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CEEEA2.0 model: A dynamic CGE model for energy-environment-economy analysis with available data and code

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ABSTRACT

The computable general equilibrium (CGE) model is a good instrument for counterfactual analysis. This kind of model is widely used in energy and environmental economics. However, the CGE models used in different studies vary greatly. As the construction of the model is a massive project, and some model settings may be wrong, it is easy to get unreasonable equilibrium solutions. Another, the code and data of most CGE models are not transparent. This paper aims to break the barrier of the CGE model criticized as “black box” and provide researchers with a CGE model with available code and data: China Energy-Environment-Economic Analysis 2.0 (CEEEA2.0) model. Taking carbon tax and energy tax as examples, this paper analyzes the impact of carbon neutrality constraints on China from 2018 to 2060. Compared with the traditional CGE model, this paper describes energy and carbon emissions more closely, couples the environmental cost into the model more scientifically and the embodied carbon emissions in trade, and provides novel counterfactual analysis strategies. In addition, this paper introduces how to extend and adjust the model to facilitate the majority of modelers to build a CGE model according to different needs.

1. Introduction

The computable General Equilibrium (CGE) model is widely used to comprehensively evaluate various policies' effects. In the field of energy and environmental economics, different improved CGE models are widely deployed (Choi et al., 2017; García-León et al., 2021; Rao et al., 2017). Famous examples are GTAP (Moore et al., 2017), AIM/CGE, etc. (Aguiar et al., 2016; Böhringer et al., 2016; Böhringer et al., 2014; Dixon et al., 2020; Fujimori et al., 2017; Octaviano et al., 2016; Peters et al., 2011; Xu and Masui, 2009). However, due to the lack of transparency of models' code and data, many conclusions based on the CGE model are difficult to duplicate. The conclusions drawn by different models can be significantly different. There are two main reasons why it is difficult to copy the results: 1) this kind of large-scale macro model covers a wide range of aspects. It is impossible for any paper to introduce the modeling process in detail completely. 2) The data processing and the model itself have condensed many efforts of researchers, and there may be several controversial assumptions (the more complex the model is, the more assumptions exist).[1]

This paper aims to break the model barrier and provide CGE modelers with a recursive dynamic CGE model considering multi-sectors, multi-residents, energy consumption, and carbon emission. The authors had developed a set of China's Energy-Environment-Economy Analysis model (CEEEA) model. In the text, I share the code, data, and modeling details of the model to CGE modelers for the first time, hoping to provide references to CGE modelers. The simulation period of the new model shown in this paper is 2018–2060. There are three scenarios (the BAU, CT, and ET scenarios), which respectively simulate the scenario without carbon constraints, the scenario of levying carbon tax on the whole industry under carbon constraints of carbon neutrality, and the scenario of charging energy tax on primary fossil energy under carbon constraints of carbon neutrality.

The authors further extend the original model and completes the CEEEA2.0 model. The new model is more scientific and objective in processing energy and emission data, avoiding specific statistical errors made by officials, and provides various options to meet different

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[1] Usually, breaking through a strong hypothesis always leads to multiple weak hypotheses. However, these weak assumptions can also be criticized. Our researches are always based on these lovely and annoying assumptions.

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modeling requirements. Specifically, the main features of the new model are as follows:

1) The carbon tax cost is no longer included in the virtual tax in domestic output, but added into the specific value balance equation of the Constant Elasticity of Substitution (CES) function.[2] Previous pieces of literature used the form of virtual sales tax to simulate carbon pricing on enterprises (Jia and Lin, 2021). In such a strategy, policy cost will directly increase the producer price and change consumers' behavior[3] at the commodity level. However, such kind of setting strategies may be biased: it ignores enterprises' decision-making in the production process. Taking carbon tax as an example, enterprises usually calculate the unit cost of energy input as the sum of energy price and carbon price, rather than only considering energy price. The new model incorporates the policy cost into the fossil energy CES function to simulate the carbon cost increased by enterprises due to fossil energy input. By doing so, the changes in production preference and total output strategy under the carbon constraint of enterprises can also be simulated.
2) Provide a benchmark boundary for all counterfactual scenarios, making the comparative study more scientific. Most CGE papers set many policy details, then simulate and compare without a benchmark. Taking the comparison between carbon tax and carbon trading as an example, it may be concluded that the emission mitigation capacity and negative impact on the carbon tax's Gross Domestic Product (GDP) are less than that of carbon trading (Or vice versa) (Zhou et al., 2021). However, this conclusion is unreasonable, because the carbon tax rate and the carbon cap of carbon trading are usually given subjectively. Suppose the authors raise the carbon tax rate to make the emission reduction effect the same as that of carbon trading. In that case, they may come to different conclusions, such as, the emission trading may cause less GDP loss in the same emission mitigation effect. Based on such thoughts, this paper uses specific technical measures to make some sets of low-carbon policies endogenous and carbon emissions (or GDP) exogenous to simulate the impact of different policies in the condition that the effects on carbon emissions (or GDP) in these scenarios are the same. Doing this can ensure that the impact of each scenario can be compared under the same benchmark.
3) The accounting of carbon emission responsibilities is accurate in this paper. Some literature only considers the emission of primary fossil energy on the production side. The new model calculates the carbon emissions on the consumption side of each industry from the perspective of the actual energy consumption and regarding the carbon emission calculation rules of IPCC. To prevent double-counting, the new model deducts the carbon emissions in the products provided by energy processing enterprises. In addition, the new model re-calculates the energy consumption of energy processing enterprises through their products and the energy consumption of downstream enterprises. Finally, the paper obtains more objective energy consumption and carbon emission data.
4) The embodied carbon emission is coupled in the new model. The new model couples the embodied carbon emissions calculated by input-output technology into the equation system. The new model can get total embodied emissions from domestic production, total embodied emissions from domestic consumption, and net embodied emissions of trade balance in each period under different scenarios. The new model provides excellent convenience for carbon emission-related problems.
5) Richer model decomposition. The new model's enterprise production structure includes the primary energy and secondary energy in the input factors, not just limited to capital and labor. In addition, the model decomposes capital endowment into general capital and special capital. The former can transfer among industries with full liquidity, while the latter only serves specific industries, having no liquidity. Such decomposition is more convenient to simulate the social investment structure and production mode, as well as the characteristics of different capital.

Taking carbon tax and energy tax as examples, this paper analyzes the impact on energy, the environment, and the economy under carbon neutralization constraints (2018–2060). This paper introduces data processing, model structure, dynamic strategy, and different disposal strategies of the model. This paper shares the data and code for the reference of the modelers.

In the rest of the paper, how to compile the Social Accounting Matrix (SAM) and calculate additional information (such as energy consumption) are introduced in Section 2. Section 3 expresses the model framework, which consists of six blocks. Dynamic strategy is presented in Section 3.8. Different model variants for different needs are also introduced in Section 4. The brief introduction of the case study is provided in Section 5. How to run the model based on the given data and code is explained in Section 5.3. Results and discussion of the simulation are interpreted in Section 6. All the equations of the CEEEA 2.0 model are introduced in Appendix A.

2. SAM and energy data

2.1. The construction of SAM

Most of the data required by the Social Accounting Matrix (SAM) can be obtained through national input-output tables. The database of the new model is the 2018 input-output table of 153 sectors in China. According to the research needs, the model reclassifies these sectors into 21 departments (see Table B.1 in Appendix B for details). In addition, due to the lack of tariff data in China's input-output table, the tariff data was filled by consulting the data in customs administration and relevant China's CGE literature (Xie et al., 2019). Through the data of various types of income in rural and urban populations in the China Statistical Yearbook, the share of labor income and capital income is calculated. The share is brought into SAM to obtain different types of factor income of different groups. Based on the income, consumption, and population data in the China Statistical Yearbook, the total savings of urban and rural residents are calculated.

2.2. Energy balance data

The model requires the China energy statistical yearbook data to obtain the energy consumption in different industries and energy sources. Since there are only 47 industry classifications in the energy consumption data in the yearbook, which do not match the classification in China's input-output table and the SAM, the model needs to match the energy data to SAM. The match table between China energy statistical yearbook and the SAM is presented in Table B.2.

In addition, based on the actual output of coke and power (considering the loss in processing) in the yearbook, the coal consumption in the power and coking industries is deduced, which is unmatched by the public data. To more accurately simulate the technology of energy processing enterprises, the new model discards the coal consumption data of these two industries in the statistical yearbook. Instead, the study gets the coal consumption data by calculating public data, such as coal consumption and coking loss rate in the coking industry. Similarly, the coal consumption of thermal power enterprises is calculated through the

[2] Environment policy cost is simulated by virtual sales tax in some CGE models, coupled in domestic output bundle. For example, the cost is coupled into the model through the top level of CES nesting in production block, or embodied in CET function in trade block.

[3] Consumers here indicate all the buyers of the products, including households, enterprises, governments, and foreign activities.

power consumption, power generation structure, standard coal conversion coefficient, coal consumption per kilowatt-hour, and transmission and distribution loss in 2018. The calculated coal consumption of thermal power is 13% higher than that presented in the yearbook in 2018.

After matching industries and data, we need to fill the gap between the physical amount of energy input in the China energy statistical yearbook and the energy input value in the input-output table. In some cases, the input of industry *i* to energy *eni* is zero, but in the China energy statistical yearbook, the corresponding energy consumption data is not zero but a small value (or vice versa). Note that the energy input data in the energy yearbook is physical data, and energy input data in SAM or input-output table is monetary data. The model relates the physical quantity and value quantity through the method of a linear relationship (Fujimori et al., 2012). Therefore, the input of industry *i* to energy *eni* should be (or not be) 0 at the same time in both physical and value quantities. Thus, the study sets these data to 0 if the quantity is small. Or to set a corresponding value according to the share of relevant industries.

Because the model splits different power generation structures in the power industry, but China's input-output table does not separate the power industry, it is necessary to split the power data manually. Firstly, the output value of each power supply is divided according to the power generation rate. In addition, the input rate of raw coal, buildings, metal products, nonmetallic minerals, building materials, as well as factor inputs are split according to different power supply structures. Finally, we assume that the intermediate input between power sources is concentrated in their own power supply, which can be understood as that the auxiliary power all comes from themselves rather than from the power grid.

All energy data in this paper are converted into million tons of standard coal. Therefore, in the model, the consumption of these energy sources can be directly calculated linearly, and the carbon dioxide emission caused by energy consumption can also be calculated through the carbon dioxide emission coefficient of specific energy sources.

3. The model framework of the CEEEA/CGE 2.0 model

The new model is based on GAMS software using the MCP solver.[4] The model consists of six blocks: production block, income & expenditure block, trade block, energy-environment block, market-clearing & macroscopic closure block, and macro-indicator block. The first five blocks are the main body of the model, and the last one consists of lots of aggregate calculations for better analysis. Another, the model embodies model correctness check and dynamic approach.

The model classifies 21 sectors, two household groups, and a total of 3158 effective equations and variables (taking the BAU scenario as an example). The new model couples the calculation method of embodied carbon emissions based on Input-output Technology into the model (Lin and Sun, 2010). The model can easily simulate various policies to analyze the embodied carbon emissions embodied in production, consumption, and trade. The specific equation system can be found in Appendix A, and the meanings of all variables and equations can be found in the notes of the code.

3.1. Production block

In the production block, we consider the 7-tier nested production technology. Except that Leontief production technology is applied to the aggregated intermediate input, the other input parts are CES production technology. In addition to the conventional capital and labor, the new model carefully splits the whole energy input (Fig. 1). In addition to the primary energy (raw coal, crude oil, natural gas, and renewable energy), secondary energy (thermal power generation, refined oil, and refined gas) is also considered. In addition, the model distinguishes between energy processing enterprises and non-energy processing enterprises in substitution elasticity settings. The former has lower substitution elasticity on the input in its primary raw materials, which means energy processing enterprises cannot easily change the energy input structure.

Another, this paper assumes that intermediate input has a substitution relationship with factor input (using CES function), rather than a complementary relationship (using Leontief function), which is different from AIM/CGE2.0 model (Fujimori et al., 2012) and TERM model (Horridge and Wittwer, 2010). Generally speaking, factors can also replace intermediate inputs.

Referring to AIM/CGE model, the CEEEA2.0 model also considers Additional Energy Efficiency Improvement (ADEEI) to simulate the additional energy efficiency of enterprises in response to rising energy prices. For details, see Eqs. (A.4), (A.5), and (A.7) in Appendix A, or Fujimori et al. (2012). To better simulate enterprise behavior, the new model also assumes that the policy cost (PLC) caused by energy and environmental policies can change the tendency of enterprise production decision-making and the product's price (see Eq. (A.16) in Appendix A).

In addition, the policy cost caused by energy and environmental policy is also reflected in production technology, rather than in enterprise tax or factor input.[5] The advantage of this is that it can better simulate the production behavior of enterprises. If the policy cost is levied in the form of enterprise tax, the enterprise will only adjust the output; If it is levied from the perspective of energy cost, enterprises will not only adjust output but also adjust input preference in production. Due to the existence of policy costs, the cost of each unit of energy consumption includes both the energy price and the cost of energy and environmental policies to enterprises. This part of the cost should also be included in the production decision-making of enterprises.

What is more innovative about the new model is that the capital is divided into general-purpose capital and special capital, and the two kinds of capital are aggregated through CES production technology. The factor endowment of the former can flow freely among different industries, while the latter cannot. This can better simulate the factor flow and factor changes in different industries. This paper temporarily sets the initial rate of general capital and special capital in 2018 as 1:1 for analysis. If any research can break through and optimize this initial share, the new model will continuously optimize and update these data.

Generally speaking, there are two kinds of modeling methods for simulating the process of CES production technology. Taking the two factors into one products as an example, the first kind is to construct the production relationship through a CES production function, a product substitution function, and a value balance equation, which can be pre-

[4] MCP solver is the solver for solving Mixed Complementarity Problems. Compared with NLP (Non-linear Problem) solver, the MCP solver does not need the objective function and requires the number of free endogenous variables (endogenous variables without upper and lower bounds) to equal the number of and does not allow inequalities in the equations. These properties perfectly match the needs of CGE modeling, and modelers can reduce the probability of error and debug time in such a strict environment.

[5] These environmental policy costs are usually coupled in the model through indirect tax or as a commodity. In the first kind of coupling method, The production preference of enterprises is difficult to be simulated, because the production decision (first-order condition) of enterprises does not include policy cost, and the policy cost is only included in the final output of enterprises; that is, such setting methods may only effectively simulate the changes in commodity market. The second type of setting regard emission as a factor input in the CES production function. However, energy and carbon emissions are usually not substitutes, so the CES function is not very applicable. However, using the Leontief function can solve this problem.

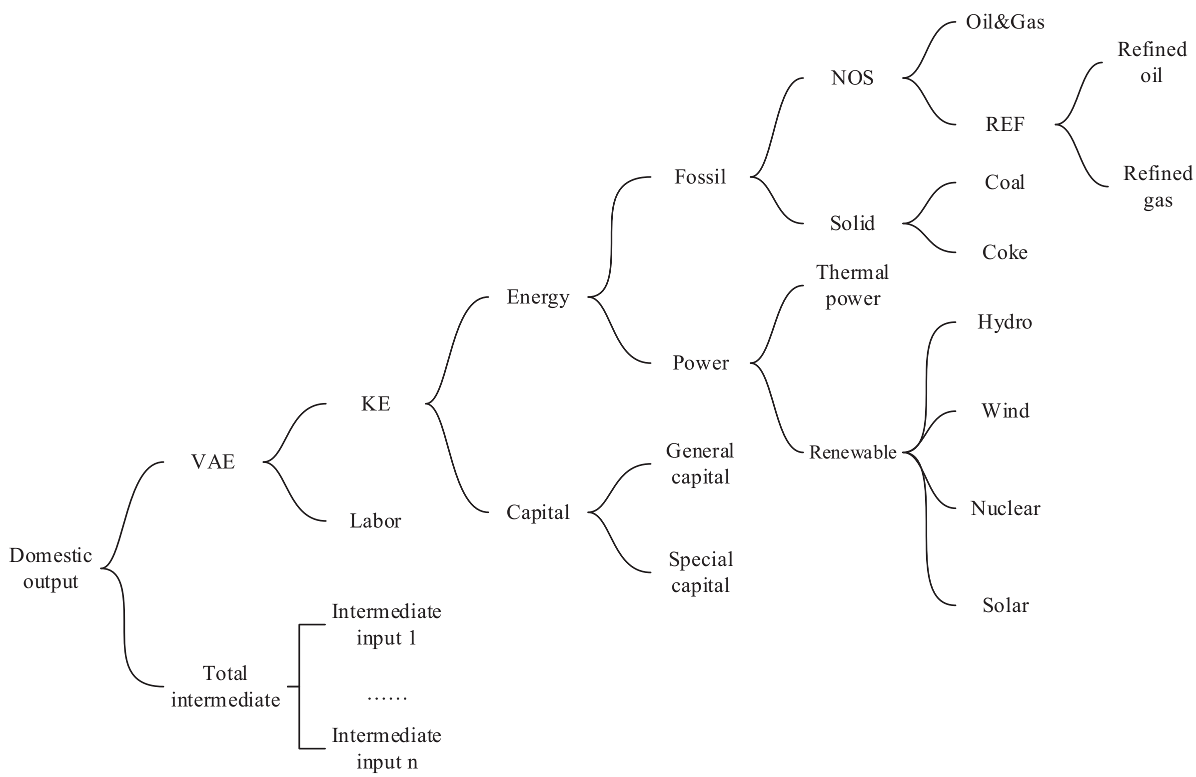

Fig. 1. Framework in production block.
Notes: The curve represents the input technology is simulated by the CES production function, and the broken line represents the input technology is simulated by the Leontief production function.

sented by:

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

$$\frac{p1_j}{p2_j} = \frac{\delta_j}{1-\delta_j}\left(\frac{X2_j}{X1_j}\right)^{1-\rho_j} \tag{2}$$

$$py_j Y_j = p1_j X1_j + p2_j X2_j \tag{3}$$

Where $X1_j$ and $X2_j$ are two input factors, and $p1_j$ and $p2_j$ are their prices. Y_j and py_j are the output and its price. α_j and δ_j are the scale parameter and share parameter in the CES function, and ρ_j is the elasticity parameter. Eq. (2) is derived from the quotient of two partial derivative equations ($\partial L_j/X1_j$ and $\partial L_j/X2_j$), after obtaining the partial derivative equation of the Lagrange equation. Eq. (3) is the value balance of input and output.

The second kind is to construct production relations through the CES production function and the demand functions of two inputs (the first-order condition of the CES function):

$$Y_j = \alpha_j\left[\delta_j X1_j^{\rho_j} + \left(1-\delta_j\right)X2_j^{\rho_j}\right]^{1/\rho_j} \tag{4}$$

$$X1_j = \left[\frac{\alpha_j^{\rho_j}\delta_j py_j}{p1_j}\right]^{1/\left(1-\rho_j\right)} Y_j \tag{5}$$

$$X2_j = \left[\frac{\alpha_j^{\rho_j}\left(1-\delta_j\right)py_j}{p2_j}\right]^{1/\left(1-\rho_j\right)} Y_j \tag{6}$$

The two modeling technologies are equivalent, and this model uses the first type of CES nesting technology in the production block, and uses the second type in the trade block.

3.2. Income and expenditure block

This block mainly describes the cash flow among residents, enterprises, government, and foreign countries. Residents obtain capital return and labor return by providing labor and capital. In addition, some residents receive transfer payments from the government. The money they receive is used for residents' consumption, savings, and direct tax payment. Enterprises earn income by selling products. The income obtained is used to pay labor remuneration, return on capital, enterprise tax, and the cost of energy and environmental policies. The government's revenue comes from direct taxes on residents, indirect taxes on enterprises, energy and environmental policies, and tariffs. Government revenue is ultimately used for government consumption and transfer payments. The income of the rest of the world comes from domestic imports, and foreign expenditure comes from domestic exports. The unbalanced part is the trade deficit.

The residents' demand function of the new model is based on Linear Expenditure System (LES) function. The primary purpose of using the LES function is to simulate the long-term Engel curve. The proportion of residents' food consumption will gradually decrease with the increase in income, and the share of spending on services and luxury goods will gradually increase. The Engel curve cannot be simulated in the demand function derived from CES or Cobb Douglas (CD) utility function. Therefore, to simulate the scenario in the long run (2018–2060), the new model uses the LES function as the demand function.

3.3. Trade block

The block describes the process of enterprise trade. Here we introduce the Armington hypothesis. Import, export, and domestic production for domestic consumption are connected through CES and Constant Elasticity of Transformation (CET) functions. In addition, the prices of import and export commodities are settled in foreign currencies, and the model considers domestic enterprise tax and tariffs in the trade process. Before distributing export goods and domestic consumer goods, domestic enterprises are levied enterprise tax (or indirect tax) by the government. Before Armington goods were formed, imported goods were taxed by the government. Therefore, the changes caused by these behaviors will be reflected in the first-order conditions of CES and CET functions (Eqs. (A.56), (A.59), and (A.60) of Appendix A).

3.4. Energy-environment block

The energy-environment block describes the relationship between the economic activities of enterprises, energy, CO_2 emissions, and the enterprise costs brought by energy and environmental policies. The new model connects the value quantity of enterprise energy input with the physical quantity through a linear relationship (Eqs. (A.61) and (A.62)). The block also describes the environmental and energy policy on enterprise cost (Eq. (A.68)), and this part of the cost will eventually be reflected in the enterprise's production decision and production cost (see the equation about PLC in the production block).

Compared with the general CGE model, the new model more finely describes the energy-related CO_2 emissions based on the power-responsibility relationship of CO_2 emission. For non-energy processing enterprises, carbon emissions can be obtained by summing up all kinds of fossil energy consumption (consider thermal power consumption) and multiplying it by carbon dioxide emission coefficients. It should be noted that the model should consider CO_2 emissions in power consumption. The new model assumes that the power consumption of all enterprises has the same share of power sources, except for power generations. Power generations only consume electricity from their own sources. Here, we assume that all power consumption of power generation enterprises comes from their own. Therefore, we can calculate the carbon emission in power consumption by the share of power consumption and coal consumption of thermal power generation (Eq. (A.63)). For energy processing enterprises, we need to subtract the carbon emissions from the secondary energy supplied by these enterprises to calculate carbon emissions. Therefore, the calculation rule is slightly different (Eq. (A.64)–(A.67)). If the readers need to change the model to the model of other countries, please pay attention to modifying the efficiency parameters of energy processing enterprises and CO_2 emission factors.

Note that the model only considers energy-related emissions, excluding respiration of animals and plants, and decomposition of microorganisms. The model also does not consider the process emissions of non-fossil energy, such as the carbon emissions of cement. The main reason is that we only focus on energy-related carbon emission changes caused by energy and environmental policies. In addition, we do not have data on cement consumption in various industries (although most of them are for construction), and buildings will absorb carbon dioxide during air drying, form carbon sinks, and absorb nearly half of the previous carbon emissions (Xi et al., 2016). Therefore, the carbon emission of cement in the whole life cycle is relatively complex, and it is not taken into account.

3.5. Market-clearing and macroscopic closure block

This block describes the market-clearing principle and the basic assumptions of macro closure. The new model takes Neoclassicism as the primary condition of macro closure. The new model assumes complete competition between the labor market and general capital market, and there is no unemployment and capital redundancy. In addition, Armington commodities are entirely consumed for household consumption, government consumption, investment, and intermediate input. This paper holds that the macro closure condition of Neoclassicism is more suitable for analyzing the long-term model, because, in the long run, the problem of unemployment is stable. The neoclassical hypothesis is more appropriate than Keynes's hypothesis.

3.6. Macro-indicator block

The calculation equations of various macro indicators are added to the new model to analyze better the model results, especially several equations used to calculate the embodied carbon emissions (Eq. (A.76)–(A.89)) in Appendix A). In addition, the new model calculates the producer price index (PPI), consumer price index (CPI), the share of renewable energy, the share of power consumption, total power consumption, total energy consumption, and total carbon emission.

3.6.1. Embodied carbon emissions

According to the calculation rules of embodied carbon emissions in different literature (Ahmad and Wyckoff, 2003; Lin and Sun, 2010; Wiebe and Yamano, 2016), the new model considers calculating embodied carbon emissions through input-output technology. Together with the energy balance account, such technology can easily calculate the direct and indirect CO_2 emissions and embodied carbon emissions (Meng et al., 2018). It seems it is the first time coupling embodied carbon emissions to the CGE model, compared with the well-known model, such as the GTAP model, CoPs model, and AIM/CGE model. Carbon emissions can be divided into four parts according to the production place and consuming place (Table 1). The embodied carbon emission of domestic production for domestic consumption is the first part (I); the embodied carbon emissions from domestic production to external consumption are the second part (II); the embodied carbon emissions from foreign production to domestic consumption are the third part (III); the embodied carbon emissions of foreign production to foreign consumption are the fourth part (IV).

Through this strategy, the model can define different embodied carbon emissions: embodied emissions from domestic production (EEP, I + II); embodied emissions from domestic consumption (EEC, I + III); embodied emissions within export products (EEE, II + IV); embodied emissions within imports (EEI, III + IV). Finally, we can define the net embodied carbon emissions in the trade balance (EEB) as EEP-EEC. The specific calculation process is complex and involves multi-step matrix operation, and the details and proofs can be referred to (Lin and Sun, 2010). Based on the idea of "Leontief inverse", the new model uses input-output technology to couple the embodied carbon emissions into the model and calculate the above indicators. However, there is no carbon content information about imports, so, following the literature on input-output analysis (Lin and Sun, 2010), we use domestic production technology to simulate the carbon emission of imported products.

Input-output analysis is the equivalent calculation in the form of matrix. However, its essence is still numerical calculation. Therefore, we coupled the matrix calculation into the numerical calculation equations of the CGE model, so that each time the model gets the optimal solution, it can obtain the embodied carbon emission under the current scenario in the specific year. Generally speaking, almost all input-output analysis techniques can be coupled into the CGE model. The coupling method is available in the code.

Note that the calculation in the input-output analysis is based on the value. When we need to couple the input-output technology into the CGE model, the final demand, intermediate input, import and export, and other data need the use the value instead of the quantity. Otherwise, the calculation will get an abnormal value.

Table 1
Four categories of embodied emissions.

		Consumption	
		Domestic	External
Production	Domestic	I	II
	External	III	IV

3.6.2. Social welfare

The new model calculates the change in social welfare in two ways: Equivalent Variation (EV) and Compensate Variation (CV). The former is similar to the Hicksian value (Sugawara and Nikaido, 2014), and adopts the idea of the Laspeyre index to construct the utility changes using the base period's price. Generally speaking, it measures the change of residents' welfare/utility under the policy impact on monetary units. The latter, the CV, is based on the current price. Its economic meaning is how much residents' income can be reduced/increased to return to the original utility level.

Fig. 2 shows the meaning of EV intuitively. Suppose that the price vector in the BAU scenario is **P**0, and the income of the residents is YH0, so the budget line is (**P**0, YH0). In such conditions, the equilibrium consumption vector of the residents is **XP**0, and the indifference curve is IC0. When the policy changes (in this paper, it is the ETS construction), the new budget line is (**P**1, YH1), determined by residents' income YH1 and commodity price **P**1. The new indifference curve is IC1, and the equilibrium consumption vector is **XP**1. We assume that under the condition of constant price (P0), if we want to meet the utility of IC1, the revenue needs to be increased to YHEV1 from YH0 in the BAU scenario. Then, the budget line is (**P**0, YHEV1), and the budget line intersects the IC1 at **XPEV**1. Then, we can measure the gap between XPEV1 and YH0 to measure the change in residents' welfare under the impact of carbon trading. The mathematical expression is as follows:

$$EV = e(\boldsymbol{P}0, u(\boldsymbol{XP}1)) - e(\boldsymbol{P}0, u(\boldsymbol{XP}0)) \tag{7}$$

Where $e(\boldsymbol{P}0, u)$ is the expenditure function and $u(\boldsymbol{XP}1)$ is the utility at the consumption vector $\boldsymbol{XP}1$. This paper's CEEEA2.0 model applies linear expenditure system as utility function rather than CD function.

For CV, the analysis is similar. See Fig. 3 for its graphical interpretation, and the formula is as follows:

$$CV = e(\boldsymbol{P}1, u(\boldsymbol{XP}1)) - e(\boldsymbol{P}1, u(\boldsymbol{XP}0)) \tag{8}$$

Generally, the estimated value of EV is higher, and the estimated value of CV is lower, but the real social welfare change should be between the two. It should be noted that the EV or CV measured in this paper is actually the money needed to meet the current utility level. In essence, it is also a negative indicator (the less money you spend, the better utility you get). Therefore, the relationship between EV and CV is similar to that between CPI and GDP deflator.

In addition, we can also make a simple understanding through the equations. Due to the substitution effect of consumers, given a certain price level, the expenditure level is the lowest when the utility is

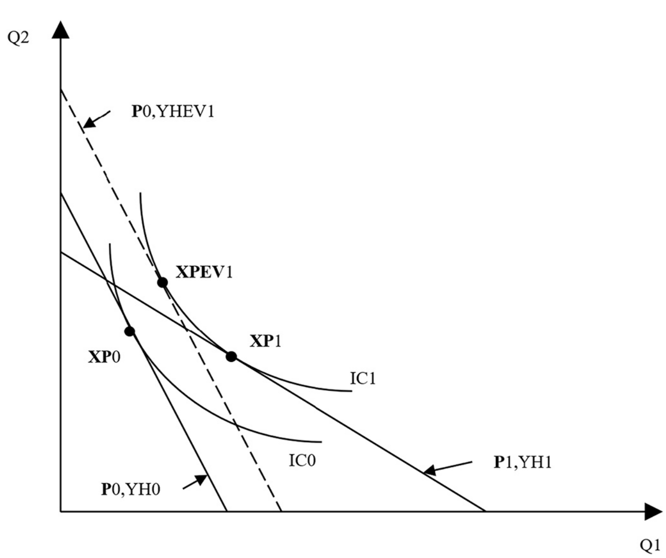

Fig. 2. Using equivalent variation to measure social welfare change.

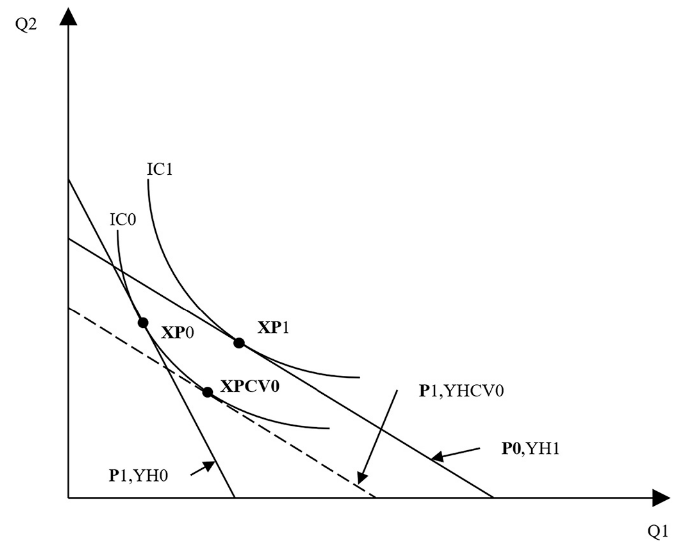

Fig. 3. Using compensate variation for measuring social welfare change.

maximized. So, $e(\boldsymbol{P}0, u(\boldsymbol{XP}0))$ is lower than $e(\boldsymbol{P}1, u(\boldsymbol{XP}0))$, while $e(\boldsymbol{P}0, u(\boldsymbol{XP}1))$ is higher than $e(\boldsymbol{P}1, u(\boldsymbol{XP}1))$, leading EV is higher than CV.

Taking the case study of this paper as an example, we estimate the welfare loss of urban residents by EV method as 1.69%, while the loss estimated by the CV method is 1.72%. Therefore, the real welfare loss should be between 1.69%–1.72%.

3.6.3. Other macro indicators

GDP. The model also calculates real GDP through the expenditure method for analysis, not nominal GDP. The advantage of using real GDP is that it can more effectively measure the level of economic development. However, in the long-term model, the relative price change is significant, and there may be some disputes about whether the real GDP is applicable.

PPI and CPI. We refer to the conventional PPI and CPI to analyze the price changes in the counterfactual scenario relative to the benchmark scenario:

$$PPI_j = \frac{p_j^z}{p_j^{zBAU}} \times 100 \tag{9}$$

$$CPI_j = \frac{\sum_j p_j^q \frac{\sum_l X_{j,l}^{pBAU}}{\sum_{j,l} X_{j,l}^{pBAU}}}{\sum_j p_j^{qBAU} \frac{\sum_l X_{j,l}^{pBAU}}{\sum_{j,l} X_{j,l}^{pBAU}}} \times 100 \tag{10}$$

Where p_j^z is the producers' price (without tax) in the counterfactual scenarios, while p_j^{zBAU} denotes the price in the benchmark scenario. $\sum_l X_{j,l}^{pBAU} / \sum_{j,l} X_{j,l}^{pBAU}$ expresses the residents' consumption basket under the benchmark scenario. p_j^q and p_j^{qBAU} are the commodity prices (Armington price) in the counterfactual and benchmark scenarios, respectively.

The energy and environment-related macro index. To make the model's results easy to understand, we calculate the share of renewable energy, the share of power consumption, total power consumption, total energy consumption, and carbon emission in every scenario and period.

Another, the S-G utility function and LES function are applied to express the behavior of households. To simulate the change of Engel's coefficient, the new model adopts the LES demand function. The LES inclusion function is derived from the Stone-Geary (S-G) utility function. Therefore, in the utility function of residents, we use the Stone-Geary utility function (Eq. (A.99) of Appendix A).

3.7. Model correctness test

In this paper, Walras dummy variables are set for the product market to balance the number of variables and equations and test whether the model is set correctly. If the model setting is correct, the value of the Walras dummy variable should be 0 or the minimum value (Walras and Walras2 in Eqs. (A.71) and (A.73) of Appendix A). The BAU scenario and other counterfactual scenarios of this model have passed the test of Walras dummy variable.

In addition, the paper also verifies the correctness of the new model through different GDP accounting methods. We calculate nominal GDP by income method (return on labor + return on capital + government income)[6] and expenditure method (government consumption + resident consumption + investment + net export) respectively, and then let one subtract another (Eq. (A.98) of Appendix A). Theoretically, the value obtained must also be 0 or minimum in each scenario. The scenarios of this model have also passed the test of accounting GDP, which further proves the correctness of the model.

3.8. Dynamic strategy

The dynamic strategy used in the new model is complex: firstly, through the exogenous assumed growth rate of GDP, carbon emission, and power consumption, the dynamic parameters in technology changes are calibrated: the annual change of TFP (*c_TFP* in Eq. (A.1)), the change of AEEI (*c_AEEI* in Eq. (A.14)) and the change of power efficiency (*c_ELE* in Eq. (A.14)) are obtained.[7] Then these dynamic parameters are brought into the formal scenario system model, and the data in each scenario are dynamically solved by recursive means.

Precisely, to simulate the changes in technology, we constructed a scenario to simulate the changes of these dynamic parameters. In this scenario, GDP, carbon emissions, and electricity consumption are exogenous variables, while *c_TFP*, *c_AEEI*, and *c_ELE* are endogenous variables. After these dynamic parameters are calibrated, the model deploys the values of these parameters into the formal scenario analysis. In the formal scenario, GDP, carbon emissions, and electricity consumption are endogenous variables, while *c_TFP*, *c_AEEI*, and *c_ELE* are exogenous variables for simulating the technological progress of each period.

In short, the new model uses prior macro data to calibrate the dynamic parameters of the model, and finally recursively applies these parameters for the simulation. The advantage of such a strategy is that it can better control the exogenous variables to avoid unreasonable simulation results in the BAU scenario. Doing so can make the model have substantial flexibility. We can apply different macro backgrounds according to different background assumptions and then carry out scenario analysis.

In addition, because the model is based on the macro closure of Neoclassicism, the change of factor endowment is also the main driving force of economic growth. Like most CGE models, in addition to the technological progress introduced above, this paper also considers the changes in the labor force (by assumed population growth) and fixed assets (by perpetual inventory method).

4. Different options/variants

4.1. S-G, CES, C—D, or CDE in utility function?

The utility function used in the new model is the S-G function,which is similar to ORANI-G model (Horridge and Wittwer, 2010),[8] rather than the very popular C—D function, which is used by the AIM/CGE model (Fujimori et al., 2012).The main reason is that the simulation target period of the model is too long (2018–2060), so the model cannot ignore the influence of Engel's coefficient. Taking the S-G function as utility function and LES function as demand function can reasonably simulate the influence of Engel coefficient, but there are also some defects:

1) The function assumes that all goods should be standard goods, not inferior goods.
2) The price elasticity of all goods is less than 1.
3) The relationships between goods are complements, not substitutes.

Suppose the demand function derived from the C—D utility function is adopted. In that case, the consumption share of various commodities remains unchanged (the characteristics of the C—D function), which cannot simulate the change in consumption tendency caused by residents' income growth. However, it can solve the third defect of the LES function.

Suppose the demand function derived from the CES utility function (or Hicksian demand function) is adopted. In that case, the consumption share of each commodity is variable, which can also solve the third defect of the LES function. However, it can still not simulate the change in consumption tendency caused by residents' income growth. The same is true for the Translog function. Therefore, there is a trade-off in the choice of the utility function and its demand function. This paper suggests that the CES function or C—D function can be selected when the simulation period is relatively short or it is necessary to pay attention to the substitution relationship of consumer goods. If the simulation period is long and it is not essential to consider the substitution relationship of consumer goods, the S-G utility function and LES function can be selected.

Of course, like the GTAP standard model (Corong et al., 2017), we can also adopt the constant differences of elasticities (CDE) system. The advantage of such a setting is that there is a room to set the estimated income elasticity and price elasticity of product consumption, so that the income elasticity and price elasticity in the existing literature can be used for calibration, which is more in line with the actual situation. However, it is a very difficult project to estimate the income and price elasticity of different household group plus various commodities. However, we still believe that if we have enough data base in the future, we can convert the utility function into more flexible CDE functions.

4.2. Keynes or neoclassical?

For the macro closure of the CGE factor market, the most popular is the macro closure based on Neoclassicism. This kind of closure characteristic is that all prices are completely elastic and endogenously determined by the model. There is full employment in the factor market, and the model needs to give the factor endowment (exogenous) to determine the supply of each factor. In short, factor prices are endogenous, and factor endowments are exogenous, and there is no

[6] Because the model does not consider the profit of the enterprise, the enterprise surplus is 0. Therefore, the GDP calculated by the income method only needs to consider the income of residents and the government.

[7] Strictly speaking, the value of calibrated *c_TFP*, *c_AEEI* and *c_ELE* does not fully represent the corresponding efficiency change. Only their overall change process can represent their efficiency change. Suppose that the last two values are 0, C_ TFP can represent the change of total factor productivity considering energy input, because *c_TFP* at this time indicates that the total output can increase *c_TFP* units for each corresponding unit of capital, energy and labor inputs. However, If the values of the latter two are not 0, when calculating the actual TFP change, it is necessary to consider the TFP changes caused by the change of these two kinds of efficiency changes.

[8] The description of the model could be found at: https://www.copsmodels.com/ftp/gpextra/oranig06doc.pdf. In household utility function (page 28 in the PDF file), the commodity composites are aggregated by a Klein-Rubin, leading to the linear expenditure system (LES). Here the Klein-Rubin function is the same as the S-G function in this study.

unemployment. According to Keynesian theory, in the case of macroeconomic depression, a large number of labor forces are unemployed, and capital is idle. Therefore, what restricts economic development is not resource endowment, but unemployment and idleness. In that case, factor employment is endogenous and determined by factor demand, while the prices of labor and commodities are rigid. Under the condition of Keynes' macro closure, the price of factors is exogenous, and the total demand of factors is endogenous without the restriction of the endowment.

Generally speaking, the paper suggests that when considering long-term simulation, we can consider using the macro closure of Neoclassicism because it is difficult to set a reasonable curve of the long-term unemployment rate, and it is also difficult to set a reasonable factor and labor return curve. The direct assumption of full employment is also relatively objective. When simulating the short-term impact (or studying the impact of Finance on employment), Keynesian macro closure can (must) be used.

4.3. Elasticity adjusting

The elastic setting of the CES function is not determined by the model itself, but externally given by the modeler. Therefore, there always has been great criticism on the elasticity settings. Fortunately, elasticity mainly affects the prediction ability of the CGE model, not the ability of scenario analysis. Therefore, in the scenario analysis, the change conclusions are generally robust. The elasticity set in this paper refers to the elasticity set in AIM/CGE2.0 and Lou (2015). In addition, these elasticities can be adjusted under certain circumstances. The principles are as follows: if the model is set up in developing countries and the economic structure changes rapidly, the substitution elasticity can be appropriately increased; if the simulation period of the model is long, the substitution elasticity can also be increased appropriately; for energy processing enterprises or enterprises whose technology is challenging to change, the CES function of specific production technology should be transformed (CES becomes Leontief production function), or the substitution elasticity should be reduced.

5. Case study

5.1. The comparison between energy resource tax and carbon tax

Many papers have studied the carbon tax's impact and mechanism because the carbon tax is an excellent means of carbon emission reduction (Beck et al., 2016; Cao et al., 2021; Chen and Hafstead, 2019; Ntombela et al., 2019). The carbon tax directly affects energy users, increases their energy use costs, and then changes their production and consumption behavior (Liu and Lu, 2015). However, another means of carbon emission mitigation may be ignored: the energy resource tax (hereinafter energy tax) (Jia et al., 2022; Jia and Lin, 2021). Energy tax can increase the price of energy and then increase the price of the downstream products. The increased price of all products can be understood as an "embodied carbon tax", but it is often ignored because the design goal of energy tax is not emission reduction (Lin and Jia, 2020).

Thus, this paper wants to compare the differences between the carbon tax and the energy tax. To make a better benchmark for comparison, the paper simulates the carbon tax scenario and energy tax scenario under the same emission mitigation level. Expressly, this paper assumes that the government has a common emission mitigation target under different scenarios. However, the government implements it in different ways, one through a carbon tax and the other through an energy tax. This assumption can make the paper have a better basis for comparing different emission reduction methods.

5.2. Scenario assumption

The study set up three scenarios: Business as Usual (BAU), carbon tax under carbon constraints (CT), and energy tax under carbon constraints (ET). In the BAU scenario, the model assumes that there is no carbon constraint, and that renewable energy has a natural substitution process for fossil energy. In such a scenario, it is assumed that the carbon peak will be reached around 2036, and then the carbon emission will decline slowly, and the carbon emission will be 8.49 trillion tons in 2060. In the CT scenario, the paper assumes that China will levy a carbon emission tax on fossil energy in 2021 and beyond. In the ET scenario, an ad valorem energy tax is imposed on all energy users from 2021 to 2060. In the counterfactual (CF) scenarios,[9] the carbon peak will be reached in 2028, and carbon emissions will decline rapidly from 2035 to 2050. By 2060, China's energy-related CO_2 emissions will be 1.81 billion tons, and the remaining carbon emissions can be neutralized by negative carbon emission technologies and carbon sink projects.[10] See Fig. 4 for the specific carbon emission path.

In the case study given by this paper, the new model sets the carbon emissions in all counterfactual scenarios as exogenous variables and sets the carbon tax rate and energy tax rate as endogenous variables. Most CGE models set a set of given/exogenous tax rates and leave carbon emissions endogenous. The implicit assumptions of the two methods are different: the former assumes that the government will actively regulate the carbon tax rate to ensure that carbon emissions can reach the given emission reduction target; the latter assumes that the government stipulates the carbon tax rate and has no target for carbon emissions. Two different hypotheses aim at different research objectives. The former can study the different effects of different low carbon strategies under the same emission reduction effect; the latter can study the impact of different strategies on various macro indicators. Generally speaking, the former is more scientific and objective when comparing different carbon pricing strategies. Because all policies have achieved the same emission reduction effect, and there is a benchmark for comparison. The case provided in this paper is to study the impact of different energy and environmental strategies. Therefore, the latter framework commonly used in most CGE models is not adopted, but the scenario assumption of the former is innovatively adopted.

5.3. How to run the model

The examples provided in this paper include two Excel files and four GMS files: 2018SAM(fnlbalanced).xlsx, Growth_Path.xlsx, DynamicParameter.gms, BAU.gms, CT.gms, and ET.gms. The first two files are the SAM (after balancing) compiled in 2018 and the exogenous given GDP, carbon emission, and power consumption data in 2018–2060. The DynamicParameter.gms file is used to calibrate *c_TFP*, *c_AEEI* and *c_ELE* based on the growth path. The equilibrium solutions of various variables obtained in DynamicParameter.gms and BAU.gms files are consistent. The only difference is that the settings of endogenous variables and exogenous variables are different. The latter sets *c_TFP*, *c_AEEI* and *c_ELE* as exogenous variables, and sets GDP, carbon emission, and power consumption as endogenous variables; The setting of the former is the opposite. The last three files are the three scenarios simulated in the case study. Therefore, the order of model operation is to calibrate dynamic parameters (DynamicParameter.gms), simulate benchmark scenario (BAU.gms), and simulate all counterfactual scenarios (CT.gms and ET.gms).

[9] We usually refer to scenarios other than the benchmark scenario as counterfactual scenarios. In this paper, counterfactual scenarios include the CT scenario and the ET scenario.

[10] This paper does not introduce negative carbon emission technology into the model. One is to avoid more model assumptions, and the other is the lack of actual input-output relationship of CCUS-related technologies and enterprises. To avoid questioning the objectivity of the model in such areas, the paper does not consider incorporating negative emission technologies such as CCUS into the macro model.

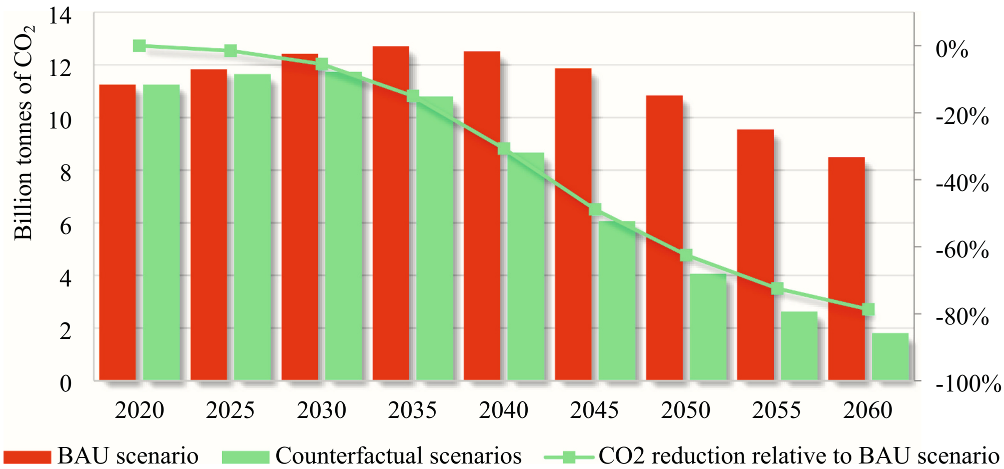

Fig. 4. CO_2 emissions during 2020–2060. Note: Emissions measured here are energy-related CO_2 emissions. The red and green bars represent the CO_2 emissions of the BAU and CF scenarios in the specific year. The green line denotes the reduction rate in CO_2 emissions in the CF scenarios compared with emissions in the BAU scenario in the specific year. The ordinate on the left measures total CO_2 emissions, and the ordinate on the right measures emission changes relative to the BAU scenario.

6. Model result interpretation

After introducing the basic assumptions, main research objectives, and innovations of the model, this paper interprets the model's results by taking the carbon/energy tax policy under carbon constraints as an example. However, we need to confirm the correctness of the modeling

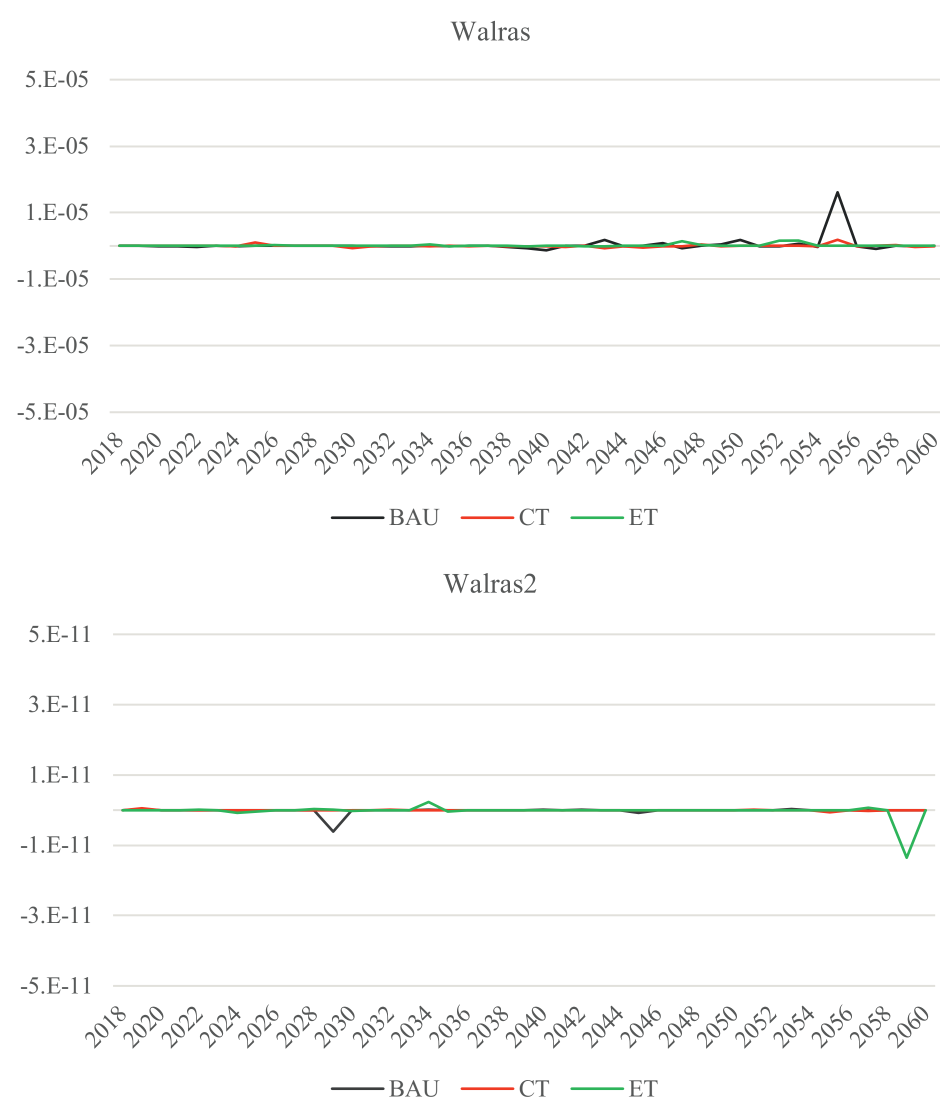

Fig. 5. Values of Walras dummy variables during 2018–2060.

before interpreting the economic significance of the model results.

6.1. Modeling check

Usually, if there are errors in the commodity or value flow in the model setting, The Walras dummy variable will deviate significantly from 0. Therefore, before analyzing the model, we first need to consider whether errors are embodied in the setting of the model. We need to pay attention to the value of the Walras dummy variable in each period of all scenarios (Fig. 5). The results show that the value of Walras basically fluctuates under 0.00001, and Walras2 directly approximates the computational limit of the GAMS program (one per trillion).

In addition, the model calculates the annual nominal GDP of each scenario through the expenditure method and income method and finds the differences (Fig. 6). If the model is set correctly, usually, the value is also a number close to 0. The results show that the difference (GDPCHK) fluctuates under 0.00001, which is very close to 0, confirming the correctness of the model itself.

6.2. Results interpretation

6.2.1. Carbon tax rate

Under the increasing carbon constraints pressure, China's carbon/energy tax rate will also be increased (Fig. 7). In 2030, the carbon tax rate will be 18 CNY/ton, while in 2060, the carbon tax rate will increase to 822 CNY/ton. The rising carbon tax also has a significant impact on China's emission reduction (Fig. 4). In 2030, without carbon constraints, China's carbon emissions will be 12.4 billion tons; however, the carbon tax will reduce China's carbon emissions to 11.7 billion tons. In 2060, the carbon emission of the BAU scenario is 85.0 billion tons, while in counterfactual scenarios, the carbon emission is 18.1 billion tons, reducing the annual carbon emission by 78.7%. Thus, the carbon tax of 822 CNY/ton still has an excellent emission reduction effect. If an ad valorem tax is levied on primary fossil energy (the energy tax), the same emission mitigation effect can be achieved when the tax rate is 82.8% in 2060.

6.2.2. Real GDP

Although the carbon/energy tax policy can significantly reduce carbon emissions, it may also have a negative impact on the economy. Moreover, with the passage of time, such negative impact may gradually increase. As the result shows (Fig. 8), in the BAU scenario in 2060, China's real GDP is 607 trillion CNY; in the CT scenario, China's real GDP in 2060 was 594 trillion CNY, indicating a decrease of about 2.12%; and in the ET scenario, the real GDP was 595 trillion CNY, denoting a decrease of about 1.88%. In the BAU scenario, the average GDP growth rate from 2020 to 2060 is 4.495%; this figure is 4.440% in the CT scenario and 4.444% in the et scenario. Therefore, over a long period (2020–2060), the carbon tax policy will reduce GDP growth by about 0.056%, while the energy tax policy will reduce GDP growth by about 0.052%. Overall, the impact of these low-carbon policies is low in the early stage but high in the later stage, which is in line with CO_2 emission reduction effects.

6.2.3. Embodied CO_2 emissions in trade

China has a positive value on embodied CO_2 emissions in trade, and about 977 million tons of CO_2 emissions were exported to other countries in 2018 (Fig. 9). However, due to the continuing revolution in consumption and production, embodied emissions in trade will gradually reduce and become negative in the 2040 BAU scenario.[11] Note that Embodied emissions are calculated based on China's technologies and production strategies in every reported year. So, under the pressure of carbon constraint, the export embodied emissions will reduce faster in the CF scenarios than in the BAU scenario. Another, because of the lower carbon intensity in sectors in the CF scenarios, embodied emission production and embodied emission consumption calculated will both be lower, resulting in a lower embodied emission balance in about the year 2044–2060.

6.2.4. Primary energy structure

Carbon and energy tax policies have significantly increased the share of renewable energy in the energy structure (Fig. 10). Without carbon constraints, the substitution of renewable energy for fossil energy is a slow process. By 2060, China's renewable energy accounted for only 27.5%, and coal still accounted for nearly half of the primary energy input. In the carbon constraint scenario considering a carbon tax, renewable energy will increase to 56.6%, and coal will decrease to 17.2% in 2060. The carbon constraint scenario considering energy tax has a more positive impact on the adjustment of energy structure: the share of renewable energy has increased to 67.5%, and the proportion of coal has decreased to 7.58%. The improvement of energy structure brought about by carbon tax and energy tax policies also helps China carry out carbon emission reduction smoothly.

6.2.5. Producer price index and Armington price

Based on the ex-factory price (excluding tax) of domestic goods under the BAU scenario, we calculated the producer price index (PPI) of each industry every year (Fig. 11). The results show that the prices of most commodities have increased to a certain extent, but the producer prices of coal, coking, oil, and gas exploitation industries will decrease in the CT scenario. The main reason is that the carbon tax reduces the demand for these energy products by increasing the cost of energy use, and then reduces the producers' price. In other industries, due to the increase in energy use cost, its cost and price have triggered a series of chain reactions, resulting in the increase of the price of its products. Among them, the most affected are energy-intensive enterprises such as thermal power enterprises and iron and steel enterprises. In 2060, PPI increased by 8.74% and 6.80% compared with the BAU scenario.

The impact of energy tax is similar, but the impact of the energy tax on price is more concentrated in energy processing enterprises (PPI increase), energy-intensive enterprises (PPI increase), and energy production enterprises (PPI decrease). The impact of the energy tax on the price of products except energy-related products is low, mainly because the price of products in these industries has a low embodied cost of energy-related products. Such as services, the main cost of these sectors may be labor input.

6.2.6. Consumer price index

Compared with PPI, the consumer price index (CPI) change is relatively mild (Fig. 12). Under the carbon constraint scenario with a carbon tax, the CPI in 2060 increased by only 1.92% compared with the BAU scenario. The main reason is that the leading consumer goods of consumers are not energy commodities, but mainly services. The service industry is less affected by carbon constraints, and its PPI increased by

[11] We considered the various technological progress rate for different enterprises. We assume the technological progress rate of low-carbon sectors is greater than that of high-carbon sectors. Therefore, the comparative advantage of the former gradually increases, leading to the share of exports increasing and the proportion of imports decreasing; On the contrary, the comparative advantage of the latter gradually decreases, leading to the percentage of exports decreasing and the ratio of imports increasing.

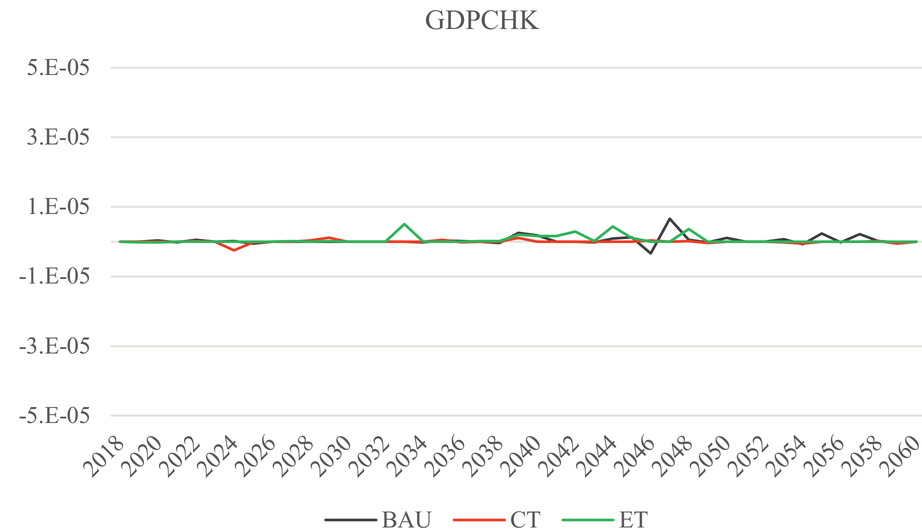

Fig. 6. Value of GDPCHK during 2018–2060.

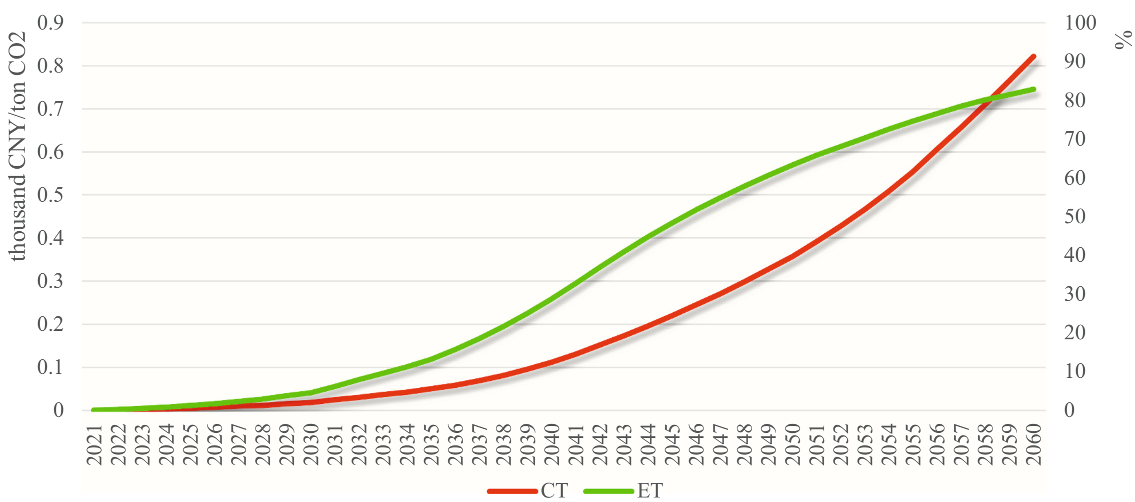

Fig. 7. Carbon tax rate during 2021–2060.
Notes: the left ordinate measures the carbon tax rate, and the right ordinate measures the energy tax rate. This paper assumes that the carbon/energy tax will be levied from 2021, so the reported carbon tax rate and energy tax rate start from 2021. The carbon tax rate and the energy tax rate are endogenous variables, while the total carbon emission is exogenous. Therefore, there is a hypothesis in the model: the government can ensure the emission mitigation of the whole society by adjusting the endogenous tax rate. Of course, we can set endogenous and exogenous variables in turn and get a new solved solution. Eventually, we will find two kinds of solved values that are precisely the same. If we set the path of the carbon/energy tax rate as an exogenous variable and the carbon emission as an endogenous variable, the economic meaning and the model interpretation becomes: what impact can the government have through such path of carbon/energy tax rate. Although the results are the same, the former embodies the meaning of carbon constraint.

only 1.78% (Fig. 11).

The CPI increase in the ET scenario is lower than in the CT scenario, mainly because the energy tax has less impact on the prices of commodities mainly consumed by consumers (Fig. 11). The price of services is also lower than that in the CT scenario. Overall, PPI only increases by 1.78% with the energy tax scenario for carbon constraint. It seems that the living standards of consumers in China will not change significantly due to carbon constraints in both carbon constraint scenarios.

7. Conclusion

This paper constructs a CEEEA2.0 model. The model is a dynamic recursive computable general equilibrium model considering energy, environment, and economy. The model (taking the CT scenario as an example, data are displayed in GAMS) has 109 groups of equations, 3158 endogenous variables, 60,734 non-zero elements, and a code length is 95844 characters. This paper shares the data and code of the whole model for the reference of readers and modelers. The new model has a detailed energy decomposition structure, a more objective coupling mode of energy-environment policy cost, and a consideration of embodied carbon emission. At the same time, it has flexible operability, can adapt to various research, and can also adjust the model according to the research needs. For example, we could adjust the model to become a multi-region model.

By interpreting the preliminary results of the model, we believe that the model's output results basically meet the expectations. For carbon tax, the primary mechanism is the carbon tax rate. Therefore, energy-intensive enterprises are under more significant cost pressure. For the energy tax, the primary mechanism is the product price in the commodity market. Therefore, its response is more concentrated in the industry and related industries and has little impact on the prices of other industries. On the whole, under the same emission reduction conditions,

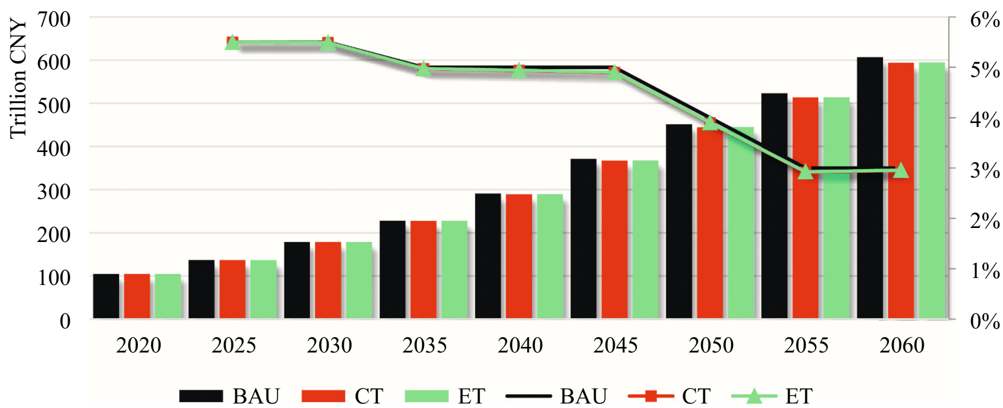

Fig. 8. Real GDP during 2020–2060.
Note: The GDP in the figure is real GDP at the 2018 price level. The black, red, and green bars represent the real GDP of the BAU scenario, CT scenario, and ET scenario in the specific year, respectively. The black, red, and green lines denote the average annual GDP growth of the three scenarios every five years. The ordinate on the left measures the total GDP; the ordinate on the right measures GDP growth.

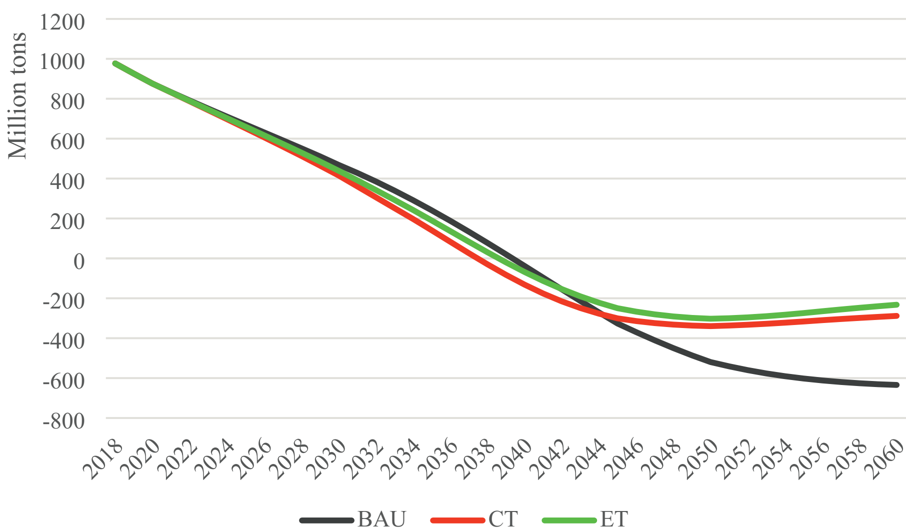

Fig. 9. Net embodied carbon emissions in trade.
Notes: This figure shows the embodied carbon emissions in international trade, that is, the CO_2 emissions produced domestically minus CO_2 emissions consumed domestically. If the embodied carbon emissions are positive, the emissions produced in the country are greater than those consumed in the country, indicating that some of the emissions are exported to foreign countries.

the impact of the energy tax on the entire economy is slightly better than that of the carbon tax on the economy.

The model still has some defects. For example, the model is still a single region model and follows the small country hypothesis. Therefore, it has no advantage to analyze the problems in international trade. It is suggested to use the GTAP model. In addition, the model does not consider the energy utilization rate of the same variety in different industries. However, the energy quality required by various sectors may differ, and the carbon emission factors may not be the same, but such simulation is not embodied in the model. If other scholars are interested in this, you are welcome to put forward opinions and help at any time. As the model system is too complex, there may be mistakes in model setting and interpretation. The authors will continue to update the model system for reference on the personal homepage on Github.[12]

Conflict of interests statement

The paper has no conflict of interest.

Financial disclosure statement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.106117.

[12] https://zhijie-jia.github.io/ or https://github.com/Zhijie-Jia/CEEEA2.0-CGE.git

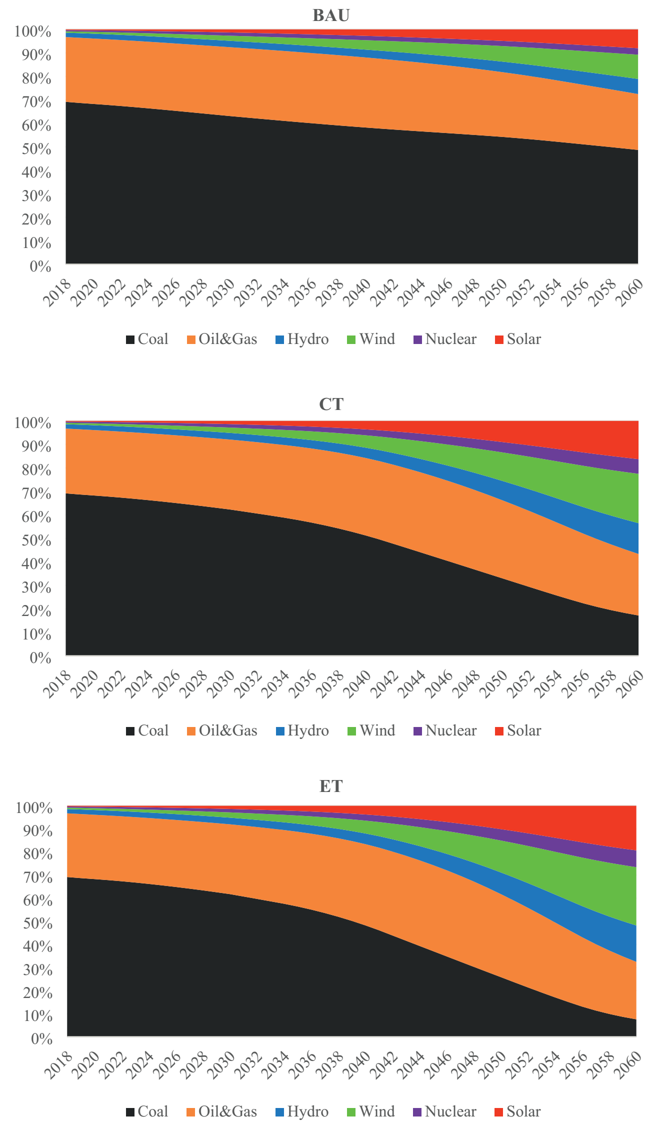

Fig. 10. Energy structure during 2018–2060.
Note: The paper considers using all primary energy to measure the energy structure, ignoring the energy conversion process. The first figure shows the natural change of energy structure in the BAU scenario from 2018 to 2060; the second figure shows the changes in the energy structure affected by a carbon tax in 2018–2060 under the CT scenario. Since we do not consider potential and revolutionary technological progress, the estimation may be relatively conservative in the model.

Appendix A. Equation system (CT scenario)

A.1. Production block

$$VAE_j = \alpha_j^{vae}\left(1 + c\_TFP \times SpecificTFP_j\right)\left[\delta_j^{vae} F_{"lab",j}^{\;\rho_j^{vae}} + \left(1 - \delta_j^{vae}\right) KE_j^{\rho_j^{vae}}\right]^{1/\rho_j^{vae}} \tag{A.1}$$

$$\frac{p^f_{"lab",j}}{p_j^{ke}} = \frac{\delta_j^{vae}}{1 - \delta_j^{vae}}\left(\frac{KE_j}{F_{"lab",j}}\right)^{1-\rho_j^{vae}} \tag{A.2}$$

$$p_j^{vae} VAE_j = p^f_{"lab",j} F_{"lab",j} + p_j^{ke} KE_j \tag{A.3}$$

$$KE_j = \alpha_j^{ke}\left[\delta_j^{ke} F_{"cap",j}^{\;\rho_j^{ke}} + \left(1 - \delta_j^{ke}\right)\left(\frac{ENE_j}{1 - ADEEI_j}\right)^{\rho_j^{ke}}\right]^{1/\rho_j^{ke}} \tag{A.4}$$

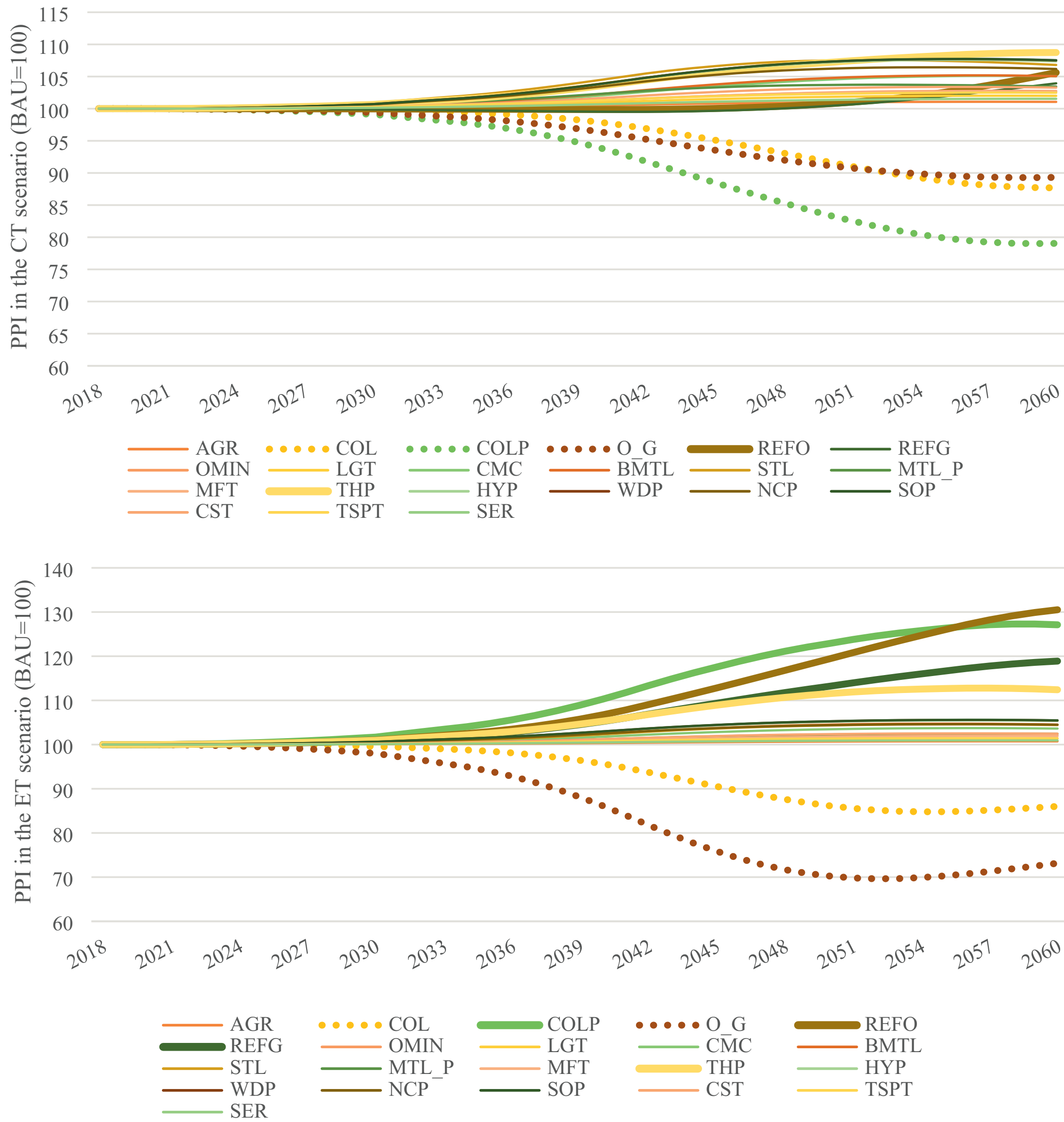

Fig. 11. producer price index changes (without indirect tax) during 2018–2060.
Note: Based on the BAU scenario (BAU = 100), this figure measures the producer price index (excluding tax) of each product every year. The letters in the legend are the abbreviations of various sectors, respectively indicating 1) agriculture, 2) coal production, 3) coal processing, 4) oil and gas production, 5) oil processing, 6) natural gas processing, 7) other mining industries, 8) light industry, 9) chemical industry, 10) building materials, 11) iron and steel, 12) other metals and their products, 13) manufacturing, 14) thermal power, 15) hydropower, 16) wind power, 17) nuclear power, 18) solar power, 19) construction, 20) transportation, and 21) services.

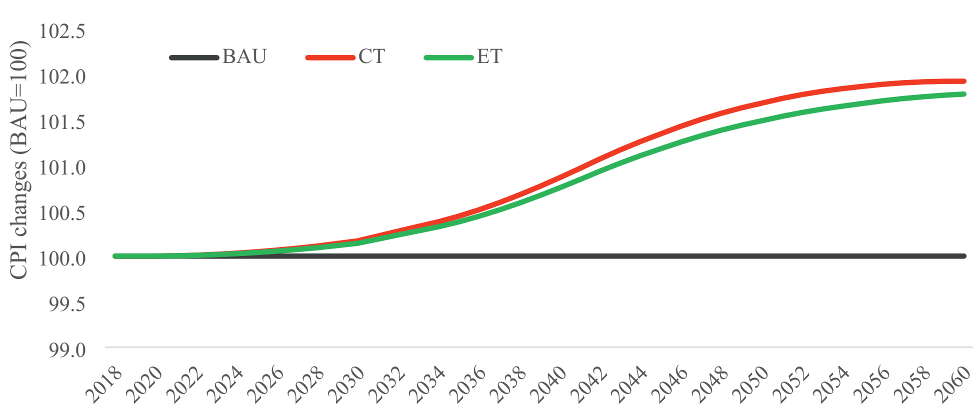

Fig. 12. Consumer price index changes during 2018–2060.
Note: The figure presents the changes in the consumer price index during 2018–2060 in the CT scenario (BAU = 100 each year). The CPI constructed by the model is based on the consumption weight of the BAU scenario. Therefore, the index will overestimate the impact of price changes on residents because it ignores the changes in consumer behavior. If the consumption weight of the CT scenario is taken as the benchmark weight, the impact will be underestimated. However, there is little difference between the two.

$$\frac{p^{f}_{"cap",j}}{p^{ene}_{j}} = \frac{\delta^{ke}_{j}}{1-\delta^{ke}_{j}} \left(\frac{\frac{ENE_j}{1-ADEEI_j}}{F_{"cap",j}} \right)^{1-\rho^{ke}_{j}} \tag{A.5}$$

$$p^{ke}_{j} KE_j = p^{f}_{"cap",j} F_{"cap",j} + p^{ene}_{j} ENE_j \tag{A.6}$$

$$ADEEI_j = 1 - \left[\frac{p^{ene}_{j}}{p^{eneBAU}_{j}} \right]^{-\sigma^{eff}} \tag{A.7}$$

$$F_{"cap",j} = \alpha^{f}_{j} \left[\delta^{f}_{j} F^{g}_{"cap",j}{}^{\rho^{f}_{j}} + \left(1-\delta^{f}_{j}\right) F^{s}_{"cap",j}{}^{\rho^{f}_{j}} \right]^{1/\rho^{f}_{j}} \tag{A.8}$$

$$\frac{p^{fg}_{"cap"}}{p^{fs}_{"cap",j}} = \frac{\delta^{f}_{j}}{1-\delta^{f}_{j}} \left(\frac{F^{s}_{"cap",j}}{F^{g}_{"cap",j}} \right)^{1-\rho^{f}_{j}} \tag{A.9}$$

$$p^{f}_{"cap",j} F_{"cap",j} = p^{fg}_{"cap"} F^{g}_{"cap",j} + p^{fs}_{"cap",j} F^{s}_{"cap",j} \tag{A.10}$$

$$ENE_j = \alpha^{ene}_{j} \left[\delta^{ene}_{j} ELC_j^{\rho^{ene}_{j}} + \left(1-\delta^{ene}_{j}\right) FOSSIL_j^{\rho^{ene}_{j}} \right]^{1/\rho^{ene}_{j}} \tag{A.11}$$

$$\frac{p^{elc}_{j}}{p^{fossil}_{j}} = \frac{\delta^{ene}_{j}}{1-\delta^{ene}_{j}} \left(\frac{FOSSIL_j}{ELC_j} \right)^{1-\rho^{ene}_{j}} \tag{A.12}$$

$$p^{ene}_{j} ENE_j = p^{elc}_{j} ELC_j + p^{fossil}_{j} FOSSIL_j \tag{A.13}$$

$$FOSSIL_j = \alpha^{fossil}_{j} \left(1 + c\_AEEI_j\right) \left[\delta^{fossil}_{j} SOLID_j^{\rho^{fossil}_{j}} + \left(1-\delta^{fossil}_{j}\right) NOS_j^{\rho^{fossil}_{j}} \right]^{1/\rho^{fossil}_{j}} \tag{A.14}$$

$$\frac{p^{solid}_{j}}{p^{nos}_{j}} = \frac{\delta^{fossil}_{j}}{1-\delta^{fossil}_{j}} \left(\frac{NOS_j}{SOLID_j} \right)^{1-\rho^{fossil}_{j}} \tag{A.15}$$

$$p^{fossil}_{j} FOSSIL_j = p^{solid}_{j} SOLID_j + p^{nos}_{j} NOS_j + PLC_j \tag{A.16}$$

$$SOLID_j = \alpha^{solid}_{j} \left[\delta^{solid}_{j} X_{"coal",j}{}^{\rho^{solid}_{j}} + \left(1-\delta^{solid}_{j}\right) X_{"colp",j}{}^{\rho^{solid}_{j}} \right]^{1/\rho^{solid}_{j}} \quad \text{if } X_{"colp",j} \neq 0 \quad \text{in SAM} \tag{A.17}$$

$$\frac{p^{x}_{"coal"}}{p^{x}_{"colp"}} = \frac{\delta^{solid}_{j}}{1-\delta^{solid}_{j}} \left(\frac{X_{"colp",j}}{X_{"coal",j}} \right)^{1-\rho^{solid}_{j}} \quad \text{if } X_{"colp",j} \neq 0 \quad \text{in SAM} \tag{A.18}$$

$$p^{solid}_{j} SOLID_j = p^{x}_{"coal"} X_{"coal",j} + p^{x}_{"colp"} X_{"colp",j} \quad \text{if } X_{"colp",j} \neq 0 \quad \text{in SAM} \tag{A.19}$$

$$SOLID_j = X_{"coal",j} \quad \text{if } X_{"colp",j} = 0 \quad \text{in SAM} \tag{A.20}$$

$$p^{solid}_{j} = p^{x}_{"coal"} \quad \text{if } X_{"colp",j} = 0 \quad \text{in SAM} \tag{A.21}$$

$$X_{"colp",j} = 0 \quad \text{if } X_{"colp",j} = 0 \quad \text{in SAM} \tag{A.22}$$

The above 6 equations describes how to handle input with zero value in CES production function. E.g. Some firms do not use coke as energy input. In such case, the value of coke input of the firm is zero, that makes error in CES function. So it is required to define the price and quantity directly instead of using CES function bundles. The model have solved such problems in several function bundles. But the paper only show once here for example.

$$NOS_j = \alpha^{nos}_{j} \left[\delta^{nos}_{j} X_{"o\_g",j}{}^{\rho^{nos}_{j}} + \left(1-\delta^{nos}_{j}\right) REF_j^{\rho^{nos}_{j}} \right]^{1/\rho^{nos}_{j}} \tag{A.23}$$

$$\frac{p^{x}_{"o\_g"}}{p^{ref}_{j}} = \frac{\delta^{nos}_{j}}{1-\delta^{nos}_{j}} \left(\frac{REF_j}{X_{"o\_g",j}} \right)^{1-\rho^{nos}_{j}} \tag{A.24}$$

$$p^{nos}_{j} NOS_j = p^{x}_{"o\_g"} X_{"o\_g",j} + p^{ref}_{j} REF_j \tag{A.25}$$

$$REF_j = \alpha^{ref}_{j} \left[\delta^{ref}_{j} X_{"refo",j}{}^{\rho^{ref}_{j}} + \left(1-\delta^{ref}_{j}\right) X_{"refg",j}{}^{\rho^{ref}_{j}} \right]^{1/\rho^{ref}_{j}} \tag{A.26}$$

$$\frac{p^{x}_{"refo"}}{p^{x}_{"refg"}} = \frac{\delta^{ref}_{j}}{1-\delta^{ref}_{j}} \left(\frac{X_{"refg",j}}{X_{"refo",j}} \right)^{1-\rho^{ref}_{j}} \tag{A.27}$$

$$p_j^{ref}REF_j = p^x_{"refo"}X_{"refo",j} + p^x_{"refg"}X_{"refg",j} \tag{A.28}$$

$$ELC_j = \alpha_j^{elc}(1 + c\_ELE)\left[\delta_j^{elc}X_{"thp",j}{}^{\rho_j^{elc}} + \left(1 - \delta_j^{elc}\right)RENEWABLE_j{}^{\rho_j^{elc}}\right]^{1/\rho_j^{elc}} \tag{A.29}$$

$$\frac{p^x_{"thp"}}{p_j^{renewable}} = \frac{\delta_j^{elc}}{1 - \delta_j^{elc}}\left(\frac{RENEWABLE_j}{X_{"thp",j}}\right)^{1-\rho_j^{elc}} \tag{A.30}$$

$$p_j^{elc}ELC_j = p^x_{"thp"}X_{"thp",j} + p_j^{renewable}RENEWABLE_j \tag{A.31}$$

$$RENEWABLE_j = \alpha_j^{renewable}\left[\delta_j^{hyp}X_{"hyp",j}{}^{\rho_j^{renewable}} + \delta_j^{wdp}X_{"wdp",j}{}^{\rho_j^{renewable}} + \delta_j^{ncp}X_{"ncp",j}{}^{\rho_j^{renewable}} + \delta_j^{sop}X_{"sop",j}{}^{\rho_j^{renewable}}\right]^{1/\rho_j^{renewable}} \tag{A.32}$$

$$\frac{p^x_{"sop"}}{p^x_{"hyp"}} = \frac{\delta_j^{sop}}{\delta_j^{hyp}}\left(\frac{X_{"hyp",j}}{X_{"sop",j}}\right)^{1-\rho_j^{renewable}} \tag{A.33}$$

$$\frac{p^x_{"sop"}}{p^x_{"wdp"}} = \frac{\delta_j^{sop}}{\delta_j^{wdp}}\left(\frac{X_{"wdp",j}}{X_{"sop",j}}\right)^{1-\rho_j^{renewable}} \tag{A.34}$$

$$\frac{p^x_{"sop"}}{p^x_{"ncp"}} = \frac{\delta_j^{sop}}{\delta_j^{ncp}}\left(\frac{X_{"ncp",j}}{X_{"sop",j}}\right)^{1-\rho_j^{renewable}} \tag{A.35}$$

$$p_j^{renewable}RENEWABLE_j = p^x_{"hyp"}X_{"hyp",j} + p^x_{"wdp"}X_{"wdp",j} + p^x_{"ncp"}X_{"ncp",j} + p^x_{"sop"}X_{"sop",j} \tag{A.36}$$

$$p^x_{eni} = p^q_{eni} \tag{A.37}$$

This equation defines that all the energy input prices in above equations are equal to relevant Armington prices. Of course, we can also give different assumptions here.

$$X_{neni,j} = ax_{neni,j}TX_j \tag{A.38}$$

$$p_j^{tx} = \sum_{neni} ax_{neni,j}p_j^q \tag{A.39}$$

$$Z_j = \alpha_j^z\left[\delta_j^z VAE_j{}^{\rho_j^z} + \left(1 - \delta_j^z\right)TX_j{}^{\rho_j^z}\right]^{1/\rho_j^z} \tag{A.40}$$

$$\frac{p_j^{vae}}{p_j^{tx}} = \frac{\delta_j^z}{1 - \delta_j^z}\left(\frac{TX_j}{VAE_j}\right)^{1-\rho_j^z} \tag{A.41}$$

$$p_j^z Z_j = p_j^{vae}VAE_j + p_j^{tx}TX_j \tag{A.42}$$

A.2. Income and expenditure block

$$Td_l = \tau_l^d \sum_{h,j} p^f_{h,j}F_j rff_{l,h} \tag{A.43}$$

$$Tz_i = \tau_i^z p_i^z Z_i / \left(1 - \tau_i^z\right) \tag{A.44}$$

$$Tm_i = \tau_i^m p_i^m M_i \tag{A.45}$$

$$Xg_i = \mu_i \frac{\sum_l Td_l + \sum_i (Tz_i + Tm_i + PLC_i) - Sg}{p_i^q} \tag{A.46}$$

$$Xv_i = \lambda_i \frac{\sum_l Sp_l + Sg + \varepsilon Sf}{p_i^q} \tag{A.47}$$

$$Sp_l = ssp_l \sum_{h,j} p^f_{h,j}F_j rff_{l,h} \tag{A.48}$$

$$Sg = ssg\left[\sum_l Td_l + \sum_i (Tz_i + Tm_i + PLC_i)\right] \tag{A.49}$$

$$Xp_{i,l} = Sub_{i,l}^{LES} + \frac{\beta_{i,l}^{LES}}{p_i^q}\left(\sum_{h,j} p_{h,j}^f F_j rff_{l,h} - Sp_l - Td_l - \sum_j p_j^q Sub_{i,l}^{LES}\right) \tag{A.50}$$

$$HOHincome_l = \sum_{h,j} p_{h,j}^f F_j rff_{l,h} \tag{A.51}$$

A.3. Trade block

$$p_i^e = \varepsilon p_i^{We} \tag{A.52}$$

$$p_i^m = \varepsilon p_i^{Wm} \tag{A.53}$$

$$Sf = \sum_i p_i^{Wm} M_i - \sum_i p_i^{We} E_i \tag{A.54}$$

$$Q_i = \gamma_i \left(\delta m_i {M_i}^{\eta_i} + \delta d_i {D_i}^{\eta_i}\right)^{1/\eta_i} \tag{A.55}$$

$$M_i = \left[\frac{{\gamma_i}^{\eta_i} \delta m_i p_i^q}{(1+\tau_i^m) p_i^m}\right]^{\frac{1}{1-\eta_i}} Q_i \tag{A.56}$$

$$D_i = \left[\frac{{\gamma_i}^{\eta_i} \delta d_i p_i^q}{p_i^d}\right]^{\frac{1}{1-\eta_i}} Q_i \tag{A.57}$$

$$Z_i = \theta_i \left(\xi e_i E_i^{\phi_i} + \xi d_i D_i^{\phi_i}\right)^{\frac{1}{\phi_i}} \tag{A.58}$$

$$E_i = \left[\frac{{\theta_i}^{\phi_i} \xi e_i \frac{p_i^z}{1-\tau_i^z}}{p_i^e}\right]^{\frac{1}{1-\phi_i}} Z_i \tag{A.59}$$

$$D_i = \left[\frac{{\theta_i}^{\phi_i} \xi d_i \frac{p_i^z}{1-\tau_i^z}}{p_i^d}\right]^{\frac{1}{1-\phi_i}} Z_i \tag{A.60}$$

A.4. Energy-environment block

$$coe_{eni,j} X_{eni,j} = Energy_{eni,j} \tag{A.61}$$

$$coe_{eni,l} X_{eni,l} = Energy_{eni,l} \tag{A.62}$$

$$EM_{nep} = CO2_{"coal"}^{factor} Energy_{"coal","thp"} \frac{Energy_{"thp",nep}}{\sum_{enc} Energy_{"thp",enc}} + CO2_{freni}^{factor} \sum_{freni} Energy_{freni,nep} \tag{A.63}$$

$$\begin{aligned} EM_{"colp"} = {} & \\ & CO2_{"coal"}^{factor} Energy_{"coal","colp"} \frac{Energy_{"coal","colp"}}{\sum_{enc} Energy_{"thp",enc}} - CO2_{"coal"}^{factor} eff^{coal\_coke} Energy_{"coal","colp"} \\ & + CO2_{freni}^{factor} \sum_{freni} Energy_{freni,"colp"} \end{aligned} \tag{A.64}$$

$$\begin{aligned} EM_{"thp"} = {} & \\ & CO2_{"coal"}^{factor} Energy_{"coal","thp"} \frac{Energy_{"coal","thp"}}{\sum_{enc} Energy_{"thp",enc}} - CO2_{"coal"}^{factor} eff^{coal\_thp} Energy_{"coal","thp"} \\ & + CO2_{freni}^{factor} \sum_{freni} Energy_{freni,"thp"} \end{aligned} \tag{A.65}$$

$$EM_{"refo"} = CO2^{factor}_{"coal"} Energy_{"coal","refo"} \frac{Energy_{"coal","refo"}}{\sum_{enc} Energy_{"thp",enc}} - CO2^{factor}_{"o\_g"} eff^{o-g-oil} Energy_{"o\_g","refo"} + CO2^{factor}_{freni} \sum_{freni} Energy_{freni,"refo"} \quad (A.66)$$

$$EM_{"refg"} = CO2^{factor}_{"coal"} Energy_{"coal","refg"} \frac{Energy_{"coal","refg"}}{\sum_{enc} Energy_{"thp",enc}} - CO2^{factor}_{"o\_g"} eff^{o-g-gas} Energy_{"o\_g","refg"} + CO2^{factor}_{freni} \sum_{freni} Energy_{freni,"refg"} \quad (A.67)$$

$$PLC_i = ctr \cdot EM_i \cdot Dummy^{cf} \quad (A.68)$$

$$Emissions = \sum_{enc} EM_{enc} \quad (A.69)$$

$$TOT\_Energy_{eni} = \sum_{enc} Energy_{eni,enc} \quad (A.70)$$

A.5. Market-clearing & macroscopic closure block

$$Q_i = \sum_l Xp_{i,l} + Xg_i + Xv_i + \sum_l X_{i,j} + Walras \quad (A.71)$$

$$\sum_j F_{"lab",j} = \sum_l FF_{l,"lab"} \quad (A.72)$$

$$p^f_{"lab",j} = \frac{\sum_i p^f_{"lab",i}}{N^i} + Walras2 \quad (A.73)$$

N^i denotes the number of the sectors. The direct meaning of this formula is that the labor prices in all sectors are equal to the average price of the whole society. The economic meaning is that the labor market is a completely competitive market, so the labor price is indistinguishable in various sectors. In addition, in the process of solving the equations, when the price of the penultimate sector is equal to the average price, the price of the last industry must be equal to the average price. Therefore, there must be an equation that is redundant. In such case, we can introduce a new Walras dummy variable to balance the number of equations and the number of endogenous variables.

$$\sum_j F^g_{"cap",j} = FF^g_{"cap"} \quad (A.74)$$

$$F^s_{"cap",j} = CAPSTK^s_j \cdot depr_j \quad (A.75)$$

A.6. Macro-indicator block

$$C^d_j = \frac{CO_2^{factor} \sum_{freni} Energy_{freni,j}}{\sum_i p^x_i X_{i,j} + \sum_h p^f_h F_{h,j} + Tz_j + Tm_j} \quad (A.76)$$

Here, our carbon emission accounting method directly considers fossil energy consumption rather than the ways above, because the total input coefficient in input-output analysis includes indirect carbon dioxide emissions caused by consumption. Therefore, direct carbon emissions from various industries must be used here.

$$A_{i,j} = \frac{p^x_i X_{i,j}}{\sum_{jj} p^x_{jj} X_{jj,j} + \sum_h p^f_h F_{h,j} + Tz_j + Tm_j} \quad (A.77)$$

$$A^m_{i,j} = \frac{p^m_i M_i}{p^q_i Q_i} A_{i,j} \quad (A.78)$$

$$I_{i,j} = \sum_{jj} \left(I_{i,jj} - A_{i,jj}\right) X^{Leontiefreverse}_{jj,j} \quad (A.79)$$

$$E^d_j = \sum_{jj} C^d_{jj} X^{Leontiefreverse}_{jj,j} \quad (A.80)$$

$$FD_j = p_i^q\left(Xg_j + Xv_j + \sum_l Xp_{j,l}\right) + p_i^e E_j - p_i^m M_j \tag{A.81}$$

$$E_j^{im-intermediate} = \sum_{jj} E_{jj}^d A_{jj,j}^m \tag{A.82}$$

$$E_j^{im} = \sum_{jj} E_{jj}^{im-intermediate} X_{jj,j}^{Leontiefreverse} \tag{A.83}$$

$$Y_j^{im} = \frac{p_j^m M_j}{p_j^q Q_j} FD_j \tag{A.84}$$

$$EEP = \sum_j E_j^d FD_j \tag{A.85}$$

$$EEC = \sum_j E_j^d\left(FD_j - p_j^e E_j\right) + \sum_j E_j^{im}\left(FD_j - p_j^e E_j\right) + \sum_j E_j^d Y_j^{im} \tag{A.86}$$

$$EEE = \sum_j E_j^d p_j^e E_j + \sum_j E_j^{im} p_j^e E_j \tag{A.87}$$

$$EEI = \sum_j E_j^d Y_j^{im} + \sum_j E_j^{im} FD_j \tag{A.88}$$

$$EEB = EEP - EEC \tag{A.89}$$

$$PPI_j = \frac{p_j^z}{p_j^{zBAU}} \times 100 \tag{A.90}$$

$$CPI_j = \frac{\sum_j p_j^q \frac{\sum_l X_{j,l}^{pBAU}}{\sum_{j,l} X_{j,l}^{pBAU}}}{\sum_j p_j^{qBAU} \frac{\sum_l X_{j,l}^{pBAU}}{\sum_{j,l} X_{j,l}^{pBAU}}} \times 100 \tag{A.91}$$

$$R\_renewable = \frac{\sum_{prrenew,enc} Energy_{prrenew,enc}}{\sum_{prene,enc} Energy_{prene,enc}} \tag{A.92}$$

$$R\_electricity = \frac{\sum_{ele,enc} Energy_{ele,enc}}{\sum_{eni,enc} Energy_{eni,enc}} \tag{A.93}$$

$$TOTelectricity = \sum_{ele,enc} Energy_{ele,enc} \tag{A.94}$$

$$EV_l = \left(UU_l - UU_l^0\right)\prod_i\left(\frac{1}{\beta_{i,l}^{LES}}\right)^{\beta_{i,l}^{LES}} \tag{A.95}$$

The variables EV_l and CV_l are the utility changes from the base year to reporting year, while the variables EV_l^{cf} and CV_l^{cf} are the utility changes from the BAU scenario to counterfacutal scenarios in a specific year.

$$CV_l = \left(UU_l - UU_l^0\right)\prod_i\left(\frac{p_i^q}{\beta_{i,l}^{LES}}\right)^{\beta_{i,l}^{LES}} \tag{A.96}$$

$$EV_l^{cf} = \left(UU_l - UU_l^{bau}\right)\prod_i\left(\frac{P_i^{q-bau}}{\beta_{i,l}^{LES}}\right)^{\beta_{i,l}^{LES}} \tag{A.97}$$

$$CV_l^{cf} = \left(UU_l - UU_l^{bau}\right)\prod_i\left(\frac{P_i^q}{\beta_{i,l}^{LES}}\right)^{\beta_{i,l}^{LES}} \tag{A.98}$$

$$GDP = \sum_j\left(Xg_j + Xv_j + \sum_l Xp_{j,l} + E_j - M_j\right) \tag{A.99}$$

$$GDPCHK = \left(\sum_{h,j} p_j^f F_{h,j} + \sum_j \left(Tz_j + Tm_j + PLC_j\right)\right) - p_i^q \sum_j \left(Xg_j + Xv_j + \sum_l Xp_{j,l} + E_j - M_j\right) \quad (A.100)$$

$$UU_l = \prod_i \left(Xp_{i,l} - Sub_{i,l}^{LES}\right)^{\beta_{i,l}^{LES}} \quad (A.101)$$

$$SW = \sum_l UU_l \quad (A.102)$$

A.7. Description of the equations

In the production block, Eq. (1) is a CES production function, describing production technologies of aggregating capital-energy and labor input in sector *j*. Eq. (2) is the first-order condition of the function. Eq. (3) is the value balance equation of the aggregation. Eqs. (1)–(3) form a standard CES production function group. Other CES nesting has a similar structure. Eqs. (A.1) to (A.42) describe enterprises' production technology, preference, and value transmission using CES nesting structure, except for Eqs. (A.38) and (A.39). Eqs. (A.38) and (A.39) express the aggregation of intermediate input without energy using the Leontief function. Eq. (A.37) assumes that the price of the energy input is the same as the price of energy Armington goods.

In the income & expenditure block, Eq. (A.43) describes the direct tax behavior, while Eq. (A.44) is the indirect tax. The indirect tax rate is based on the sales price of the enterprise. Therefore, $p_i^z Z$ in this paper, can only represent the after-tax income of the enterprise. Eq. (A.45) is the behavior of tariff. Eqs. (A.46), (A.47), and (A.50) denote government consumption, investment needs, and household consumption behaviors. Eqs. (A.48) and (A.49) are saving behavior of households and the government. Eq. (A.51) expresses the household's total income.

In trade block, Eqs. (A.52) and (A.53) express the linkage of domestic currency and international currency. Eq. (A.54) is the trade deficit. Eqs. (A.55) to (A.58) are CES function bundle based on the Armington assumption. Eqs. (A.58)–(A.60) describe the behavior of domestic enterprises selling their products to the domestic and international markets using the CET function.

In the Energy-environment block, Eqs. (A.61)–(A.62) are the linkage of value quantities of energy inputs to the physical quantity of energy inputs. Eqs. (A.63)–(A.67) calculate the CO_2 emissions of different kinds of sectors from the perspective of the consumption side. Eq. (A.68) expresses the energy and environmental policy cost. In this case, the cost is the carbon tax. Eq. (A.69) is the total CO_2 emissions, and Eq. (A.70) is total energy consumption (unit: million tons of coal equivalent).

In the market-clearing & macroscopic closure block, Eq. (A.71) describes the clearing in the commodity market. Eqs. (A.72) and (A.74) are the clearing in the factor market. Eq. (A.73) assumes that the price of general capital input is the same for every user. Eqs. (A.75) expresses special capital endowment and input.

In the macro-indicator block, Eq. (A.76) calculates the direct CO_2 emissions per unit sector *j*'s output. Eq. (A.77) is the direct input coefficient. Eq. (A.78) expresses the element in the direct requirement coefficient matrix of the intermediate input from imports. Eq. (A.79) is used to calculate the Leontief reverse of the direct input matrix. Eq. (A.80) denotes the domestic embodied emissions per unit of final demand in sector *j*. Eq. (A.81) determines the final demand. Eqs. (A.82) and (A.83) express the calculation of E_j^{im}, which are elements within a row matrix representing the emissions of imported intermediate input per unit of final demand. Eq. (A.84) is imported directed domestic final consumption. Finally, the calculation of EEP, EEC, EEE, EEI, and EEB can be conducted by Eqs. (A.85)–(A.89). Eqs. (A.90) and (A.91) are the calculation of the producer price index and consumer price index. Eq. (A.92) expresses the renewable energy rate in the power mix. Eq. (A.93) is the electricity share in total energy consumption. Eq. (A.94) calculates the total electricity consumption. Eqs. (A.95) and (A.96) are used to measure social welfare using equivalent variation and compensation variation for comparing social welfare change between the base period and the current period. Eqs. (A.97) and (A.98) are used to measure social welfare using equivalent variation and compensation variation for comparing social welfare change between the BAU scenario and other counterfactual scenarios. Eq. (A.99) is real GDP based on the 2018 price level. Eq. (A.100) checks whether the values of GDP measured in different ways are equal to each other. Eqs. (A.101) and (A.102) are the measurement of utility using the S-G utility function.

Appendix B. Matching tables

Table B.1
Matching between the input-output table and the SAM.

Abbr.	Re-classified sector in SAM	Sector in IOT	Sector code in IOT
AGR	Agriculture related sectors	Agriculture products; forest product; livestock products; fishery products; agricultural, forestry, animal husbandry and fishery service products	01001; 02002; 03003; 04004; 05005
COL	Coal production	Coal mining and washing products	06006
COLP	Coal processing	Coal processing products	25042
O_G	Oil and gas production	Oil and gas production products	07007
REFO	Refined oil	Refined petroleum and nuclear fuel processing products	25041
REFG	Refined gas	Gas production and supply	45099
OMIN	Other mining products	Ferrous metal ore mining and beneficiation products; Nonferrous metal ore mining and beneficiation products; Nonmetallic ore mining and beneficiation products; Mining ancillary activities and other mining products	08008; 09009; 10010; 11011

(continued on next page)

Table B.1 (*continued*)

Abbr.	Re-classified sector in SAM	Sector in IOT	Sector code in IOT
LGT	Light industry	Grain grinding products; Feed processing products; Vegetable oil processed products; Sugar and sugar products; Slaughtering and meat processing products; fishery product; Vegetables, fruits, nuts and other processed agricultural and sideline foods; instant food; dairy; Condiments, fermented products; Other food; Alcohol and wine; Drinks; Refined tea; Tobacco products; Cotton, chemical fiber textile and printing and dyeing finishing products; Wool textile and dyeing and finishing products; Hemp, silk and silk textiles and processed products; Knitted or crocheted articles; textile made-up article; Textile clothing; Leather, fur, feather and their products; shoes; Wood processing and wood, bamboo, rattan, palm and grass products; furniture; Paper and paper products; Reproduction of printing and recording media; Handicraft Article; Cultural, educational, sports and entertainment supplies	13012; 13013; 13014; 13015; 13016; 13017; 13018; 14019; 14020; 14021; 14022; 15023; 15024; 15025; 16026; 17027; 17028; 17029; 17030; 17031; 18032; 19033; 19034; 20035; 21036; 22037; 23038; 24039; 24040
CMC	Chemicals	Basic chemical raw materials; fertilizer; pesticides; Coatings, inks, pigments and similar products; synthetic material; Special chemical products and explosives, pyrotechnics and fireworks products; Daily chemical products; Pharmaceutical products; Chemical fiber products; Rubber products; plastic	26043; 26044; 26045; 26046; 26047; 26048; 26049; 27050; 28051; 29052; 29053
BMTL	Building materials	Cement, lime and gypsum; Gypsum, cement products and similar products; Brick, tile, stone and other building materials; Glass and glass products; Ceramic products; Refractory products; Graphite and other nonmetallic products	30054; 30055; 30056; 30057; 30058; 30059; 30060
STL	Steelmaking	Steel; Steel calendaring products	31061; 31062
MTL&P	Metal and the products	Iron and ferroalloy products; Nonferrous metals and their alloys; Nonferrous metal calendaring products; Metalware	31063; 32064; 32065; 33066
MFT	Manufacturing	Boiler and prime mover; Metal processing machinery; Material Handling Equipment; Pumps, valves, compressors and similar machinery; Oven, fan, packaging and other equipment; Cultural and office machinery; Other general equipment; Special equipment for mining, metallurgy and construction; Special equipment for chemical, wood and nonmetallic processing; Special machinery for agriculture, forestry, animal husbandry and fishery; Medical instruments and apparatus; Other special equipment; Complete vehicle; Auto parts and accessories; Railway transportation and urban rail transit equipment; Ships and related installations; Other transportation equipment; electric machinery; Power transmission and distribution and control equipment; Wires, cables, optical cables and electrical equipment; Battery; Household appliances; Other electrical machinery and equipment; computer; Communication equipment; Radio and television equipment, radar and supporting equipment; Audio visual equipment; Electronic components; Other electronic equipment; Instruments and Apparatuses; Other manufactured products; Water production and supply; Waste resources and waste materials recycling and processing products; Metal products, machinery and equipment repair services	34067; 34068; 34069; 34070; 34072a; 34071; 34072b; 35073; 35074; 35075; 35076a; 35076b; 36077; 36078; 37079; 37080; 37081; 38082; 38083; 38084; 38085; 38086; 38087; 39088; 39089; 39090; 39091; 39092; 39093; 40094; 41095; 46100; 42096; 43097
THP	Thermal power	Power and heat production and supply	44098
HYP	Hydropower	Power and heat production and supply	44098
WDP	Wind power	Power and heat production and supply	44098
NCP	Nuclear power	Power and heat production and supply	44098
SOP	Solar power	Power and heat production and supply	44098
CST	Construction	Residential building; Sports venues and other buildings; Railway, road, tunnel and bridge engineering construction; Other civil engineering buildings; Building installation; Architectural decoration, decoration and other architectural services	47101a; 47101b; 48102a; 48102b; 49103; 50104
TSPT	Transportation	Railway passenger transport; Railway freight transportation and auxiliary activities; Urban public transport and highway passenger transport; Road freight transportation and transportation auxiliary activities; Water passenger transport; Water cargo transportation and transportation auxiliary activities; carriage of passengers by air; Air cargo transport and transport ancillary activities; Pipeline transportation; Multimodal transport and transportation agency; Handling and storage	53107; 53108; 54109; 54110; 55111; 55112; 56113; 56114; 57115; 58116; 59117
SER	Service	Wholesale; retail; Post Office; get accommodation; Restaurant; telecom; Radio, television and satellite transmission services; Internet and related services; Software services; Information technology services; Monetary and other financial services; Capital market services; Insurance; real estate; lease; Business services; Research and experimental development; Professional technical services; Technology promotion and application services; Water conservancy management; Ecological protection and environmental governance; Public facilities and land management; Resident services; Other services; education; hygiene; Social work; Press and publication; Radio, television, film and television recording production; Culture and art; Sports; entertainment; social security; Public administration and social organizations	51105; 52106; 60118; 61119; 62120; 63121; 63122; 64123; 65124; 65125; 66126; 67127; 68128; 70129; 71130; 72131; 73132; 74133; 75134; 76135; 77136; 78137; 80138; 81139; 83140; 84141; 85142; 86143; 87144; 88145; 89146; 90147; 94148; 91149

Table B.2
Matching between China Energy Statistics Yearbook and the SAM.

Industry classification in China Energy Statistical Yearbook	Abbr. in SAM	
	Coal, Coke, and Power consumption	Oil and Gas consumption
Agriculture, forestry, animal husbandry and fishery	AGR	AGR
Coal mining and washing industry	COL	COL
Oil and gas extraction industry	O_G	O_G
Ferrous metal mining and dressing industry	OMIN	OMIN
Nonferrous metal mining and dressing industry		
Non metallic ore mining and dressing industry		
Mining professional and auxiliary activities		
Other mining		
Agricultural and sideline food processing industry	LGT	LGT
Food manufacturing		
Wine, beverage and refined tea manufacturing		
Tobacco products		
textile industry		
Textile and clothing industry		
Leather, fur, feather and their products and shoemaking industry		
Wood processing and wood, bamboo, rattan, palm and grass products industry		
Furniture manufacturing		
Paper and paper products industry		
Printing and recording media reproduction industry		
Culture and education, arts and crafts, sports and entertainment products manufacturing		
Petroleum, coal and other fuel processing industries	COLP	REFO
Chemical raw materials and chemical products manufacturing	CMC	CMC
Pharmaceutical manufacturing		
Chemical fiber manufacturing		
Rubber and plastic products industry		
Non metallic mineral products industry	BMTL	BMTL
Ferrous metal smelting and rolling processing industry	STL	STL
Nonferrous metal smelting and rolling processing industry	MTL_P	MTL_P
Metal products industry		
General equipment manufacturing	MFT	MFT
Special equipment manufacturing		
Automobile manufacturing industry		
Manufacturing of railway, ship, aerospace and other transportation equipment		
Electrical machinery and equipment manufacturing		
Computer, communication and other electronic equipment manufacturing		
Instrument manufacturing		
Other manufacturing		
Comprehensive utilization of waste resources		
Metal products, machinery and equipment repair industry		
Power and heat production and supply industry	ELC	ELC
Gas production and supply industry	REFG	REFG
Construction	CST	CST
Transportation, storage and postal services	TSPT	TSPT
Wholesale and retail, accommodation and catering	SER	SER
Others		
Resident life	RUR + URB	RUR + URB

Notes: Petroleum, coal, and other fuel processing industry in the yearbook includes the refined oil sector and coke sector in the SAM. The industry is not broken down in the energy consumption data, so we assume that the coal sector, coke sector, electricity generation only consume coal product according to China's actual production structure. Another, the energy statistical yearbook does not subdivide rural residents and urban residents. Therefore, we split the residents' consumption in the energy statistical yearbook according to the proportion in the input-output table.

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