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How does tax system on energy industries affect energy demand, CO_2 emissions, and economy in China?

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ABSTRACT

Energy savings and CO_2 emission reduction have become a major issue in recent years. Taxes on energy production sectors may be an effective way to save energy, reduce CO_2 emissions, and improve environmental quality. This paper constructs a dynamic recursive Computable General Equilibrium (CGE) model to analyze the impact of the energy tax on energy, economy, and environment from the perspective of tax rates and tax forms (specific tax and ad valorem tax). The results show that adjusting the tax system and the tax rate has important implications for energy conservation while having minor impacts on the output of other industries. The impact of an increasing energy tax on the energy demand is greater than the impact on sectoral output, indicating that energy efficiency will be increased to some extent. The CO_2 reduction will increase over time when an ad valorem tax is implemented on enterprises. We found that ad valorem tax has greater elasticity of economic output, energy demand, and CO_2 emission reduction. The results support the direction of China's resource tax reform. However, we argue that it is better to increase the tax rate relatively and relax the control on energy prices so that energy efficiency will increase.

1. Introduction

Climate change caused by Greenhouse Gas (GHG) has become a major problem that requires an urgent solution. Energy savings and CO_2 emission reduction have become major topics of discussion and have been widely researched (Fan et al., 2016; Li and Jia, 2016). Several scholars have been working on methods for sustainable development (Moran et al., 2008; van Weenen, 1995). Low-carbon economy is currently a very hot topic, and many policy instruments aimed at achieving it, such as resource tax(Frestad, 2010; Xu et al., 2015), carbon tax (Chen et al., 2017; Li and Jia, 2017) and emission trading scheme (Babatunde et al., 2017; Hart and Zhong, 2014; Li et al., 2017; Song et al., 2018) have been studied or implemented.

Taxes can not only distribute income, adjust corporate structure (Fang et al., 2017; Jia and Ma, 2017), but also regulate economic and resource balance. Taxes on energy production sectors or energy consumption may be an effective way to save energy, reduce CO_2 emissions and improve environmental quality. Hu et al. (2018) analyzed the effects of different environmental tax returning rate on China's economy, and concluded that environmental tax is not harmful to economy; moreover, it can effectively curb the SO_2 emissions of pollution-intensive sectors. Kaplowitz and McCright (2015) examined how specific persuasive messages and policy characteristics affect supports for a gasoline tax increase using eight survey experiments. Many studies have focused on economic or environmental effects of a CO_2 tax such as Mardones and Baeza (2018), Mardones and Flores (2018), Chen and Nie (2016), Li et al. (2018) and Wang et al. (2018).

Several works of literature have studied the effect of tax reform on energy industries (Jorgenson and Wilcoxen, 1997; Weinthal and Jones Luong, 2001). Deroubaix and Lévèque (2006) examined the political controversies caused by environmental tax reform project and the why it eventual collapsed, hoping it could help to solve the political difficulties of implementing environmental policies. Rocchi et al. (2014) analyzed the potential influences of energy tax directive reform on price levels in the various industries in 27 EU countries. Orlov (2015) analyzed the economy-wide effects of reducing export taxes on crude oil as well as oil products compensated by increasing the royalty on crude oil using Computable General Equilibrium (CGE) model. The research found that the method provides a certain gain of allocative efficiency; however, the policy is not superior. Thampapillai et al. (2014) illustrated how the re-investment of the resource rent tax and other

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government revenue from mining can reduce the depreciation of the mine.

In addition, some prior studies focused on resources tax. Frestad (2010) studied corporate hedging under a resource rent tax regime. Zhang et al. (2013) analyzed the impacts of resource tax reform using the CGE model in Xinjiang province, China. They found that the main influence of the reform is just good to local government finances, but energy conservation or emission reduction. Similarly, Tang et al. (2017) analyzed the impact of China's coal resource tax reform (from specific tax to ad valorem tax) in December 2014 using CGE model, and the results indicate that the reform policy would improve the energy structure: coal consumption will suffer a great decrease while cleaner energy will increase. Liu et al. (2017) analyzed the impact of China's resource tax reform on the coal industry by applying a two-stage dynamic game model that takes the coal production industry and thermal power plants as the players.

However, these studies only focus on tax reform on energy production sectors (such as coal production sector). Few pieces of literature focus on the impact of tax changes (both in tax forms and in tax rates) in the energy industry on energy, economy, and environment. Energy production sectors are the lifeline of a country and the tax rate on these sectors may directly affect the economy and security of the country, as well as energy saving and CO_2 emissions reduction. Thus, this paper explores the different results of different tax forms and rates, answers the question of which tax form and rate will have a better impact on the economy, energy, and environment, and presents the conclusion and findings of the study and proposes several policy implications further. The contributions of this paper are as follows:

1) This paper established a dynamic recursive CGE model to analyze the impact of different tax reforms and tax rates. We explained the modeling process in more details relative to other studies, hoping to provide some references for other CGE modelers.
2) This paper considers the impact of different tax systems (fixed tax, specific tax, and ad valorem tax) in different tax rates on energy, the economy and the environment. Compared with the previous research, this paper is more comprehensive from a research perspective.
3) This paper obtains several interesting findings and proposes some specific implications for China, especially regarding China's resources tax reform in the coal industry.

The basic structure of this paper is organized as follows: the introduction and literature review are presented in Section 1. The research background is introduced in Section 2. CGE model and the method of model dynamics are introduced in Section 3. The data source and the scenario design are described in Section 4. The simulation results and discussions are provided in Section 5. Sensitivity analysis is Provided in Section 6. The conclusions and policy implications are proposed in Section 7. Abbreviations in this paper are listed in Appendix A to make this paper more concise and easy to read.

2. The process of China's resource tax reform

Resource tax is levied on individuals or industries and imposed based on the amount of initial resources. The purpose of the tax is to promote the rational development and utilization of enterprises resources and to facilitate the overall function of taxation leverage cooperating with other taxes. Table 1 lists several major events in China's resource tax.

China's resource tax was levied in 1984, and crude oil, natural gas, and coal were levied first. Resource tax had been a specific tax for many years. Taking the coal industry as an example, the resource tax is 2–5 CNY per ton of raw coal and eight CNY for coking coal before the year of 2009. That is almost no tax at all (less than 1% of sales revenue). Moreover, tax rates also had no moderating effect on the market.

Table 1
The process of China's resource tax reform.

Year	Process of China's resource tax
1984	Creating resource taxes on crude oil, natural gas, coal, and iron ore
1994	Establishing comprehensive resource tax on all mineral resources
2004	Adjust the standards for taxation on some items such as coal, crude oil, natural gas, and manganese ore, etc.
2006	Cancellation of 30% reduction of non-ferrous metal mineral resources tax policy; adjustment of iron ore resource tax reduction policies, etc.
2007	Raise the tax rate of coking coal resources; adjust the tax reform policy for salt resources
2010	Tax reform for crude oil and natural gas piloted in Xinjiang (specific collection to ad valorem collection)
2011	Natural gas resource tax becomes ad valorem tax nationwide
2014	Coal resource tax becomes ad valorem tax nationwide

In order to protect resources. The tax had been reformed from specific tax to ad valorem tax one after another. In this paper, we mainly focus on the tax on energy production enterprises instead of the whole resource tax.

3. Methodology

3.1. CGE model

Computable General Equilibrium (CGE) model is widely used for the analysis of policy impact (Borgomeo et al., 2018; Dai et al., 2016; Hosoe, 2015; Qian et al., 2017). Different from an input-output model (Chen et al., 2018; Cui et al., 2015) or a game theory analyses, the CGE model can better analyze the impact of target issue on the whole society. We summarize three characteristics of the CGE model in this paper (Bye et al., 2018; He and Lin, 2017; Hosoe, 2018).

1) The behaviors of producers' pursuing profit maximization and consumers' pursuing utility maximization are clearly reflected by the relationship between supply and demand.
2) The quantity and relative price are both endogenous in the model, and the resource allocation method is determined by the general equilibrium model structure with Walras's law.
3) The focus of this model is on simulating the behavior of the economic entity (government, enterprises, and household). The resources of the economy in the model have been fully utilized.

The CGE model built in this paper is based on a standard CGE model in Hosoe et al. (2010). We then extract some intermediate input into factors using Constant Elasticity of Substitution (CES) functions, while the original model uses the Cobb Douglas production function in the bundle of factors (labor and capital). We also separate households into two parts: one is rural population, the other is urban population. As the original model does not aim to analyze energy and environmental issues, we have added an energy-environmental block into the model and have made the static model dynamic.

The basic modeling structure is based on Lin and Jia (2019) and Lin and Jia (2018a), which consists of five blocks: production block, income-expenditure block, trade block, energy-environmental block and macroscopic-closure & market-clearing block. The framework of this paper's model is depicted in Fig. 1.

3.1.1. Production block

The CGE model in this paper assumes that one sector produces only one product. The production block has six levels of nesting. Value-Added & Energy (VAE) and intermediate input make up the domestic output bundle following a Leontief production function. In the 2nd level, VAE is a bundle that consists of Capital-Energy bundle and labor input following a Constant Elasticity of Substitution (CES) function.

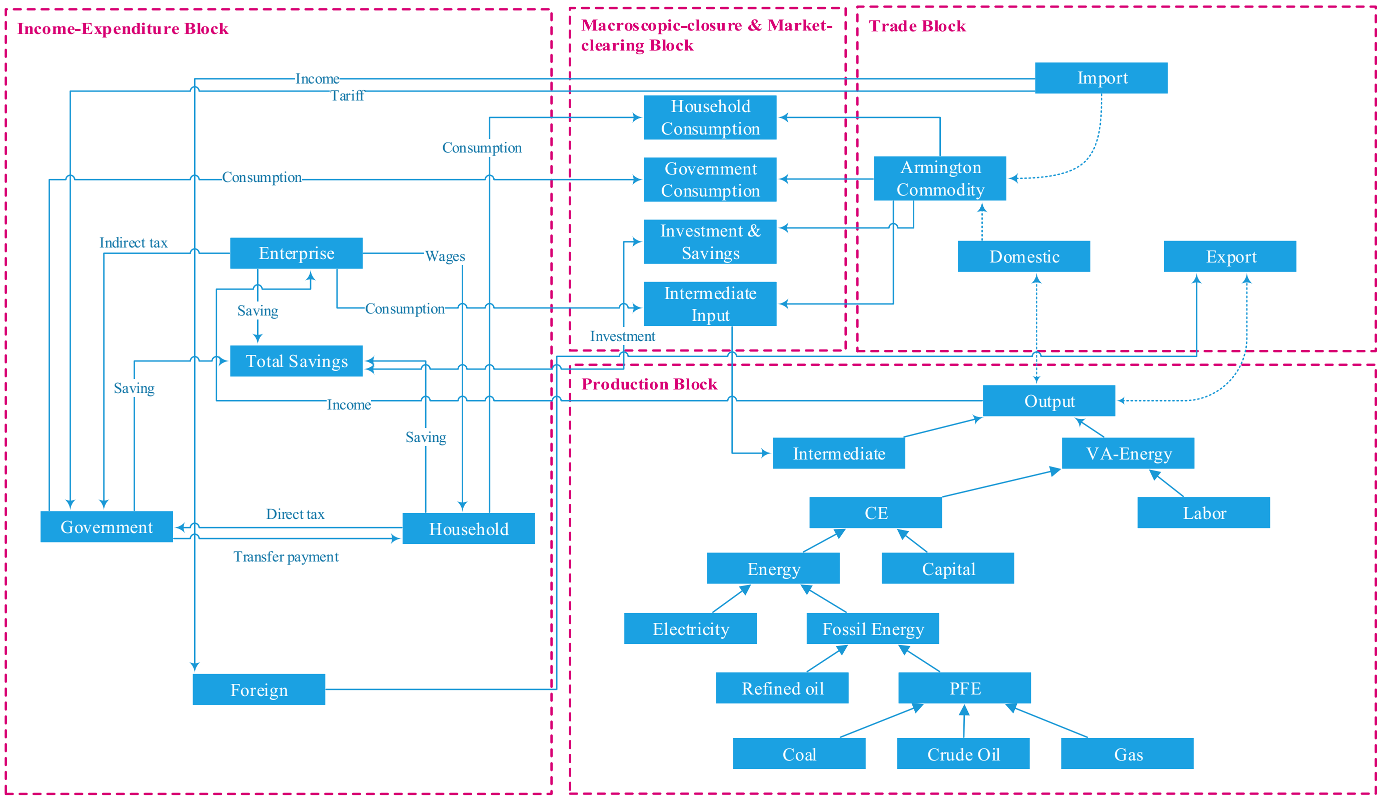


Fig. 1. The framework of the CGE model in this paper.

The 3rd level is CE bundle, which consists of capital input and energy input following a CES function. The energy bundle consists of electricity and fossil energy input following a CES production function. Fossil energy is the bundle combined with refined oil and Primary Fossil Energy (PFE) following a CES function. The last level of nesting is PFE bundle, which consists of coal, crude oil and gas input following a CES function. The elasticity of this block is set according to Fujimori et al. (2012), both in non-energy conversion sectors and energy conversion sectors. The production structure of non-energy conversion sectors is illustrated in Fig. 2 and the production structure of non-energy conversion sectors is illustrated in Fig. 3.

3.1.2. Income-expenditure block

This block introduces four social subjects: government, enterprise, households, and the rest of the world. They have their own balanced approach. Details can refer to Lin and Jia (2018b). The trade deficit is exogenous, according to Hosoe et al. (2010).

3.1.3. Energy-environmental block

This block describes how physical quantities of energy consumption and value quantities of energy input are related, and how to measure CO_2 emissions created by activities, which is similar to Fujimori et al. (2012).

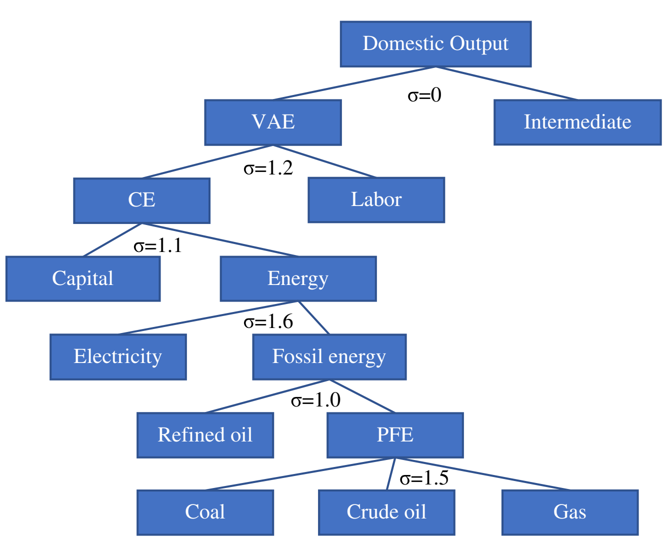


Fig. 2. The production structure of non-energy conversion sectors in the CGE model.

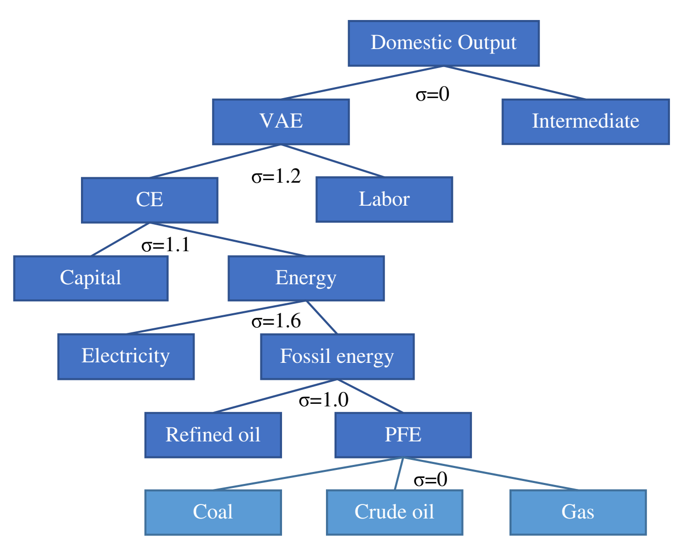


Fig. 3. The production structure of energy conversion sectors in the CGE model.

3.1.4. Trade block

Like most studies, Armington assumption is introduced into the CGE model (Beck et al., 2018; Lin and Wu, 2018; Wu et al., 2017). By using CES function (see Eqs. (1) to (3)), we differentiate domestic production from domestic consumption goods and import goods from domestic consumption. Using CET (Constant Elasticity of Transformation) functions, we simulate enterprises' distributions of production in the domestic market and international market, as shown in Eqs. (4) to (6). Tariffs and indirect taxes also play a role in the production decision of industries in this block.

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

$$M_i = \left[\frac{\gamma_i^{\eta_i} \delta m_i PQ_i}{(1+\tau_i^m) PM_i}\right]^{\frac{1}{1-\eta_i}} Q_i \tag{2}$$

$$D_i = \left[\frac{\gamma_i^{\eta_i} \delta d_i PQ_i}{PD_i}\right]^{\frac{1}{1-\eta_i}} Q_i \tag{3}$$

$$Z_i = \theta_i \left(\xi e_i E_i^{\phi_i} + \xi d_i D_i^{\phi_i}\right)^{\frac{1}{\phi_i}} \tag{4}$$

$$E_i = \left[\frac{\theta_i^{\phi_i} \xi e_i (1 + Tz_i/Z_i/PZ_i) PZ_i}{PE_i}\right]^{\frac{1}{1-\phi_i}} Z_i \tag{5}$$

$$D_i = \left[\frac{\theta_i^{\phi_i} \xi d_i (1 + Tz_i/Z_i/PZ_i) PZ_i}{PD_i}\right]^{\frac{1}{1-\phi_i}} Z_i \tag{6}$$

where Q_i and PQ_i are the quantity and price of Armington commodity of the sector *i*. M_i and PM_i are the quantity and the price of imported products of sector *i*. D_i and PD_i are the quantity and the price of domestic production goods for the domestic consumption of the sector *i*. δm_i and δd_i are import and domestic distribution factor of production function of Armington composite commodity. γ_i and θ_i denote scale coefficient of CET and CES function. η_i and ϕ_i are substitution parameter and transformation parameter based on calculations of elasticity of substitution and elasticity of transformation, respectively. τ_i^m is the tariff rate of the sector *i*. Z_i and PZ_i are the quantity and price of domestic output of the sector *i*. E_i and PE_i represent the quantity and the price of exported products of sector *i*. ξe_i and ξd_i are export and domestic distribution factor of the production function of the domestic commodity.

3.1.5. Macroscopic-closure & market-clearing block

Government budget balance, foreign trade balance, and investment-saving balance are three market closure principles are taken into account in this model. And we also considered two principles of market clearing: one is Armington commodity and the other is factors (labor and capital). All are simple assumption of the CGE model, which can refer to Hosoe (2004).

3.1.6. The setting of tax form and tax rate

Three kinds of tax forms are assumed in this paper: fixed tax, specific tax, and ad valorem tax. The first is a fixed amount of taxation in a period, which is independent of economic conditions. The tax department generally imposes fixed taxation on privately or individually owned business. The second is based on the sale amounts of productions/resources, and this tax form is the initial resource tax form in China. In China, some kinds of tariffs, resource taxes, excise taxes, travel taxes, and salt taxes are imposed at the form of specific taxes. The last type of taxation is based on the sale's value of productions/resources (quantity multiplied by price). The three kinds of tax form can be expressed by the mathematical statement like the following equations.

$$Tz_i = Fix_i \tag{7}$$

$$Tz_i = \tau_i^z Z_i \tag{8}$$

$$Tz_i = \tau_i^z PZ_i Z_i \tag{9}$$

where Tz_i is the tax on the sector *i*. Fix_i represents the amount of fixed tax on the sector *i*. τ_i^z denotes the tax rate. Z_i is the amount of domestic output of the sector *i*. PZ_i represents the price of domestic output of the sector *i*. Eq. (7) is the fixed tax, while Eq. (8) is specific tax and Eq. (9) is ad valorem tax. This paper assumes that all other industries are on ad valorem duty except for fossil energy production industries (coal, oil and gas production industries) which are on specific duty during 2012–2018.

3.2. Model dynamics

In this paper, a recursive method is used to make the CGE model dynamic. Some of the exogenous variables/parameters are updated in different periods, after, the new equilibrium is solved over again. This paper considers three principles for the model dynamic: capital accumulation, the population growth and technological progress (which is measured by Autonomous Energy Efficiency Improvement, AEEI). Capital input is equal to capital depreciation and it is calculated via a perpetual inventory method: capital depreciation is determined by the capital stock of the current period, depreciation rate and social investment. The capital depreciation rate is illustrated in Table 2.

AEEI in CGE model is considered in this study according to the relevant literature (Li et al., 2017) and *Medium and Long-term Energy Saving Special Planning* (National Development and Reform Commission, 2005). Table 3 depicts the value of the parameter of AEEI in each sector.

Labor endowment, which is an exogenous variable, is determined by *National Population Development Plan* (2016–2030) (The Central People's Government of the People's Republic of China, 2017). Table 3 shows the population growth rate in this paper.

4. Data source and scenario design

4.1. Data source and Social Accounting Matrix

The 2012 China Input-Output Table (CIOT) is used to construct a Social Accounting Matrix (SAM) in this paper which is a basic datum of the CGE model (China Input-Output Association, 2015). To analyze energy issues, an energy balance table is constructed and the data of this table was obtained from China Statistical Yearbook (National Bureau of Statistics,

Table 2
AEEI, capital depreciation rate and capital stock of each sector in CGE model.[a]

Sector's abbr.[b]	AEEI	Depreciation rate	Capital stock
AGR	0.025	0.050	4516.3
COL	0.006	0.062	1549.6
OIL	0.006	0.065	1174.0
GAS	0.006	0.065	263.4
REF	0.006	0.065	1353.3
CMC	0.015	0.055	6363.6
MTL	0.025	0.055	7085.1
MTP	0.02	0.055	1526.7
ELC	0.025	0.048	9136.3
TRA	0.033	0.052	9654.0
CST	0.006	0.055	2992.6
RST	0.01	0.052	30,068.9
OTH	0.016	0.055	26,228.8
SER	0.023	0.045	38,443.5

[a] AEEI will be in half after 2020.
[b] Sector's abbreviations can be referred to Table 5.

Table 3
Population growth rate in this paper.

Year	Population growth rate
2012–2015	0.60%
2016–2020	0.60%
2021–2025	0.21%
2026–2030	0.15%

2015). Compared with Global Carbon Budget 2017 (Le Quéré et al., 2017), we declare that the CO_2 emission in this study is only from energy consumption, and excludes biological breath, microbial decomposition, and carbon sinks and carbon emissions from land and sea. We reclassify the 139 sectors in the CIOT into 14 sectors, as shown in Table 4.

4.2. Scenario design

In order to promote energy conservation and environmental protection, China began implementing the reform of ad valorem taxation on coal resources nationwide from December 2014 (Ministry of Finance of China, 2014). Thus, this paper assumes fossil energy production industries (coal, oil and gas industries) are on specific duty rather than ad valorem duty before 2017, which means we assume that the government collects specific taxes on fossil energy companies. Moreover, in this paper we consider the three kinds of tax form: the tax based on production (specific tax, which is simulated by S, S− and S+ scenarios), the tax based on a fixed amount (fixed tax, which is simulated by F, F− and F+ scenarios) and the tax based on the value of sale (ad valorem tax, which is simulated by A, A− and A+ scenarios). We consider scenario S as the Business as Usual (BaU) scenario where fossil fuel companies pay taxes as specific tax during 2012–2030. In the countermeasure (CM) scenarios, such as A and F scenarios, the tax form of fossil energy industries will be changed in 2018. We also establish six scenarios to simulate the changes in tax rates based on different rules: S− and S+ scenarios are scenarios where the tax rate of fossil energy sectors falls or rises by 20% under the S scenario. F−, F+, A−, and A+ scenarios are similar to S− and S+ scenarios. The scenario design of tax form on energy production industries is illustrated in Table 5.

5. Results and discussion

5.1. Economic impact

5.1.1. GDP

Gross Domestic Product (GDP) in 2030 is illustrated in Fig. 4. GDP will reach 105.94, 105.95, 105.93, 105.94, 105.94, 105.95, 105.86, 105.90, and 105.80 trillion Yuan under the S, S−, S+, F, F−, F+, A, A−, and A+ scenarios, respectively. The GDP variations in these CM scenarios relative to the S scenarios will be −0.005%, 0.010%, −0.001%, 0.005%, −0.005%, 0.080%, 0.037%, and 0.132%, respectively. We found that the tax rate in the ad valorem tax system has a significant negative correlation with GDP, which means higher tax rate of fossil energy will result in lower GDP performance. The result also shows, by comparing S, F, and A scenarios, that the tax form will less significantly influence GDP than the tax rate. GDP is lowest in A scenario, compared with S, F, and A scenarios. In addition, we found that the tax rate in fixed tax form would have positive correlations on GDP to some extent, indicating that the tax rate for fixed taxes is already too low and not suitable for the changing economy over time as discussed in Section 5.1.2. Moreover, the GDP elasticity with respect to tax rates is analyzed, and we conclude the following findings:

1) GDP performance will be better in scenarios of specific tax and fixed tax, and it will be worse in the ad valorem tax scenario. The reason may be that although the ad valorem tax is feasible and can better reflect the market rules (increasing or decreasing prices of products), the ad valorem taxes are higher than specific taxes due to the rise in energy products (see Section 5.1.2). Therefore, the GDP loss caused by chain reaction is higher (which will be explained in Sections 5.1.3 and 5.1.4).
2) The elasticity of GDP with respect to the tax rate is highest in the scenarios with the ad valorem tax and lowest in the scenarios with fixed tax, which means increasing tax rate on enterprises based on ad valorem duty will result in more GDP loss. The high sensitivity of GDP to ad valorem tax rate indicates that the government should pay more attention to tax rates when enterprises are on ad valorem duty.

5.1.2. Indirect tax

Fig. 5 and Table 6 show the changes in indirect tax in all industries in all scenarios in 2030 relative to the S scenario. The changes in the tax form in the fossil energy sectors will directly affect the indirect tax of these sectors by −57.04% to 119.80% in 2030 relative to the S scenario. It should be declared that we assume tax reform is implemented in 2018, and the differences in indirect tax between these scenarios are little but the gap will increase over time. For other industries, the impact on the indirect tax will be no more than −4.28% to 2.47%, which is significantly lower than the impact of the tax of energy production sectors. In addition, the tax structure of indirect tax in all scenarios in 2030 is shown in Table 7. We found that the proportion of indirect tax on fossil energy production sectors is sensitive to the tax form and the tax rate: it will be 1.96%–7.27% in 2030.

The impact of the tax rate and the tax form in energy production sectors on the indirect tax of other industries is relatively low, which can be nearly negligible. The main reason is that taxation has led to higher energy prices, but energy factors are only small part of the costs of other downstream companies, and therefore there are insignificant effects on their costs and outputs (see Sections 5.1.3 and 5.1.4). The indirect taxation of non-energy production companies will not change much because the impact of the energy tax on the non-energy output is not very large, indicating that the energy tax has less negative effects on other

Table 4
Description and coverage of industry classification and population classification.

Abbr.	Industries
AGR	Agriculture, forestry, animal husbandry and fishery
COL	Coal mining and washing industry
OIL	Petroleum exploitation
GAS	Natural gas exploitation
REF	Refined oil
CMC	Chemicals
MTL	Metal smelting and rolling products
MTP	Metal products
ELC	Electricity
TRA	Transportation, warehousing and postal services
CST	Construction
RST	Real Estate
OTH	Other industry
SER	Services
RUR	Rural residents
CTZ	Urban residents

Table 5
Scenario design of tax form on energy production industries.

Scenarios	Tax form	Changes
S	Specific tax	0%
S−	Specific tax	−20%
S+	Specific tax	+20%
F	Fixed tax	0%
F−	Fixed tax	−20%
F+	Fixed tax	+20%
A	Ad valorem tax	0%
A−	Ad valorem tax	−20%
A+	Ad valorem tax	+20%

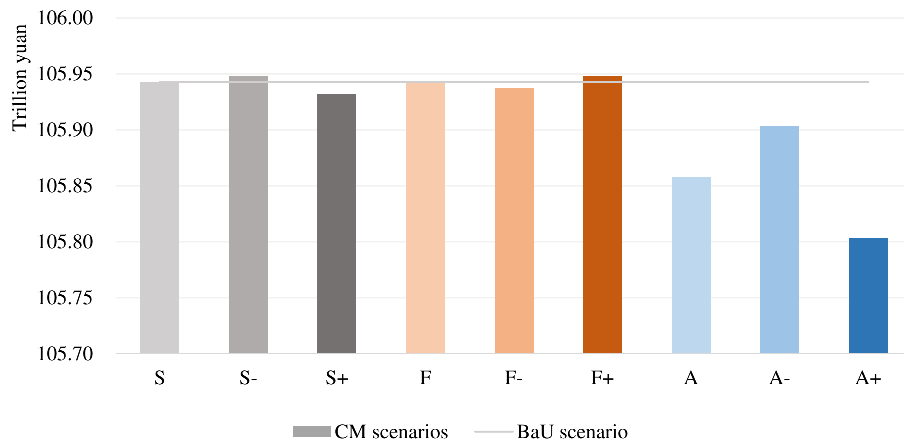


Fig. 4. GDP in all scenarios in 2030.

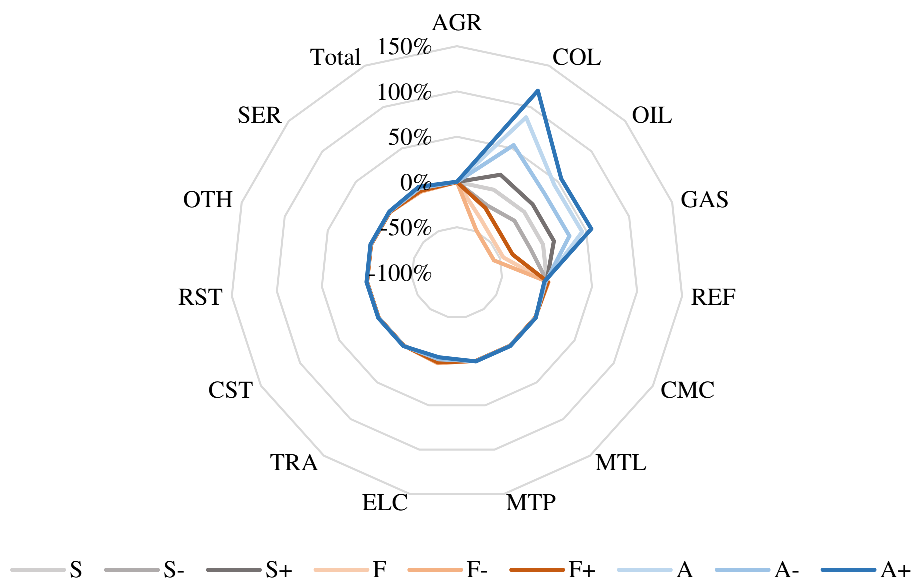


Fig. 5. The variation of indirect tax of all industries in all scenarios relative to S scenario in 2030.

industries. Interestingly, we found that the change in the indirect tax on main downstream enterprises of energy production sectors (such as refined oil and electricity) is the opposite of the change in energy production sectors. For example, electricity tax will increase while the tax on the coal industry will reduce in S+ scenario. The main reason is the price factor, which is illustrated in Fig. 6. Moreover, we found that the changes in the tax form can significantly impact on indirect tax as well as their tax rates, especially in ad valorem tax.

5.1.3. Commodity price

Fig. 7 illustrates the variation of the commodity price in all CM scenarios relative to the S scenario in 2030. The prices will reduce in S−, F, F−, and F+ scenarios while it will rise in S+, A, A−, and A+ scenarios. The price in fossil energy production will be affected in the range of −4.58% to 8.54% while other prices will be affected by not more than 2%. The main reason is that the fossil energy industries are basic industries of an economy so that the commodity prices and energy prices remain

Table 6
The variation of indirect tax of all industries in all scenarios relative to S scenario in 2030 (%).

Scenario	AGR	COL	OIL	GAS	REF	CMC	MTL	MTP	ELC	TRA	CST	RST	OTH	SER
S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S−	−0.05	−18.73	−14.53	−14.64	0.53	−0.08	−0.05	−0.08	0.77	−0.08	−0.07	−0.08	−0.09	−0.12
S+	0.05	18.19	12.47	12.61	−0.50	0.08	0.05	0.07	−0.72	0.08	0.06	0.07	0.08	0.11
F	−0.14	−35.29	−46.30	−46.16	1.34	−0.23	−0.13	−0.21	1.96	−0.24	−0.17	−0.18	−0.24	−0.31
F−	−0.17	−48.23	−57.04	−56.92	1.69	−0.28	−0.16	−0.26	2.47	−0.29	−0.22	−0.23	−0.29	−0.39
F+	−0.11	−22.35	−35.56	−35.39	0.99	−0.18	−0.11	−0.17	1.45	−0.18	−0.12	−0.13	−0.19	−0.22
A	0.20	87.64	44.68	45.47	−2.25	0.34	0.22	0.32	−3.19	0.34	0.28	0.32	0.37	0.47
A−	0.12	53.95	30.18	30.60	−1.39	0.21	0.13	0.19	−1.98	0.21	0.18	0.20	0.22	0.30
A+	0.26	119.80	54.90	56.06	−3.03	0.46	0.31	0.43	−4.28	0.46	0.36	0.44	0.50	0.63

Table 7
Tax structure of indirect tax in all scenarios in 2030.

Scenario	Indirect tax			The proportion of indirect tax	
	Energy sectors	Non-energy sectors	Total indirect tax	Proportion of fossil energy tax	Proportion of non-fossil energy tax
S	801.68	18,899.36	19,701.04	4.07%	95.93%
S−	669.44	18,893.28	19,562.72	3.42%	96.58%
S+	923.10	18,905.00	19,828.10	4.66%	95.34%
F	471.69	18,882.38	19,354.07	2.44%	97.56%
F−	377.35	18,878.43	19,255.78	1.96%	98.04%
F+	566.03	18,886.42	19,452.44	2.91%	97.09%
A	1320.80	18,923.23	20,244.04	6.52%	93.48%
A−	1132.67	18,914.32	20,046.99	5.65%	94.35%
A+	1484.90	18,931.14	20,416.04	7.27%	92.73%

basically synchronized in the direction of change, with other conditions unchanged. In this section, we obtain several results:

1) The fixed tax will reduce prices in all production while the ad valorem tax will increase them.
2) Increasing tax rates on energy productions will raise commodity prices.
3) The elasticity of prices in fossil energy production with respect to energy tax is higher that of non-energy prices.
4) Price is more vulnerable to ad valorem tax rate than fixed tax and specific tax, which is similar to the result of GDP.

5.1.4. Industrial output

The variation in industrial output in all CM scenarios relative to S scenario in 2030 is depicted in Fig. 8. In F, F− and F+ scenarios, the output of coal, oil and gas industries will increase by 2.61–4.73%, 15.31–24.36%, and 14.86–24.71%, respectively, and the output of refined oil and electricity will increase by 1.48–2.56% and 1.87–3.22% while the outputs of other industries will be less affected. The output of coal, oil, and gas will be directly affected by the tax form and tax rates, and this influence will initially involve energy transformation industries (such as refined oil and electricity industries), and finally spread to all industries. Through changes in sectoral output, we found that adjusting the tax form and tax rates have great potential for energy conservation, while they have a minor impact on the output of other industries.

5.1.5. International competitiveness of industries

China is a big net exporter of goods. So this paper wonders if the changes of tax form will impact on the international competitiveness of export-oriented industries. Firstly, we figured out an indicator, export divided by total output in SAM, then selected those industries whose indicator is above 1%, and analyze the changes in export of these industries. As depicted in Fig. 9, we found that the export of the refined oil industry will decrease more than 2% when the tax system changes from specific to ad valorem. If fixed tax is implemented in energy production industries, the industry will increase more than 2% of exports. However, other industries show a stable performance in export and commodity price (Section 5.1.3). It seems that the taxes have few effects on competitiveness of the Chinese economy.

5.2. Energy impact

5.2.1. Fossil energy demand

Demands for coal, crude oil, natural gas and refined oil in all sectors in all scenarios in 2030 are illustrated in Figs. 10, 11, 12 and 13, respectively. Fossil energy demands for the coal, oil and gas industry are most affected by the changes in energy tax by-36.07% to 26.46%. The next is the downstream industries, such as refined oil and electricity by −8.02% to 4.57%. The results show that electricity is still the biggest coal consumer accounting for 44.68% of total coal demand in 2030. The coal demand of the electricity industry is also the most vulnerable

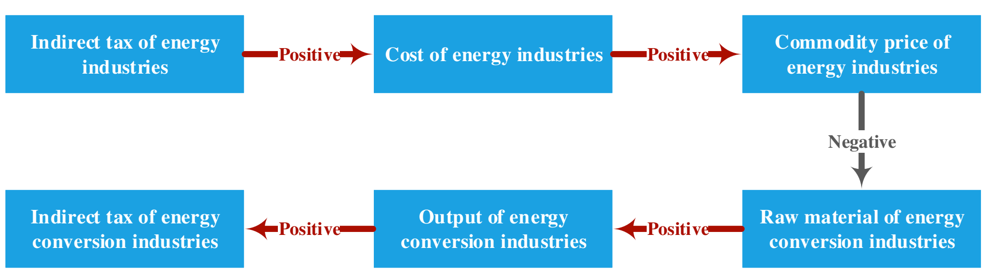


Fig. 6. The relationship between tax on energy industries and energy conversion industries when tax on energy industries changes.

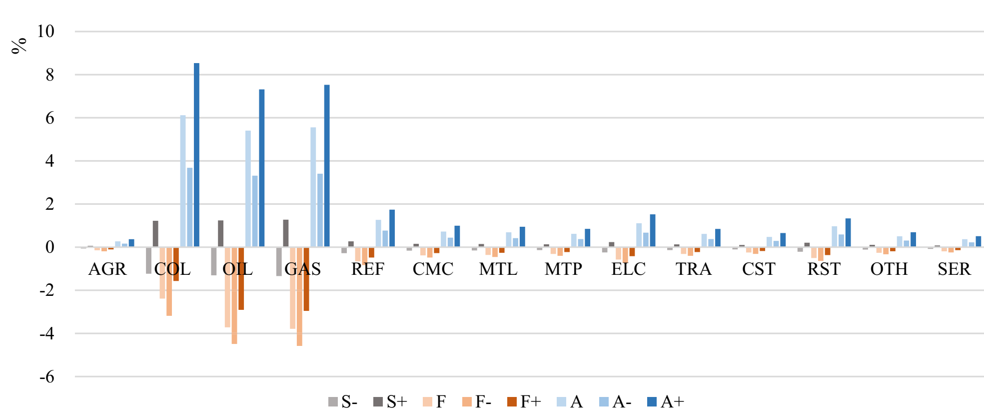


Fig. 7. The variation of commodity price in all CM scenarios relative to S scenario in 2030.

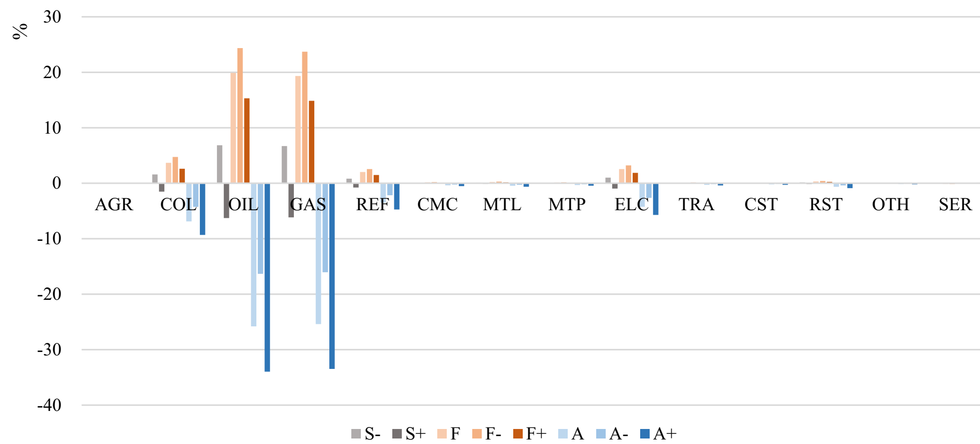


Fig. 8. The variation of industrial output in all CM scenarios relative to S scenario in 2030.

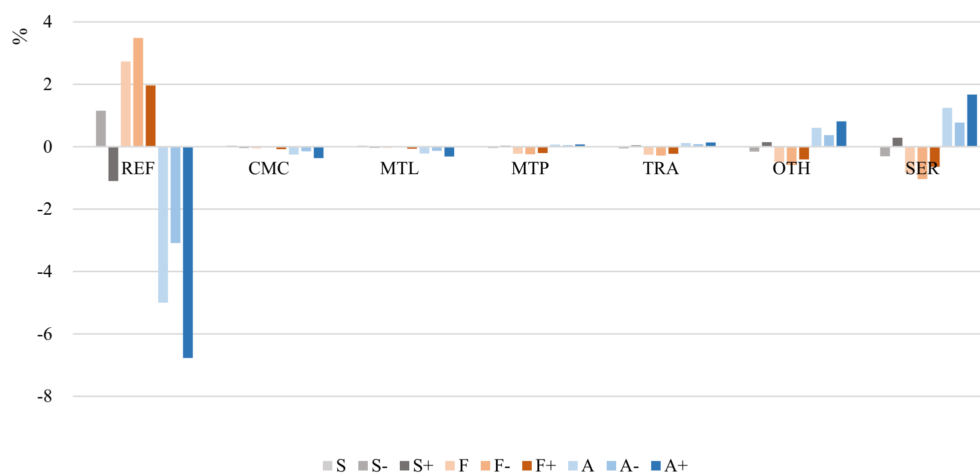


Fig. 9. The variation of export in all CM scenarios relative to S scenario in 2030.

industry to the changes in energy tax form and tax rates except for fossil energy industries. Demand will range from 1559.57 million tons of coal equivalent (Mtce) to 1772.97 Mtce. Almost all crude oil is consumed by the petroleum processing industry. Changes in the tax form and tax rates can also change the oil demand of the petroleum processing industry: consumption will be 955.69 Mtce in A+ scenario and 1066.26 Mtce in F− scenario. The demand for natural gas is relatively low in China and the impact is similar to coal demand. The transportation industry is the biggest consumer of refined oil which accounts for 50% of refined oil consumption in China. Unlike electricity or refined oil industries, transportation is nearly less affected by energy tax. The main reason is that the increase in energy tax will directly and significantly raise the cost of energy price, but indirectly and modestly increase the price of refined oil (which can refer to Section 5.1.3), so that the cost of transportation

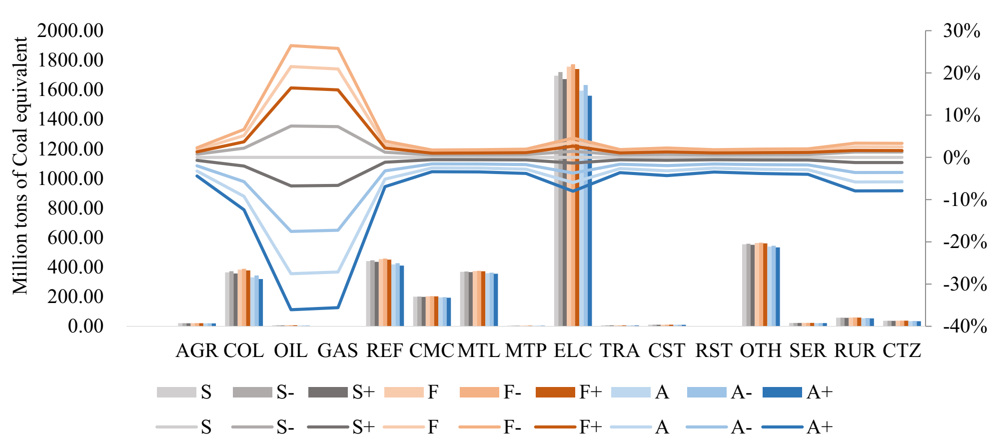


Fig. 10. Coal demand of all sectors and the variation of coal demand in all CM scenarios relative to S scenario in 2030.

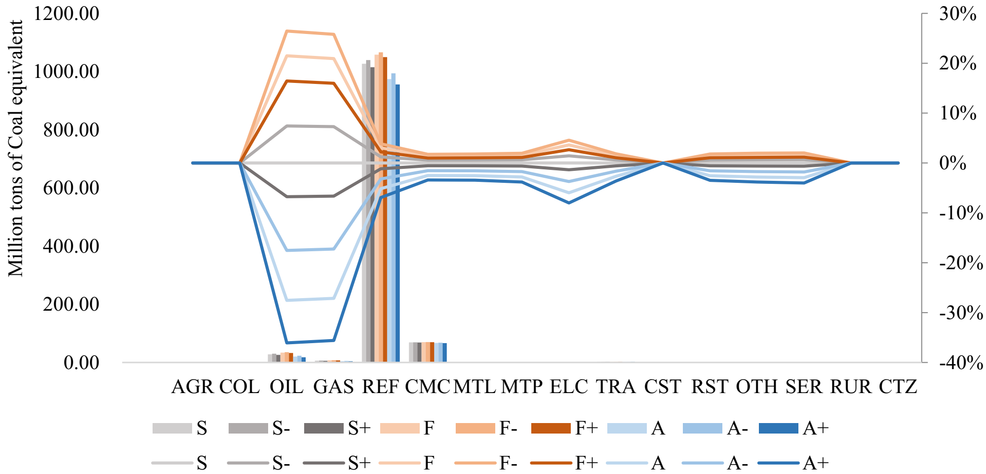


Fig. 11. Crude oil demand of all sectors and the variation of crude oil demand in all CM scenarios relative to S scenario in 2030.

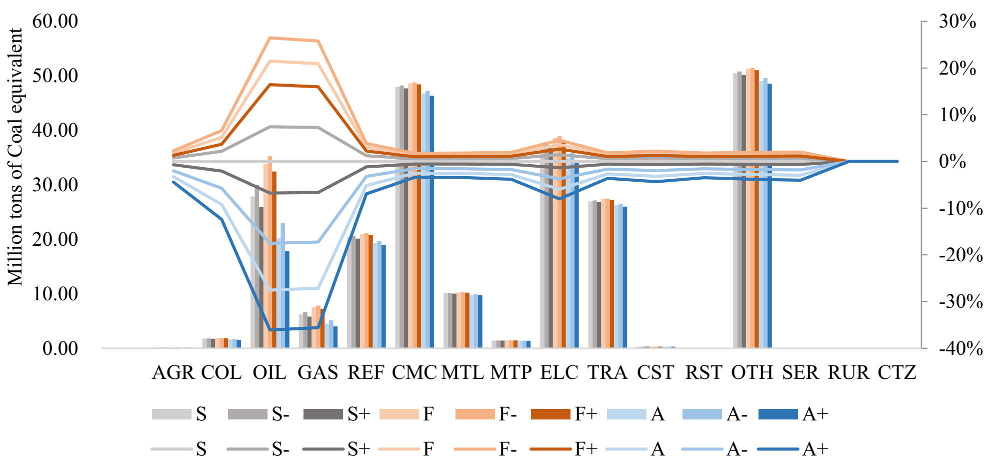


Fig. 12. Natural gas demand of all sectors and the variation of natural gas demand in all CM scenarios relative to S scenario in 2030.

will be affected moderately. Moreover, we noticed that the changes in the energy demand are similar to the variations in industrial output, which is determined by the enterprise production function.

As for the demand for fossil energy by residents, we found that the coal demand of the rural population is more affected than that of urban population. The reason may be that coal is needed by rural people in northern China to keep the house warm in winter, unlike the urban population. Also, the price elasticity of low income people is greater than that of high income people. However, we observe the opposite impact on the household demand for gasoline or diesel (refined oil). Urban

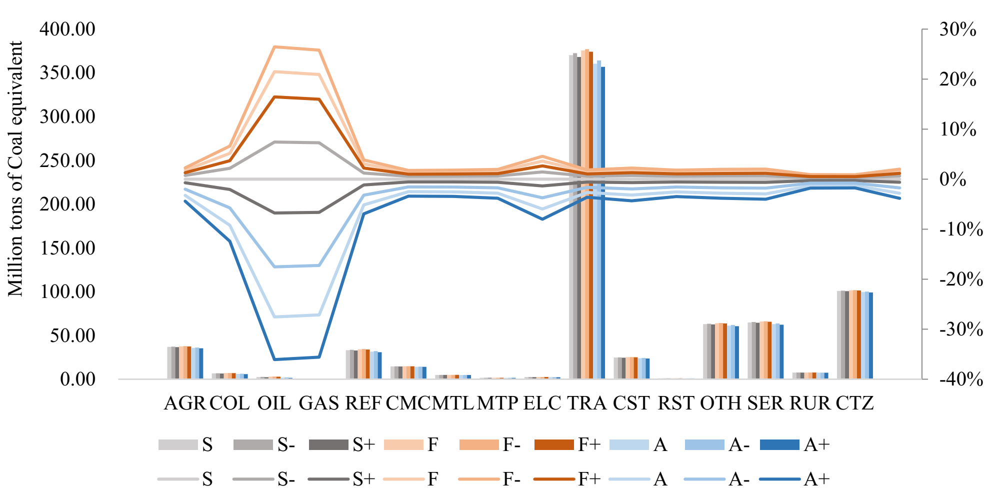


Fig. 13. Refined oil demand of all sectors and the variation of refined oil demand in all CM scenarios relative to S scenario in 2030.

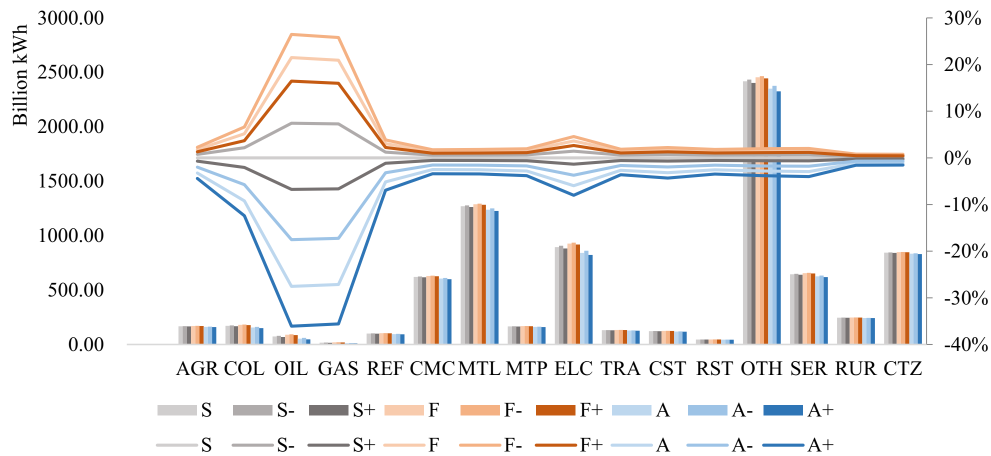


Fig. 14. Electricity demand of all sectors and the variation of electricity demand in all CM scenarios relative to S scenario in 2030.

residents will change their demands for refined oil more than rural residents. This is because the demand of urban population is far higher than that of rural people: the consumption of town is 13.28 times that of the countryside.

5.2.2. Electricity demand

The electricity demand of all sectors and the variation of it in all CM scenarios relative to S scenario in 2030 are illustrated in Fig. 14. The variation in the electricity demand is similar to the variation in fossil energy demand. The total electricity demand will be 7935.11, 7997.58, 7875.86, 8090.08, 8130.77, 8048.57, 7670.02, 7770.90, and 7577.19 billion kWh (B-kWh) in the S, S−, S+, F, F−, F+, A, A−, and A+ scenarios respectively. This indicates a change of 0.00%, 0.79%, −0.75%, 1.95%, 2.47%, 1.43%, −3.34%, −2.07%, and −4.51% relative to the S scenario. The impact on residents' electricity demand is insignificant, as the impact on residents is the last link in the transmission mechanism (fossil energy companies - energy transformation companies – other companies - residents). Moreover, we found that the impact of a rising energy tax on energy demand is greater than the impact on sectoral output. So it can be argued that energy efficiency will increase to some extent, which is discussed in Section 5.2.3.

5.2.3. Energy efficiency

The variation in energy efficiency in all CM scenarios relative to S scenario in 2030 is illustrated in Fig. 15. Energy efficiency in this paper is calculated by domestic output divided by energy consumption in each sector. Energy efficiency will increase in S+, A, A−, and A+ scenarios by 0.38–4.53% and will reduce in S−, F, F−, and F+ scenarios by −2.23% to −0.40%. The tax rates and the tax form can directly impact on the variation of energy efficiency. Moreover, we found that the elasticity of energy efficiency with respect to ad valorem tax rate is higher than that of fixed and specific tax, which means that higher ad valorem tax can result in higher energy efficiency in all industries in China, especially in the agriculture, construction and service industries, by 4.53%, 4.22 and 4.28% respectively.

5.3. Environment impact

5.3.1. CO_2 reduction

Fig. 16 shows CO_2 emissions reductions during 2017–2030 in all CM scenarios relative to the S scenario. The reduction in S+, A, A− and A+ scenarios will be 0.16–0.19 billion tons of CO_2 (Bt-CO_2), 0.19–0.73 Bt-CO_2, −0.015-0.45 Bt-CO_2 and 0.40–0.98 Bt-CO_2 respectively during 2018–2030. In the S+, F, F− and F+ scenarios, CO_2 emissions will increase by 0.18–0.21 Bt-CO_2, 0.32–0.44 Bt-CO_2, 0.52–0.55 Bt-CO_2 and 0.10–0.32 Bt-CO_2, respectively. Although CO_2 emissions will decrease in the S scenario, the positive impact on CO_2 reduction will reduce year by year. For instance, the reduction will be 0.19 Bt-CO_2 in 2018 but will be 0.16 Bt-CO_2 in 2030. There will be no long-term significant benefits for reducing CO_2 emissions. However, we found that in the ad valorem tax scenarios, the reduction will increase over time. Moreover, we also found that the capacity of CO_2 emissions control under ad

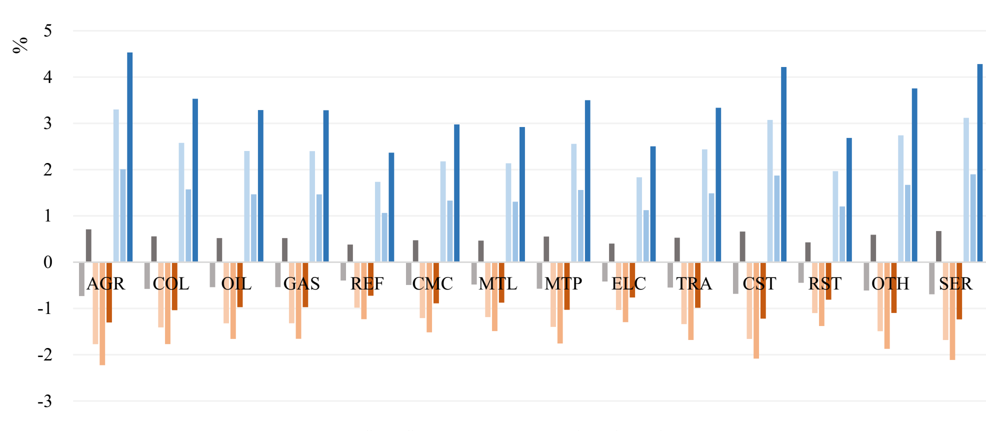
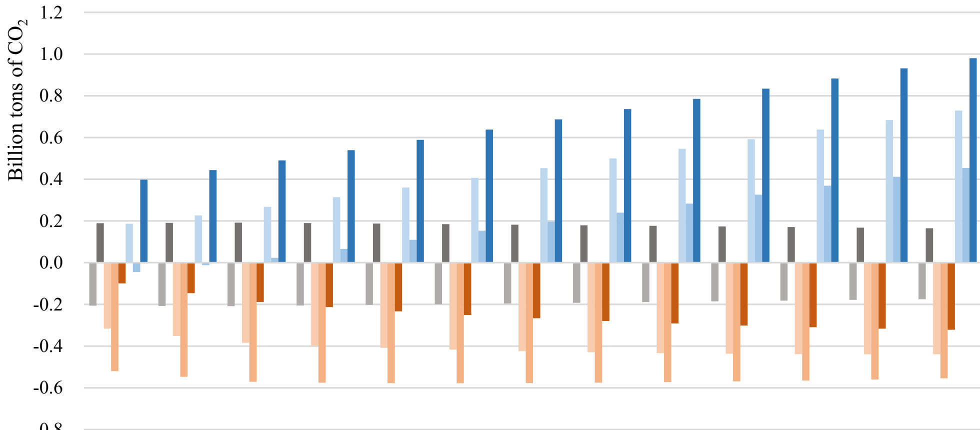


Fig. 15. The variation of energy efficiency in all CM scenarios relative to S scenario in 2030.



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
S-	-0.21	-0.21	-0.21	-0.21	-0.20	-0.20	-0.20	-0.19	-0.19	-0.19	-0.18	-0.18	-0.18
S+	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.17	0.17	0.17	0.16
F	-0.32	-0.35	-0.38	-0.40	-0.41	-0.42	-0.42	-0.43	-0.43	-0.44	-0.44	-0.44	-0.44
F-	-0.52	-0.55	-0.57	-0.58	-0.58	-0.58	-0.58	-0.58	-0.57	-0.57	-0.56	-0.56	-0.55
F+	-0.10	-0.15	-0.19	-0.21	-0.23	-0.25	-0.27	-0.28	-0.29	-0.30	-0.31	-0.32	-0.32
A	0.19	0.23	0.27	0.31	0.36	0.41	0.45	0.50	0.55	0.59	0.64	0.68	0.73
A-	-0.05	-0.01	0.02	0.07	0.11	0.15	0.20	0.24	0.28	0.33	0.37	0.41	0.45
A+	0.40	0.44	0.49	0.54	0.59	0.64	0.69	0.74	0.79	0.83	0.88	0.93	0.98

Fig. 16. CO_2 emissions reduction during 2017–2030 in all CM scenarios relative to S scenario.

valorem tax is greater than under specific tax, and the latter is greater than the fixed tax. The result shows that the elasticity of ad valorem tax is higher than that of fixed tax and specific tax, which means a higher tax rate can result in greater CO_2 reduction.

5.3.2. CO_2 emission intensity

CO_2 emission intensity is calculated by CO_2 emissions divided by GDP. CO_2 emission intensity (CI) during 2017–2030 in all CM scenarios relative to S scenario is illustrated in Fig. 17. CI will be 0.156 tons of CO_2/thousand yuan in 2017 and will reduce to 0.128 tons of CO_2/thousand yuan in 2030 in S scenario. CI in the S−, S+, F, F−, F+, A, A−, and A+ scenarios in 2030 will be 0.130, 0.127, 0.132, 0.133, 0.131, 0.121, 0.124, and 0.119 tons of CO_2/thousand yuan, respectively. The results show that the ad valorem tax can reduce CO_2 emission intensity more significantly than other tax forms. More so, the reduction will increase over time, indicating that ad valorem tax has the highest efficiency of long term emission reduction, especially in high tax rate scenario.

According to Intended Nationally Determined Contributions of China, China tries to achieve the peaking of CO_2 emissions around 2030 and lower CO_2 emissions per unit of GDP by 60%to 65% from the 2005 level. According to data in Global Carbon Budget and National Bureau of Statistics of China, 2030 the emission intensity should under 0.126 tons of CO_2/thousand yuan. The results in this paper show that

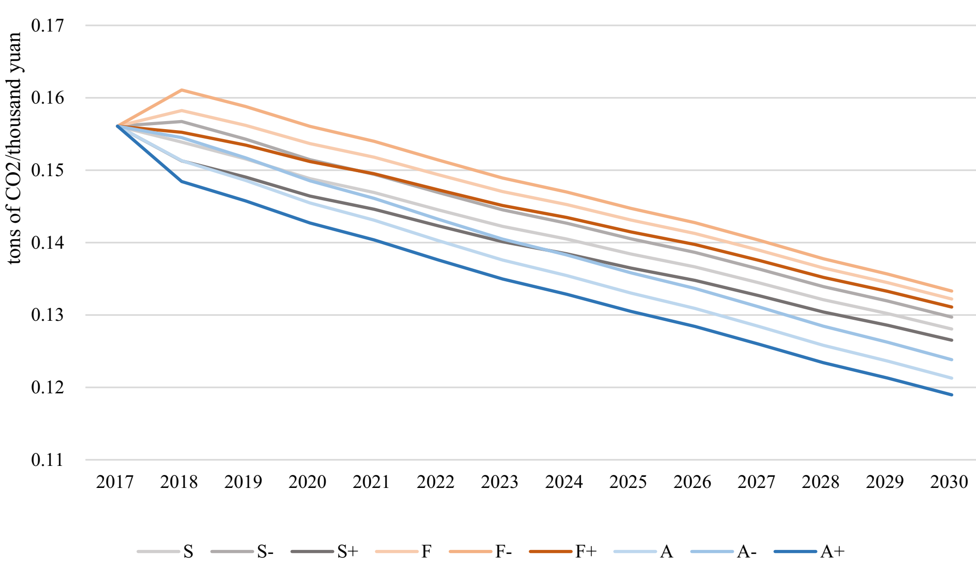


Fig. 17. CO_2 emission intensity during 2017–2030 in all CM scenarios relative to S scenario.

Table 8
Sensitivity analysis.

Scenario	Key indicators (2030)	Elasticity of domestic output		AEEI	
		−10%	+10%	−10%	+10%
S	CO2 emissions	−1.042%	0.921%	−2.777%	2.828%
	GDP	−0.008%	0.007%	−3.086%	3.165%
F	CO2 emissions	−1.128%	0.997%	−2.913%	2.972%
	GDP	−0.005%	0.004%	−3.082%	3.160%
A	CO2 emissions	−0.895%	0.789%	−2.921%	2.983%
	GDP	−0.010%	0.009%	−3.096%	3.175%

peak will be not achieved by doing nothing about emission reduction work. However, the target of carbon intensity could be achieved in A, A− and A+ scenarios.

6. Sensitivity analysis

As some of the parameters are subjective. This paper conducts a sensitivity analysis to test the sensitivity of these subjective parameters, such as elasticity and AEEI (Table 8). We assumes that the value of these parameters decrease or increase by 10%, we then re-run our model to see the changes in these key indicators. We found that the elasticity has less impact on GDP, but it will decrease or increase CO2 emissions to a certain extent, from −1.128% to 0.997%. When elasticity changes, CO2 emissions are more vulnerable in fixed tax scenario and GDP is more vulnerable in ad valorem tax scenario. The key indicators are more sensitive to the value of AEEI than elasticity, as AEEI will increase or decrease the output year by year. However, in general, the sensitivity of key indicators to these parameters is not high.

7. Conclusions, policy implication and limitations

7.1. Conclusions

This paper constructs a dynamic recursive CGE model to analyze the impact of energy resource tax on energy, economy and the environment from the perspective of tax form and tax rates. The conclusions of the study are as follows:

GDP performance is better in specific tax and fixed tax scenarios and worse in ad valorem tax scenario. The proportion of indirect tax on fossil energy production sectors is sensitive to the tax form and tax rate: it will be 1.96% to 7.27% in 2030. The change in indirect tax on the main downstream enterprises of energy production sectors is opposite the change in energy production sectors. Increasing the tax rates of energy production will increase commodity prices. The fixed tax will reduce prices in all production while the ad valorem tax will increase the price. The elasticity of prices in fossil energy production with respect to energy tax is higher that of non-energy prices. Adjusting the tax system and the tax rate has important implications for energy conservation, while having a minor impact on the output of other industries. The impact of an increasing energy tax on energy demand is greater than the impact on sectoral output, indicating that energy efficiency will increase to some extent. In ad valorem tax scenarios, the reduction will increase over time.

Generally, the high sensitivity of GDP, energy demand, commodity price and CO_2 reduction to ad valorem tax rate indicates that governments should pay more attention to tax rates of enterprises which are on ad valorem duty. Moreover, we found that it is unrealistic to attempt to use the changes in the tax rate of resources tax to achieve the goal of economic welfare and emission reductions. Higher emission reduction capacity will result in greater GDP loss using the method of changing the tax rate.

7.2. Policy implication

According to the conclusions of this study, this paper provides the following policy suggestions:

1) The relatively low rates for resources tax, including coal, oil, and natural gas, leading to a relatively low utilization cost of these resources, which is difficult to promote the rational development and utilization of resources. It is also not conducive for the formation of a reasonable price mechanism for energy resources. Therefore, we suggest that increasing the tax rate of energy resource is very necessary.
2) Ad valorem tax can promote energy efficiency in all industries and reduce CO_2 emissions. Therefore, this paper supports the direction of China's resource tax reform. However, we noticed that the government wants to ensure that the overall burden of coal companies will not increase when reforming coal resource tax. We argue that it is not reasonable to leave the burden of fossil energy industries unchanged in the process of China's resource tax reform. As the elasticity of CO_2 reduction on ad valorem tax rate is greater than other tax forms, it is better to increase the tax rate and relax control on energy prices reasonably, so that price can guide the market. More so, the negative impact on non-energy sectors and household is not significant (see Sections 5.1 and 5.2).
3) As the price and output of coal are less sensitive to resource taxes than oil and natural gas, while China's coal consumption is huge, the tax rate on coal can be moderately increased after China's resource tax reform, but the tax rate on oil and natural gas should not be excessively increased.

7.3. Limitations

This paper compares the effects of different tax systems on energy, economy, and environment by using a dynamic recursive CGE model. However, some problems still exist that need to be further addressed. For example, although oil and gas account for a small proportion of total primary energy consumption, price controls in these two markets may have a negative impact on the accuracy of model simulations. The authors will endeavor to tackle this problem in the future.

Declaration of competing interest

We declare no conflict of interest.

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Appendix A. Main abbreviations

Table A.1
The main abbreviations in this paper.

Abbr.	Full name
PFE	Primary Fossil Energy
CE	Capital-Energy bundle

Table A.1 (*continued*)

Abbr.	Full name
VAE	Value-Added & Energy
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CO_2	Carbon dioxide
AEEI	Autonomous Energy Efficiency Improvement
GDP	Gross Domestic Product
CI	CO_2 emission intensity
SAM	Social Accounting Matrix
CGE	Computable General Equilibrium
CM	Counter-measured scenario
S/S−/S+	Scenarios that energy sectors are on Specific duty
F/F−/F+	Scenarios that energy sectors are on Fixed duty
A/A−/A+	Scenarios that energy sectors are on Ad valorem duty

Appendix B. Framework of CGE model in this paper

B.1. Production block

$$PFE_i = \alpha_i^{pfe}\left[\delta_i^{pfe,coal}COAL_i^{\rho_i^{pfe}} + \delta_i^{pfe,oil}OIL_i^{\rho_i^{pfe}} + \left(1-\delta_i^{pfe,coal}-\delta_i^{pfe,oil}\right)GAS_i^{\rho_i^{pfe}}\right]^{1/\rho_i^{pfe}} \tag{B.1}$$

$$\frac{PCOAL_i}{POIL_i} = \frac{\delta_i^{pfe,coal}}{\delta_i^{pfe,oil}}\left(\frac{OIL_i}{COAL_i}\right)^{\left(1-\rho_i^{pfe}\right)} \tag{B.2}$$

$$\frac{PCOAL_i}{PGAS_i} = \frac{\delta_i^{pfe,coal}}{1-\delta_i^{pfe,coal}-\delta_i^{pfe,oil}}\left(\frac{GAS_i}{COAL_i}\right)^{\left(1-\rho_i^{pfe}\right)} \tag{B.3}$$

$$PFE_iPPFE_i = COAL_iPCOAL_i + OIL_iPOIL_i + GAS_iPGAS_i \tag{B.4}$$

$$FOSSIL_i = \alpha_i^{fossil}\left[\delta_i^{fossil}PFE_i^{\rho_i^{fossil}} + \left(1-\delta_i^{fossil}\right)REF_i^{\rho_i^{fossil}}\right]^{1/\rho_i^{fossil}} \tag{B.5}$$

$$\frac{PPFE_i}{PREF_i} = \frac{\delta_i^{fossil}}{1-\delta_i^{fossil}}\left(\frac{REF_i}{PFE_i}\right)^{\left(1-\rho_i^{fossil}\right)} \tag{B.6}$$

$$FOSSIL_iPFOSSIL_i = PFE_iPPFE_i + REF_iPREF_i \tag{B.7}$$

$$ENE_i = \alpha_i^{ene}\left[\delta_i^{ene}ELE_i^{\rho_i^{ene}} + (1-\delta_i^{ene})FOSSIL_i^{\rho_i^{ene}}\right]^{1/\rho_i^{ene}} \tag{B.8}$$

$$\frac{PELE_i}{PFOSSIL_i} = \frac{\delta_i^{ene}}{1-\delta_i^{ene}}\left(\frac{FOSSIL_i}{ELE_i}\right)^{\left(1-\rho_i^{ene}\right)} \tag{B.9}$$

$$ENE_iPENE_i = ELE_iPELE_i + FOSSIL_iPFOSSIL_i \tag{B.10}$$

$$CE_i = \alpha_i^{ke}\left[\delta_i^{ke}ENE_i^{\rho_i^{ke}} + \left(1-\delta_i^{ke}\right)CAP_i^{\rho_i^{ke}}\right]^{1/\rho_i^{ke}} \tag{B.11}$$

$$\frac{PENE_i}{PCAP_i} = \frac{\delta_i^{ke}}{1-\delta_i^{ke}}\left(\frac{CAP_i}{ENE_i}\right)^{\left(1-\rho_i^{ke}\right)} \tag{B.12}$$

$$CE_iPCE_i = ENE_iPENE_i + CAP_iPCAP_i \tag{B.13}$$

$$VAE_i = \alpha_i^{vae}\left[\delta_i^{vae}CE_i^{\rho_i^{vae}} + (1-\delta_i^{vae})LAB_i^{\rho_i^{vae}}\right]^{1/\rho_i^{vae}} \tag{B.14}$$

$$\frac{PCE_i}{PLAB_i} = \frac{\delta_i^{vae}}{1-\delta_i^{vae}}\left(\frac{LAB_i}{CE_i}\right)^{\left(1-\rho_i^{vae}\right)} \tag{B.15}$$

$$VAE_iPVAE_i = CE_iPCE_i + LAB_iPLAB_i \tag{B.16}$$

$$INT_{i,j} = a_{i,j}^{INT} Z_j \tag{B.17}$$

$$VAE_j = a_j^{VAE} Z_j \tag{B.18}$$

$$PZ_j = a_j^{vae} PVAE + \sum_i a_{i,j}^{INT} PQ_i \tag{B.19}$$

B.2. Income-expenditure block

$$SP_l = ss_l{}^p \sum_i \left(\gamma_l^{lab} LAB_i \cdot PLAB_i + \gamma_l^{cap} CAP_i \cdot PCAP_i \right) \tag{B.20}$$

$$SG = ss^g \left(\sum_l TD_l + \sum_i TZ_i + \sum_i TM_i \right) \tag{B.21}$$

$$XP_{i,l} = \frac{\beta_{i,l}{}^{xp}}{PQ_i} \left(\sum_i \left(\gamma_l^{lab} LAB_i \cdot PLAB_i + \gamma_l^{cap} CAP_i \cdot PCAP_i \right) - SP_l - TD_l \right) \tag{B.22}$$

$$XG_i = \frac{\mu_i}{PQ_i} \left(\sum_l TD_l + \sum_i TZ_i + \sum_i TM_i - SG \right) \tag{B.23}$$

$$TD_l = \tau_l^d \sum_i \left(\gamma_l^{lab} LAB_i \cdot PLAB_i + \gamma_l^{cap} CAP_i \cdot PCAP_i \right) \tag{B.24}$$

$$TZ_i = FIX_i, \text{ if it is fixed tax} TZ_i = \tau^z Z_i, \text{ if it is specific tax} TZ_i = \tau^z PZ_i Z_i, \text{ if it is ad valorem tax} \tag{B.25}$$

$$TM_i = \tau^m PM_i M_i \tag{B.26}$$

B.3. Trade block

$$PE_i = \varepsilon PWE_i \tag{B.27}$$

$$PM_i = \varepsilon PWM_i \tag{B.28}$$

$$\sum_i PWE_i E_i + SF = \sum_i PWM_i M_i \tag{B.29}$$

$$Q_i = \gamma_i \left(\delta m_i M_i{}^{\eta_i} + \delta d_i D_i{}^{\eta_i} \right)^{1/\eta_i} \tag{B.30}$$

$$M_i = \left[\frac{\gamma_i{}^{\eta_i} \delta m_i PQ_i}{(1+\tau_i^m) PM_i} \right]^{\frac{1}{1-\eta_i}} Q_i \tag{B.31}$$

$$D_i = \left[\frac{\gamma_i{}^{\eta_i} \delta d_i PQ_i}{PD_i} \right]^{\frac{1}{1-\eta_i}} Q_i \tag{B.32}$$

$$Z_i = \theta_i \left(\xi e_i E_i^{\phi_i} + \xi d_i D_i^{\phi_i} \right)^{\frac{1}{\phi_i}} \tag{B.33}$$

$$E_i = \left[\frac{\theta_i{}^{\phi_i} \xi e_i (1 + TZ_i/Z_i/PZ_i) PZ_i}{PE_i} \right]^{\frac{1}{1-\phi_i}} Z_i \tag{B.34}$$

$$D_i = \left[\frac{\theta_i{}^{\phi_i} \xi d_i (1 + TZ_i/Z_i/PZ_i) PZ_i}{PD_i} \right]^{\frac{1}{1-\phi_i}} Z_i \tag{B.35}$$

B.4. Energy and environmental block

$$EM_i = ENE\_COAL_i \times \gamma^{coal} + ENE\_OIL_i \times \gamma^{oil} + ENE\_GAS_i \times \gamma^{gas} \tag{B.36}$$

$$COAL_i = \chi_i^{coal} \times ENE\_COAL_i \tag{B.37}$$

$$OIL_i = \chi_i^{oil} \times ENE\_OIL_i \tag{B.38}$$

$$GAS_i = \chi_i^{gas} \times ENE\_GAS_i \tag{B.39}$$

B.5. macroscopic-closure & market-clearing block

$$XV_i = \frac{\lambda_i}{PQ_i}\left(\sum\nolimits_l SP_l + SG + \varepsilon SF\right) \tag{B.40}$$

$$Q_i = \sum_l XP_{i,l} + XG_i + XV_i + \sum_j X_{i,j} \tag{B.41}$$

$$\sum_i LAB_i = \sum_l FF_l^{lab} \tag{B.42}$$

$$\sum_i CAP_i = \sum_l FF_l^{cap} \tag{B.43}$$

B.6. Objective function

$$TOTUU = \sum_l \left(\prod_i XP_{i,l}{}^{\alpha_{i,l}} \right) \tag{B.44}$$

B.7. Description of the equations

Eqs. (B.1) to (B.4) are a bundle of CES production function. The first is the CES function, the second is the first-order condition of the CES function, and the last is the value balance equation. From Eqs. (B.1) to (B.16), all of them are CES based bundles in production block. Eqs. (B.17) to (B.19) describe the equation bundle of Leontief production function.

Income and expenditure block expresses the behaviors of household savings (Eq. (B.20)), government savings (Eq. (B.21)), household consumption (Eq. (B.22)), government consumption (Eq. (B.23)), direct tax (Eq. (B.24)), indirect tax (Eq. (B.25)), and tariff (Eq. (B.26)).

Eqs. (B.27) and (B.28) describe the relationship between domestic price and international price. Eq. (B.29) expresses trade deficit. Eqs. (B.30) to (B.32) are Armington assumption, which describe the behavior of consuming import goods and consuming domestic goods. Eq. (B.30) is a CES function and the next two equations are first order conditions of it. Similar to the former equation bundle, Eqs. (B.33) to (B.35) describe the behavior of domestic enterprises to distribute their product to domestic market and international market. Among them, Eq. (B.33) is a CET function.

Eqs. (B.36) and (B.39) describe the relationship among fossil fuel, CO_2 emissions, and factor inputs in production block.

Eq. (B.40) is mathematical expression of macroscopic closure. Eqs. (B.41), (B.42) and (B.43) are mathematical expressions of market clearing. Eq. (B.44) is utility function, which is also an objective function.

Appendix C. Simplified and balanced SAM in this paper

Table C.1
SAM in this paper.

	A	Lab	C	InT	T	R	U	G	I	R	Total
A	103,981					3599	12,519	5833	18,413	13,767	158,112
Lab	24,939										24,939
C	7296										7296
InT	7749										7749
T	1319										1319
R		7068	1115								8183
U		17,871	6180								24,052
G				7749	1319	148	436				9652
I						4437	11,097	3819		−939	18,413
R	12,827										12,827
Total	158,112	24,939	7296	7749	1319	8183	24,052	9652	18,413	12,827	

Notes: A is activity, Lab is labor, C is capital, InT is indirect tax, T is tariff, R is rural population, U is urban population, G is government, I is investment, and R is rest of the world.

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