prediction accuracy is considered to be superior.

The evaluation model includes two aspects. The first aspect is to test the coincidence degree of the relative trend of the core variables (Steps 2–8). The evaluation of the relative trend of the two sequences can be divided into the evaluation of the similarity in geometric shape (Steps 2–4) and the rate of change relative to the starting point (Steps 5–7). In the evaluation of similarity, the geometric translation of two sequences does not change the original result; in the evaluation of the rate of change, the multiplication of two sequences does not change the original result. The similarity and the rate of change can well reflect the coincidence degree of the relative trend of two sequences. The second aspect is to verify the coincidence degree of the absolute data of core variables (Steps 9–10). This part mainly analyses the proximity of the two sequences in terms of data. A higher degree of proximity indicates a higher degree of agreement in absolute data and vice versa. Therefore, this comprehensive evaluation model can more comprehensively analyse the simulation model's accuracy and stability.

Herein, the GDP of the three major industries, along with the total population, are chosen as key state variables and serve as test indicators for each module (Fig. 2(a–d)) within the simulation model. The evaluation results are presented in Table 3, which demonstrates that the relative trend of the four core variables exceeds 0.7, while the comprehensive evaluation value remains below 0.125. Therefore, it is considered that the simulation model has a good agreement with reality, and the model can be used. In addition, except for the tertiary sector, the comprehensive evaluation values of the other three variables are all less than 0.0555. Therefore, except for the tertiary industry module, the fit between the other three modules and reality is excellent.

4.2. Utility analysis

To reveal the multi-impact of a carbon tax policy, this study delves into the alterations of some variables within the simulation model. Owing to the substantial base numbers of certain variables within the simulation model, the increase or decrease of these variables is not obvious on the whole. To increase the observability of the difference of variables in different scenarios, the study takes the difference of variables in scenarios 1 and 2 as the observation object.

Table 3
Evaluation results of the simulation model.

Variable	Total population	GDP		
		Primary sector	Secondary sector	Tertiary sector
Relative trend	0.9710	0.9577	0.9861	0.9206
Comprehensive assessment	0.0027	0.0505	0.0453	0.0780

4.2.1. Economic and environmental assessment

Fig. 3 shows the simulation results for some variables in scenarios 1 and 2. Notably, the energy composition and unit consumption remain unchanged in both scenarios. Specifically, Fig. 3(a) illustrates the evolving trend of the energy composition and unit consumption. Evidently, the proportion of the three energy sources will gradually increase with the passage of time, whereas the unit consumption of the three sectors has been consistently decreasing. This shows that energy structure is being gradually optimised, and Energy efficiency is gradually improved.

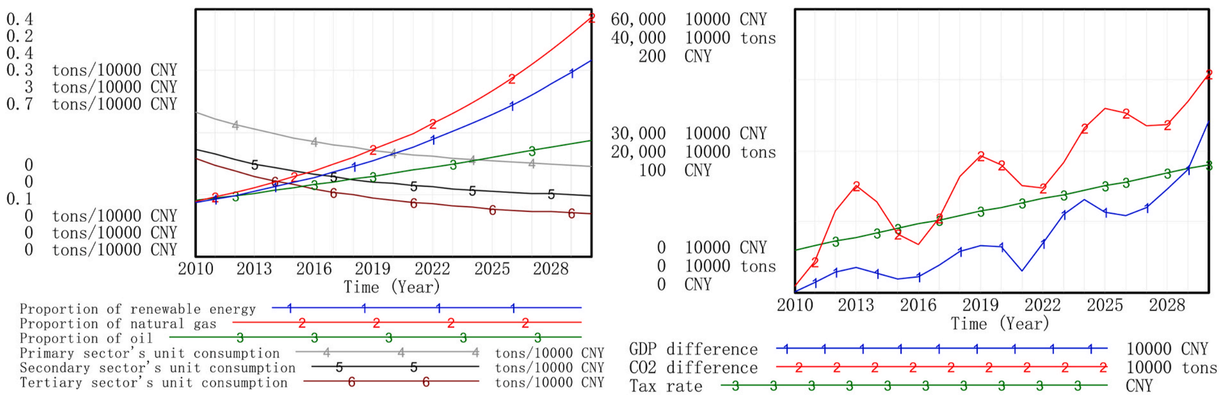
Fig. 3 (b) illustrates that under the influence of the alterable tax rate (curve 3), the reduction of CO_2 emissions (curve 2) presents a regular, fluctuating, and upward trend, while the reduction of GDP (curve 1) presents an irregular, fluctuating, and upward trend. This indicates that the enforcement of the policy on carbon taxation has a beneficial impact on the environment but has an obvious negative effect on economic development, and even the refund of tax revenue cannot fully offset the risks associated with imposing a carbon tax. In addition, in the actual situation, due to the delayed effect, the procedure of gathering and recycling these tax revenues will lead to the fluctuation of reality. Zhang and Lu [69] discovered that during the enforcement of this policy, the delayed utility will lead to fluctuations in economic development. Moreover, the aforementioned researcher [69] found that under the influence of an invariant tax rate, the carbon tax policy's emission reduction effectiveness tended to diminish. However, in reality, even without optimising the energy structure or reducing unit energy consumption, the increase in tax rates can still lead to a reduction in CO_2 emissions. Therefore, a carbon tax policy exerts a sustainable influence on the progress of a low-carbon economy.

4.2.2. Spillover effect

Except for the direct impact on GDP and CO_2 emissions, this policy also exerts a notable indirect impact on other aspects. Fig. 4 shows changes in carbon intensity, polluted population, energy consumption and industrial structure upgrading in scenarios 1 and 2 simulations. As depicted in Fig. 4, the polluted population (curve 1 in Fig. 4 (a)) and energy consumption (curve 2 in Fig. 4 (b)) will gradually decrease, while the industrial structure undergoes gradual upgrading (curve 1 in Fig. 4 (b)). However, the rate of carbon intensity reduction (curve 2 in Fig. 4 (a))will gradually decrease. Effectively reducing energy consumption, the carbon tax policy is instrumental in curbing CO_2 emissions. Consequently, as energy consumption decreases, SO_2 emissions will also be diminished, leading to a reduction in the overall number of people affected by pollution. Given that the unit consumption of the secondary sector is substantially higher than that of the primary and tertiary sectors, this policy exerts the strongest restraining effect on the development of the secondary sector. Therefore, the policy on carbon taxation can further expedite the upgrading of the industrial configuration. The effect of the carbon tax policy on achieving carbon intensity targets will gradually diminish. This is mainly due to the continuous decline in carbon intensity as the economy progresses. While the emission reduction effect may gradually increase in the actual situation, it also leads to the decline of GDP (Fig. 3 (b)). Consequently, overall, a carbon tax policy doesn't fully contribute to reducing the carbon intensity.

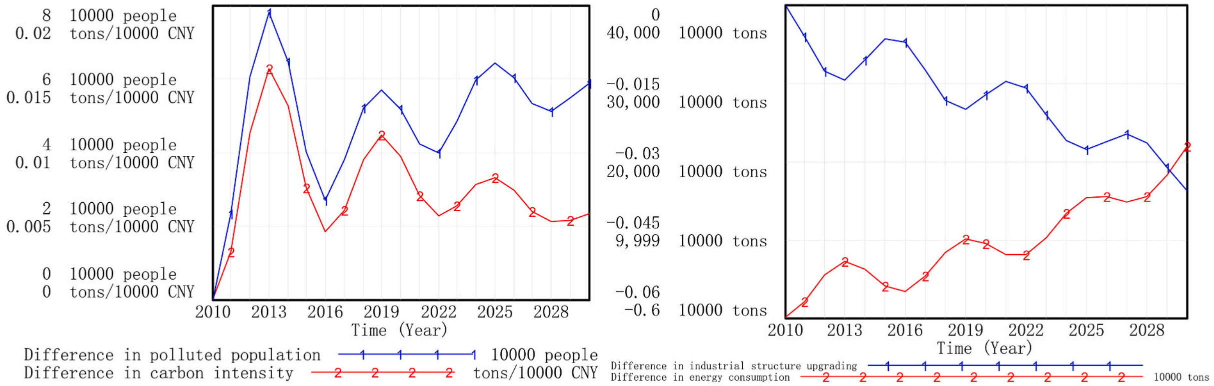
4.3. Optimisation path

The difference between scenarios can be leveraged to assess the influence of this policy on each variable. However, due to the discrepancy in the value and unit of each variable, a comparison between variables cannot be made. Therefore, the change ratio of variables under different scenarios is employed to analyse the optimisation path of the policy on carbon taxation. The simulation in Section 4.2 shows that, apart from its negative impact on the economy, this policy yields beneficial impacts in energy, the environment, health and the industrial structure. In addition, given the strong correlation between energy consumption and pollutant emissions, only CO_2 emissions, carbon intensity, the polluted population, industrial structure upgrading and GDP are selected as observational indicators in this study. The detailed findings are presented in Fig. 5.



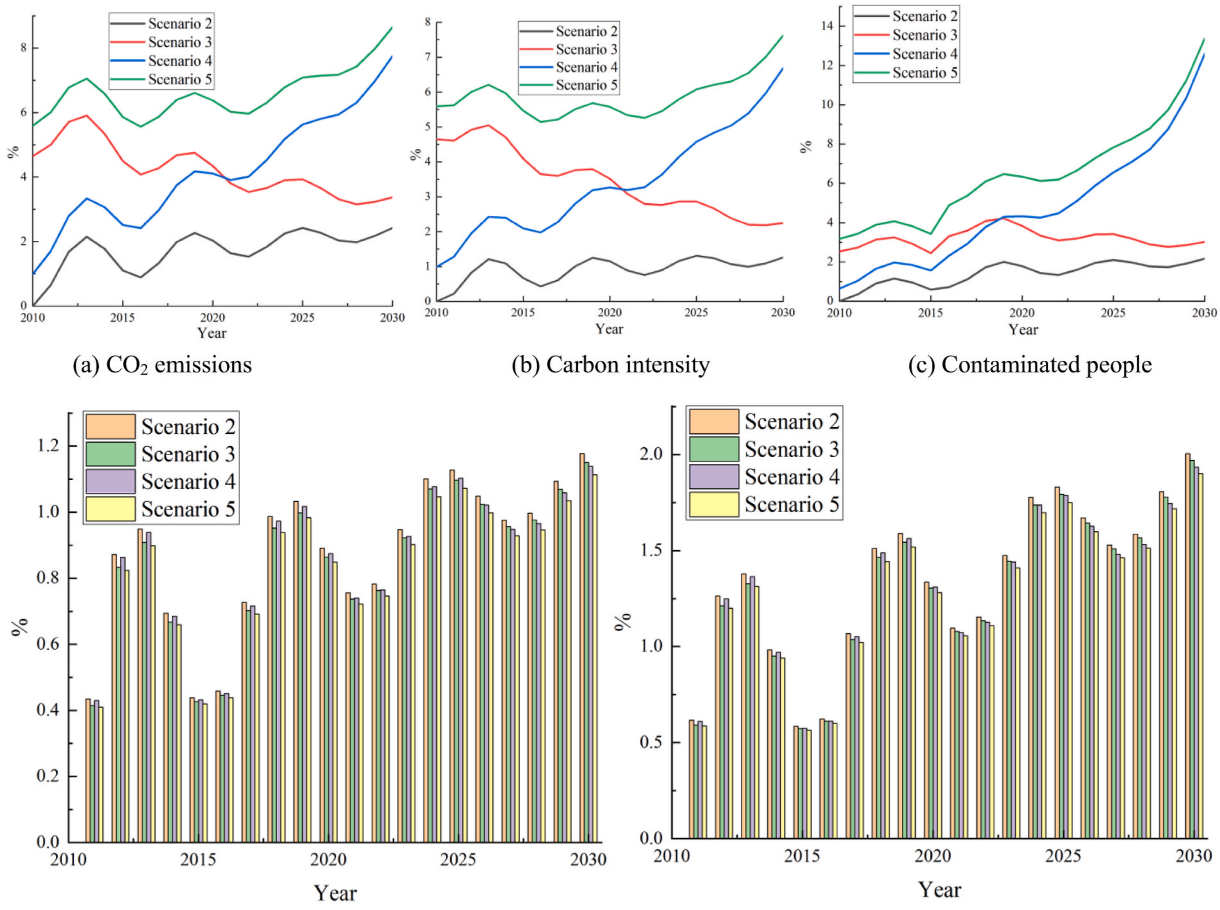
(a) Energy structure and unit energy consumption (b) Scenario difference and carbon tax rate

Fig. 3. Simulation results of key variables (difference = scenario 1 - scenario 2).



(a) Contaminated people and carbon intensity (b) Industrial structure upgrading and energy consumption

Fig. 4. Influence of the tax policy on various other variables (difference = scenario 1 - scenario 2).



(a) CO_2 emissions (b) Carbon intensity (c) Contaminated people

(d) GDP (e) Industrial structure upgrading

Fig. 5. Difference ratio of core variables under scenarios 2–5 to scenario 1. In the graph, each subplot represents a kind of variable, and the four lines in each subplot are the difference ratios of scenarios 2–5 relative to scenario 1, that is, difference ratio = |scenarios 2–5 - scenario 1|/scenario 1. (a: CO_2 emissions; b: Carbon intensity; c: Contaminated people; d: GDP; e: Industrial structure upgrading).

Fig. 5 illustrates the comparisons of CO_2 emissions (Fig. 5(a)), polluted population (Fig. 5(c)), carbon intensity (Fig. 5(b)), GDP (Fig. 5(d)) and industrial structure upgrading (Fig. 5(e)) in different scenarios. As evident from Fig. 5, the utilization of auxiliary policies (scenarios 3–5) yields greater benefits for the four indicators of CO_2 emissions (Fig. 5(a)), the polluted population (Fig. 5(c)), carbon intensity (Fig. 5(b)), and GDP (Fig. 5(d)), compared to their absence (scenario 2). However, for the industrial structure (Fig. 5(e)), the use of auxiliary policies (scenarios 3–5) will reduce the potential for industrial structure upgrading. This shows that auxiliary policies do not always strengthen the benefits and weaken the potential risks associated with a carbon tax policy.

When considering solely auxiliary policies aimed at enhancing the benefits, Fig. 5 reveals that the concurrent utilization of RDS and NES policies yields greater benefits than the implementation of a single auxiliary policy. Xiao et al. [27] discovered that the synergistic utility of multiple policies is greater than that of a single policy. In addition, it must be noted that there exist notable disparities in the reinforcing impacts of RDS and NES policies on the carbon tax policy in different periods. Among these indicators, regarding CO_2 emissions (Fig. 5(a)) and carbon intensity (Fig. 5(b)), the RDS policy exhibits a stronger impact on the carbon tax policy prior to 2021 compared to the NES policy, but the opposite is true after that. Taking the polluted population (Fig. 5(c)) and GDP (Fig. 5(d)) as reference indicators, the optimal policy adjustment nodes are in 2019 and 2027, respectively. This demonstrates that the enhancing impact of auxiliary policies on the carbon tax policy has timeliness, which suggests that policymakers need to adopt different auxiliary policies at different times. Contrary to the patterns observed for the four indicators mentioned, regarding industrial structure upgrading (Fig. 5(e)), the RDS policy exhibits a greater weakening impact on the advantages of the policy prior to 2021 compared to the NES policy. However, after 2021, the NES policy will exert a stronger weakening effect.

Concerning the degree of impact, the policy on carbon taxation exhibits minimal variation in its effects across all indicators when no auxiliary policies are adopted (scenario 2). However, after the implementation of auxiliary policies, even the introduction of a single auxiliary policy (scenario 3 or 4) can strengthen the environmental and health benefits of the policy on carbon taxation. Furthermore, if NES and RDS policies are simultaneously adopted (scenario 5), the beneficial impact of this policy can be at least doubled. For economic development, auxiliary policies can mitigate the side effects, albeit to a limited extent. In addition, although auxiliary policies will lead to a slight slowdown in the industrial structure upgrading process, the impact of this side effect is almost negligible.

5. Discussion

Following the theory of SD, a simulation model for the carbon tax policy is constructed by combining the loss aversion model and delay function. Starting from four subsystems of economy, energy, environment and health, the simulation model can comprehensively analyse the advantages and disadvantages associated with the policy. To verify the simulation model's accuracy and stability, a method is proposed that can evaluate the relative trend and absolute data of the variables comprehensively. The proposed method provides a new observation perspective for the testing and verification of simulation models.

Utilizing various simulation scenarios, the study analyses the dynamic evolution process of key variables. The simulation results of GDP and CO_2 emissions confirm that, despite this policy's energy-saving and emission-reducing benefits, it carries the potential to restrain economic growth. These results are consistent with previous studies [15–19,28,39,45–47]. In addition, the delay effect can lead to shocks within the system, and as the tax rate continues to increase, such shocks show an upward trend. This is consistent with Zhang and Lu's findings [69]. Differing from existing research, the present study expands the analysis of the indirect impact of the policy on carbon taxation. Specifically, it delves deeper into the influence of this policy on industrial structure upgrading, carbon emission intensity, public health and other aspects. This comprehensive assessment results can be used by decision-makers to formulate reasonable policies and objectives, thereby reducing the potential policy-related risks.

In terms of industrial structure upgrading, the policy on carbon taxation has indeed facilitated the optimisation of industrial structure to a certain extent, but with the continuous growth of the economy, this promotional role will be gradually weakened. Furthermore, China's carbon intensity will gradually decline due to the decrease in unit consumption, the optimisation of its energy structure, and the influence of pertinent emission reduction policies. When carbon intensity is reduced to a certain extent, carbon intensity should not be used as a short-term target, that is, setting the target should be gradually distanced from the requirements on carbon intensity. If China solely implements a carbon tax policy, the policy's impact on energy and emissions is unlikely to increase with economic growth in the future. Furthermore, Lin and Li [18] also found that a carbon tax policy didn't significantly reduce emissions in Denmark, Sweden and the Netherlands, and had no emission reduction effect whatsoever on Norway. This illustrates that for developed nations like Norway, the influence of the policy on energy conservation and emission reduction, as well as its positive spillover effects (such as industrial structure upgrading and carbon intensity targets), may not be as pronounced as in developing countries, such as South Africa. Baranzini et al. [41] also found that the carbon tax only reduced Denmark's CO_2 emissions by 4.7 % between 1998 and 2000. Bruvoll and Larsen's study indicates that the carbon tax policy contributes only 2.3 % to the reduction of Norway's carbon emissions [73]. Regarding public health, the actual influence of the policy on carbon taxation is more consistent with CO_2 emissions.

To strengthen the advantages of the policy on carbon taxation, it is necessary to introduce auxiliary policies. This study examines the reinforcing impact of auxiliary policies on this policy from the perspectives of energy efficiency and structure, respectively. The simulation outcomes reveal that the optimisation effect of the RDS policy (energy efficiency) on the carbon tax policy diminishes gradually over time in terms of economy, energy usage, environment and health. Conversely, the optimisation impact of NES policy (energy structure) will gradually increase. This shows that for countries with higher unit energy consumption (namely, developing countries), focusing on the decrease of unit energy consumption is a more appropriate approach that also stimulates the development of new energy to some extent. For countries with low unit energy consumption (i.e. developed countries), the benefits brought by reducing unit energy consumption are far lower than the benefits brought by the expansion of renewable energy. Consequently, adopting the NES policy to supersede the RDS policy becomes a necessary choice. Cui et al. also found that to attain the ambitious 1.5 °C target by the end of the century, China must completely eliminate coal usage by 2045. In addition, some scholars [74,75] believe that the policy on carbon taxation alone cannot promote the shift of the energy mix to a level that aligns with climate goals.

This study delves into the multifaceted influence of the carbon tax policy on societal development and explores the degree of enhancing the positive effects and inhibiting the adverse impact of auxiliary policies on the policy. However, this research has two notable limitations. First, it does not consider the greenhouse gas emissions generated during the execution of policies and measures. Taking the transmission system as an example, some renewable energy requires related power generation equipment to convert renewable energy into electricity, and energy consumption will also be generated during the operation phase of this equipment [76]. Second, only two auxiliary policies without strong side effects are used to explore the optimisation effect on carbon tax policy in this study. In the future, we aim to delve deeper into the practical effects of more complementary or combination policies on the carbon tax policy, such as bioenergy support policies [77,78], and carbon trading system [29].

6. Conclusions and suggestions

In accordance with the theory of SD, a carbon tax policy simulation model is constructed by integrating multiple methods. This study establishes different simulation scenarios by adjusting the parameters of some variables to analyse the benefits and risks associated with a carbon tax policy. Furthermore, an optimisation path for such a policy is explored. Additionally, an evaluation method is established to verify the usability of the model. Consequently, by observing the magnitude of changes in key variables across various scenarios, the following conclusions are derived.

First, apart from its direct impacts on the environment and the economy, the spillover effects of the policy on carbon taxation will have beneficial effects on reducing energy consumption, improving health, and achieving carbon intensity targets. By curbing the utilization of carbon-intensive energy sources, the carbon tax policy effectively achieves its objective of reducing CO_2 emissions. Simultaneously, this reduction also leads to a decline in pollutants associated with CO_2, thereby improving the level of public health. Furthermore, despite the policy's negative impact on economic growth, it simultaneously alleviates environmental pollution. Notably, the rate of growth in environmental benefits from the policy surpasses its adverse economic effects. Consequently, implementing the policy on carbon taxation is conducive to promoting the achievement of the carbon emission intensity goal.

Second, taking into account the current social development situation in China, it is imperative to introduce auxiliary policies to mitigate risks and strengthen the beneficial impacts of the policy. As Fig. 5 illustrates, without auxiliary policies, the gap between the benefits and risks associated with this policy is narrow. Conversely, with the enforcement of auxiliary policies, the policy's effect on energy efficiency and emission control experiences a significant qualitative leap, while simultaneously mitigating the economic risks arising from policy execution to a considerable degree.

Third, while strengthening the beneficial impacts of the policy on carbon taxation, auxiliary policies will also produce certain risks, but the risks generated are acceptable. The results show that when the RDS and NES policies are implemented, although the environmental and health benefits are enhanced and the negative influence on economic growth is mitigated, the procedure of industrial configuration upgrading is reduced.

Based on the above conclusions, to promote the attainment of China's emission reduction targets and mitigate the potential risks associated with the carbon tax policy, the following recommendations are worth consideration by policymakers.

First, while focusing on energy conservation and emission reduction effects, policymakers should further assess the influence of the policy on the economy, health, and other aspects. This policy will exert a positive influence on the environment and climate change, leading to improved air quality and a healthier ecological environment through the reduction of pollutant emissions. In addition, the policy will impact the costs of enterprises, which will affect employment, production and consumption and ultimately affect the economic development of society. Then, the policy will shape the energy structure and resource utilization patterns, thus affecting energy supplies and security. Finally, by reducing pollutant emissions, it may contribute positively to public health.

Second, at present, China should prioritize enhancing the market share of new energy. The simulation outcomes indicate that although the NES strategy's enhancing effect on the policy is gradually surpassing the RDS policy, the RDS policy's strengthening impact remains superior to that of solely implementing the policy on carbon taxation.

Third, to mitigate the risks associated with the policy on carbon taxation, it is advisable to introduce a carbon tax in the form of a pilot program in select cities. In our study, we found that even if auxiliary policies are used to alleviate the adverse effects of the policy, auxiliary policies may bring some other potential negative effects. Therefore, observing the advantages and disadvantages of both the policy on carbon taxation and auxiliary policies in the form of pilots can minimise the negative impact of policies.

Fourth, looking ahead, the Chinese government ought to improve energy efficiency and optimise the energy structure to guide the rapid realisation of the low-carbon economy. By fostering the adoption of energy-saving technologies, bolstering energy management and monitoring efforts, and incentivising both enterprises and residents to conserve energy and reduce emissions, the overall efficiency of energy use will be improved. These measures will also catalyse the alteration of energy production and consumption patterns and improve the efficiency of coal, oil and natural gas utilization, which will contribute to reduced energy consumption, diminished carbon emissions, and a strengthened competitive edge for the national economy.

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Ethical approval

A review and/or approval from an ethics committee was not needed for this study because it does not contain any research with human participants performed by any of the authors.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Minfei Wang: Writing – original draft, Conceptualization. **Xianquan Fang:** Writing – review & editing, Project administration. **Kanghui Zhang:** Writing – review & editing, Validation.

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.

Appendix A. Core variables and equations of subsystems

Economic subsystem

(1) Primary sector's GDP = INTEG (Primary sector's GDP growth-Primary sector's losses, 38430.8), Unit: 100 million CNY
(2) Primary sector's losses = Primary sector's carbon emissions × Tax rate/10000, Unit: 100 million CNY
(3) Primary sector's GDP growth = Primary sector's GDP × Primary sector's growth rate + Primary sector's tax reinvestment, Unit: 100 million CNY
(4) Primary sector's tax reinvestment = DELAY1I(Primary sector's tax revenue, 1,0), Unit: 100 million CNY
(5) Secondary sector's GDP = INTEG (Secondary sector's GDP growth-Secondary sector's losses, 191,627), Unit: 100 million CNY
(6) Secondary sector's GDP growth = Secondary sector's GDP × Secondary sector's growth rate + Secondary sector's tax reinvestment, Unit: 100 million CNY
(7) Secondary sector's losses = Tax rate × Secondary sector's carbon emissions/10000, Unit: 100 million CNY
(8) Secondary sector's tax reinvestment = DELAY1I(Secondary sector's tax revenue, 1,0), Unit: 100 million CNY
(9) Tertiary sector's GDP = INTEG (Tertiary sector's GDP growth-Tertiary sector's losses, 182,062), Unit: 100 million CNY
(10) Tertiary sector's GDP growth = Tertiary sector's GDP × Tertiary sector's growth rate + Tertiary sector's tax reinvestment, Unit: 100 million CNY
(11) Tertiary sector's losses = Tertiary sector's carbon emissions × Tax rate/10000, Unit: 100 million CNY
(12) Tertiary sector's tax reinvestment = DELAY1I (Tertiary sector's tax revenue, 1, 0), Unit: 100 million CNY
(13) GDP = Primary sector's GDP + Tertiary sector's GDP + Secondary sector's GDP, Unit: 100 million CNY
(14) Industrial structure upgrading = Tertiary sector's GDP/Secondary sector's GDP

Energy subsystem

(15) Primary sector's energy consumption = (Primary sector's GDP-Primary sector's tax reinvestment) × Primary sector's unit consumption+(Loss aversion index × Primary sector's tax reinvestment) × Primary sector's unit consumption, Unit: 10,000 tons
(16) Secondary sector's energy consumption = (Secondary sector's GDP-Secondary sector's tax reinvestment) × Secondary sector's unit consumption+(Loss aversion index × Secondary sector's tax reinvestment) × Secondary sector's unit consumption, Unit: 10,000 tons
(17) Tertiary sector's energy consumption = (Tertiary sector's GDP-Tertiary sector's tax reinvestment) × Tertiary sector's unit consumption+(Loss aversion index × Tertiary sector's tax reinvestment) × Tertiary sector's unit consumption, Unit: 10,000 tons
(18) Primary sector's unit consumption = (1-EXP (0.031)) × (0.189067–0.173/0.031) × EXP (-0.031 × (Time-2011)) × RDS, Unit: ton/10000 CNY
(19) Secondary sector's unit consumption = (1-EXP (0.042)) × (1.39287–1.324/0.042) × EXP (-0.042 × (Time-2010)) × RDS, Unit: ton/10000 CNY
(20) Tertiary sector's unit consumption = (1-EXP (0.072)) × (0.274643–0.306/0.072) × EXP (-0.072 × (Time-2010)) × RDS, Unit: ton/10000 CNY
(21) Proportion of crude oil = (1-EXP (-0.01826)) × (16.8 + 16.5609/0.01826) × EXP (0.01826 × (Time-2010))/100
(22) Proportion of natural gas = (1-EXP (-0.07357)) × (4.6 + 4.2563/0.07357) × EXP (0.07357 × (Time-2010))/100
(23) Proportion of renewable energy = (1-EXP (-0.06531)) × (8.4 + 8.92904/0.06531) × EXP (0.06531 × (Time-2011))/100 × R2

Environment subsystem

(24) Primary sector's carbon emissions = 44/12 × (0.4426 × 0.99 × Primary sector's energy consumption × Proportion of natural gas+0.7329 × 0.916 × Primary sector's energy consumption × (1-Proportion of natural gas-Proportion of renewable energy-Proportion of crude oil)+0.5574 × 0.987 × Primary sector's energy consumption × Proportion of crude oil), Unit: 10,000 tons
(25) Secondary sector's carbon emissions = 44/12 × (0.4426 × 0.99 × Secondary sector's energy consumption × Proportion of natural gas+0.7329 × 0.916 × Secondary sector's energy consumption × (1-Proportion of natural gas -Proportion of renewable energy-Proportion of crude oil)+0.5574 × 0.987 × Secondary sector's energy consumption × Proportion of crude oil), Unit: 10,000 tons
(26) Tertiary sector's carbon emissions = 44/12 × (0.4426 × 0.99 × Tertiary sector's energy consumption × Proportion of natural gas+0.7329 × 0.916 × Tertiary sector's energy consumption × (1-Proportion of natural gas-Proportion of renewable energy-Proportion of crude oil)+0.5574 × 0.987 × Tertiary sector's energy consumption × Proportion of crude oil), Unit: 10,000 tons
(27) Carbon emission = Primary sector's carbon emissions + Tertiary sector's carbon emissions + Secondary sector's carbon emissions, Unit: 10,000 tons
(28) Tax rate = 30+(Time-2010) × 3, Unit: CNY/ton
(29) Carbon intensity = Carbon emission/GDP, Unit: ton/10000 CNY

Health subsystem

(30) Sulfur dioxide emission = ((1-Proportion of renewable energy-Proportion of natural gas-Proportion of crude oil) × (Primary sector's energy consumption + Secondary sector's energy consumption + Tertiary sector's energy consumption)/0.7143 × 33.6/1000+(Primary sector's energy consumption + Secondary sector's energy consumption + Tertiary sector's energy consumption) × Share of crude oil consumption/1.4286 × 5.25/1000+(Primary sector's energy consumption + Secondary sector's energy consumption + Tertiary sector's energy consumption) × 0.084/1.33 × 0.63/1000) × (1-Desulfurisation rate) × 0.8, Unit: 10,000 tons
(31) Sulfur dioxide concentration = IF THEN ELSE (Sulfur dioxide emission × 1e+012/(Regional area × Atmospheric altitude) <0, 0, Sulfur dioxide emission × 1e+012/(Regional area × Atmospheric altitude)), Unit: μg/m^3
(32) Victims of sulfur dioxide exposure = Death toll × (1-1/(EXP (0.00075 × (Density of sulfur dioxide-20)))), Unit: 10,000 people
(33) Fertility rate = (1-EXP (0.048)) × (11.9–15.789/0.048) × EXP (-0.048 × (Time-2010))/1000
(34) Mortality rate = (1-EXP (0.0012)) × (7.11–7.143/0.0012) × EXP (-0.0012 × (Time-2010))/1000
(35) Birth population = Total population × Fertility rate, Unit: 10,000 people
(36) Total population = INTEG (Birth population-Death toll, 134,091), Unit: 10,000 people
(37) Death toll = Total population × Mortality rate, Unit: 10,000 people

The equations in Appendix A are based on the raw data obtained and the relevant literature. See Section 3.2 of the study for a description of the raw data. Drawing insights from the research conducted by Zhang and Lu [69], the study establishes a delay time of 1 year, and the influence variable of tax reuse quota is the total tax revenue. Simultaneously, based on the utility ratio of consumer losses and gains [79], the expenditure is estimated to be 1/2.5 of the reuse tax. Additionally, this study incorporates the industrial structure upgrading assessment model and exposure–response function from the works of Xin-gang and Jin [70] and Wu et al. [71] into the simulation model, aiming to investigate the policy's spillover effects on industrial structure and public health.

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