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The effects and reacts of COVID-19 pandemic and international oil price on energy, economy, and environment in China

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HIGHLIGHTS

• A dynamic recursive multi-sector CGE model is applied for comprehensive analysis.
• COVID-19 has a negative impact first on economy, then on energy system.
• The COVID-19 reduces oil demand and price, limiting the development of renewables.
• We should adjust the price gap between fossil and renewable in post-COVID-19 era.

ARTICLE INFO

JEL codes: I18 Q56 Q58 C68
Keywords: International oil price COVID-19 Environmental and economic impacts China Computable general equilibrium model

ABSTRACT

In 2020, the world experienced several significant events, including the COVID-19 pandemic and the collapse of international crude oil prices. Both have a great impact on a sustainable economy. Taking China as an example, we use a computable general equilibrium model with multi-sectors and multi-households and consider six different scenarios to simulate and evaluate the aggregate impacts of the pandemic and crude oil prices. We divide the impact of the pandemic into the changes of factor input and the changes of consumer preference and find that the decline of factor input is the leading cause of the economic downturn. The sharp drop in crude oil prices has a significant negative impact on the low-carbon economy. Although the pandemic has led to a decline in global carbon emissions, it is only because of the economic downturn. The epidemic situation and the change of oil price have double impacts on the economy, especially the sustainable economy. Adjusting the price gap between fossil energy and renewable energy (e.g., more stringent carbon pricing) and appropriate tax cuts on residents may be effective ways to alleviate the impact, which should be one of the environmental policies in the post-COVID-19 era.

1. Introduction

1.1. Background: COVID-19

At the end of 2019, several “unexplained pneumonia” was found in Wuhan. On January 7th, 2020, a new coronavirus was detected from patient samples. On January 30th, World Health Organization (WHO) listed it as a public health emergency with international concern. On February 11th, WHO named it Corona Virus Disease 2019 (COVID-19). The new pandemic swept the globe quickly by using more convenient transmission, causing panic among people worldwide. The panic caused the stock market to collapse, triggering the circuit breaker mechanism continuously. Also, the recent “collapse” of the OPEC + conference led to great changes in oil supply and expectations, leading to a sharp drop in oil prices in the short term. As a result, the epidemic, the stock market, and the oil price formed a corresponding trend at the beginning of 2020, which causes a significant impact and fluctuation in the world.

As of July 14th, 2020, all the patients infected by the COVID-19 were discharged from the hospital, as shown in Fig. D.1. The spread of COVID-19 is effectively brought into control by controlling mobility and increasing the intensity of public health. The reason for the large increase of new confirmed cases on February 12th is that a large number of clinically confirmed cases were counted on that day. Apart from this jumping point, the newly diagnosed cases reached a peak in early
February, and the number of inpatients reached a peak in mid-February [1]. After that, a large number of patients who completed the treatment period were discharged. By April, China had completed the epidemic control, and the main focus of work was to prevent/control imported patient and asymptomatic infections.

However, the end of the pandemic in China does not mean the end of its impact. First, the pandemic situation of the world is still rampant, which has a massive impact on the world economy. There are many export-oriented enterprises in China, and there are significant substantial obstacles in international trade during the pandemic. Secondly, the difficult task of returning people to work and reproduction in China is still arduous, especially since many micro-enterprises are facing the risks of capital chain fracture, supply chain fracture, and recruitment difficulties. Thirdly, most enterprises still work flexibly or work from home since April, and the office efficiency is lower than that of a centralized office. Finally, most universities still have not resumed classes since the beginning of 2020. However, they have adopted online teachings due to the policy trend of limiting cross-provincial flow, which hints that passenger traffic has basically stopped. Thus, understanding the economic impact of the COVID-19 pandemic from the industrial and household levels is one of this paper’s goals.

1.2. Background: International oil price

In the first half of 2020, the international oil price had a continuous slump. As shown in Fig. D.2, the decline is divided into three phases. The decline in the first phase is mainly a rebound effect of the rise in oil prices in the early stage [2]. This is since OPEC countries began to reduce crude oil production in the second half of 2019, and the oil price rose at the end of the year. Response to COVID-19 is the second phase of the fall in oil prices, which began in late January. According to the monitoring data of the Traffic Administration Bureau of the Ministry of Public Security in China, the road traffic volume during the Spring Festival holiday decreased significantly. At the same time, due to the cancellation of flights by major airlines, the global aviation industry has been greatly affected. Especially after the sixth day of the Spring Festival holiday, the road traffic volume decreased by more than 80% compared to last year. Affected by the pandemic, China’s oil demand and global aviation fuel demand rapidly declined in a short period, which had a great impact on the balance of global crude oil supply and demand. The third phase started on March 6th. The downward economic pressure caused by the global spread of the epidemic led to a sharp drop in oil demand. At the same time, the “collapse” OPEC+ meeting on the issue of production reduction resulted in a significant imbalance between the current situation and expectation of oil supply and demand, leading to a sharp drop in oil prices in the short term.

In the first half of 2020, the epidemic situation is the world’s top concern, followed by US stocks and oil prices. American stocks are relatively distant from the Chinese public. However, oil prices are different. According to the apparent consumption in 2019, China’s dependence on foreign crude oil has risen to 72.6%. The domestic crude oil production cost is more than $45, and the reserve production ratio is only about 11 years. These data show some problems. China will face lower international crude oil prices, which is a good thing for downstream enterprises. However, as the CIF price is lower than the US $45, it will significantly impact domestic crude oil extraction enterprises. If the impact is too large, it may affect the financial market and even the entire economic system. According to the apparent consumption in 2019, China’s dependence on foreign crude oil has risen to 72.6%, and the cost of domestic crude oil production is more than $45. According to the extraction rate, the production can only last about 11 years.

1.3. Topic and paper structure

In 2020, the above two events were profoundly impacting the world’s economy and low carbon step. The pandemic has reduced economic development and energy demand, and it may be temporary. The sharp drop in oil price is partly due to the decrease in oil demand, but it also promotes oil demand. Maybe we can observe a higher energy intensity index in these two years, which is not conducive to low-carbon development. Therefore, the paper wants to assess the effects and reactions of the COVID-19 pandemic and international oil prices.

There are some critical findings. The leading cause of the negative economic impact of the pandemic is the reduction of factor input. Therefore, safe and active resumption of work and production has a strong mitigation effect to the loss. The impact of lower oil prices may be temporary. However, the long-term decline needs the intervention of low-carbon policy tools such as carbon tax. The carbon tax recycling mechanism should be adopted to reduce the loss of carbon tax on social welfare.

For readers to better understand the study, we list the abbreviations in the paper, as shown in Table 1.

The basic structure of this paper is: the introduction is presented in section 1. Theoretical analysis is presented in section 2. A brief literature review and contributions are introduced in section 3. Methodology and data descriptions are introduced in section 4. The scenario design is described in section 5. The simulation results and discussions are provided in section 6. Then, we simulate and discuss the countermeasure to the impacts in section 7. The conclusions and policy implications are presented in section 8.

2. Theoretical analysis

At present, the short-term oil price fluctuations and the impact of the medium and long-term pandemic situation interact and jointly impact China’s economy [3]. As shown in Fig. 1, the decrease in energy demand caused by the pandemic is the essential background and a medium and long-term trend [4]. Meanwhile, due to the market share dispute among OPEC + countries, the crude oil price has been dramatically reduced in the short term. The sharp drop in international oil prices will have a more significant impact on domestic oil exploitation and renewable energy development and stimulate energy consumption. However, the impact on the overall social output is uncertain. However, the pandemic directly reduces the production efficiency of enterprises, limits the consumption of residents, and overall reduces the total energy consumption, CO2 emissions [5], and social output. Both of which impact China’s economy. In turn, the government and enterprises will make corresponding decisions in response to the affected economy, which will impact the oil prices and even the epidemic situation. For example, low oil prices will lead to strategic oil storage, which will increase the oil price in the short term; the increasing impact of the epidemic on the economy will cause the government to balance the impact of the pandemic and the pressure of economic downturn, and the recovery &

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**Table 1** Abbreviation in the paper.

| Abbreviation | Full name | Abbreviation | Full name |
|--------------|-----------|--------------|-----------|
| COVID-19 | Coronavirus Disease 2019 | CET | Constant Transformation Elasticity |
| WHO | World Health Organization | CEEEA | China Energy-Economy-Equilibrium Analysis |
| OPEC | Organization of Petroleum Exporting Countries | CIOT | China Input-Output Table |
| CIF | Cost Insurance and Freight | SAM | Social Accounting Matrix |
| CGE | computable general equilibrium | TFP | Total Factor Productivity |
| GDP | Gross Domestic Product | AEEI | Autonomous Energy Efficiency Improvement |
| CES | Constant Elasticity of Substitution | PFP | Proactive Fiscal Policy |
improvement of the productivity of medical supplies will play a positive role in curbing the epidemic in the world.

However, at present, the processes of the international oil price and the COVID-19 pandemic are uncertain. The number of infected persons gradually follows the logistic function even with the attention of governments, but there are still some levels of uncertainty. These uncertainties come from the possibility of the virus mutation and the government’s balance between economic pressure and epidemic pressure. The uncertainty of crude oil prices is relatively apparent. The first uncertainty is the impact of the scope and duration of the epidemic on the economy and oil demand; the second is how much production capacity OPEC+ will increase/decrease in different cases, and then how much supply-demand gap it will cause, and how much impact it will have on oil prices.

Based on the above basic logic, this paper uses the computable general equilibrium model (CGE model) to simulate and analyze the impact of these two critical events in 2020 on China’s economy, i.e., analyze the impact of international oil price fluctuation and COVID-19 pandemic on China’s economy, energy consumption, and CO₂ emissions, respectively. To better analyze and show which aspects of China’s economy will be affected, we make certain assumptions on the two events and refine the analysis from residents’ purchasing power, commodity prices and output, and international trade.

Generally speaking, the government always prioritizes the former in balancing stability, economy, and environment [6–8]. Therefore, in the period of post-COVID-19, climate change, renewable energy, and other relative issues may not be urgent and vital issues compared with stability. In particular, carbon emissions have declined over the period. Therefore, COVID-19 is a significant challenge for low-carbon development. In addition, due to the decline of international oil prices, fossil energy has a lower cost to replace renewable energy, which undoubtedly forms a vast challenge to low-carbon development. Therefore, the effectiveness of policies supporting low-carbon development, such as financial support to renewable energy, needs to be reassessed.

3. Literature review and marginal contributions

3.1. Literature review

The economic, energy, and environmental impact of COVID-19 is studied by many scholars [9]. It is generally believed that COVID-19 has a significantly negative impact on the economy, the decline of energy use, and CO₂ emissions [10,11]. Transportations suffers the most in the pandemic [12]. Wang et al. (2021) [13] found that the lockdown measures did have a noticeable effect on air quality. The control of COVID-19 also costs a lot but necessary [14]. It is found that COVID-19 has helped us to get a better air quality [15]. However, it is dangerous to rely on pandemic-driven benefits to achieving sustainable development goals [16]. The possible most effective countermeasure against the pandemic is the online working and reducing human flow. New working styles and lifestyles may bring new opportunities to the world [17] and structural reform, new technology, and re-integration [18]. As the new workflow requires much support on hardware and software, the developing nations and emerging nations may suffer more in the pandemic [19,20].

The COVID-19 pandemic damages economies considerably; however, the reduction in emissions is less than proportionate [21]. The lockdown policy reduces the income of residents and reduces their expenditure, which is also the income of enterprises or other residents. Therefore, the whole economy may fall into a vicious economic downturn [22]. Many studies assess the economic impact of the pandemic. Zhang et al. (2020) [23] evaluated the impact of COVID-19 on China’s macroeconomy and agri-food system. The pandemic did reduce CO₂ emissions. However, the effect is not that large [24]. Smith et al. (2021) [25] predicted that CO₂ emissions would rebound within two years and argued that the pandemic would not provide countries with a solid reason to delay climate change mitigation efforts.

Some scholars analyzed the impact of the pandemic using a computable general equilibrium model. Such as, Lahcen et al. (2020) [21] applied a CGE model in Belgium to analyze the impact on the economy and CO₂ emissions. However, the paper did not take the impact of oil prices into account when discussing CO₂ emissions. As of April 2020, the sharp drop in oil prices has triggered a series of economic turbulence. Maxim and Zander (2020) [26] applied another CGE model in Australia to simulate the pathway to lower emissions, higher GDP, and higher employment. They suggested a reduction of tax and mixed-recycling approach for economic recovery. However, the paper ignores the burden of the government. Most CGE models do not consider the impact of the government deficit, so almost all CGE models will draw similar conclusions: tax reduction and tax recovery plans can stimulate...
the economy and improve the welfare of residents. However, the potential harm of expansionary fiscal policy is not reflected in the model, so the model and suggestions may be biased. Zidouemba et al. (2020) [27] constructed a single country’s CGE model to analyze the impact on households’ food security in Burkina Faso, and suggested that the pandemic contributes to a worsening of food security.

Another, some scholars focused on the international oil price fluctuation impact. Liu et al. [28] provided evidence that the threat of dynamic jumps still exists in the global oil market after the 2008 global financial crisis, while the stocks and commodities of China’s petrochemical markets are both affected by global oil prices. In our study, we focus on the reduction of oil price, then the energy rebound effects of the paper is a topic that cannot be bypassed. If the oil price plummeted, oil consumption and storage behavior would be the first to react [29–32].

As section 2 shows, COVID-19 leads to a decline of oil demand while the price will increase it, which is the long-run effects and how to react is the key topic of the paper.

As mentioned above, some of the literature’s results need to be further discussed, and some of the literature explored the impacts on other countries, not China. This paper, however, wants to fill the knowledge gap to explore the aggregate impacts of the COVID-19 pandemic in the context of international oil price decline in China.

3.2. Marginal contributions

The contributions of the paper are:

1. Under the same model framework, this paper analyzes the impact of COVID-19 and oil price fluctuations on energy, economy, and environment. The results show that the negative impact of the pandemic on the economy is far more significant than the impact on the environment and energy, and the pandemic has certain obstacles to the development of renewable energy. Lower oil prices will have a greater impact on renewable energy. Therefore, China needs to continue promoting renewable energy development in the Post COVID-19 Era.

2. The conclusion highlights the importance of returning to work and warns that the carbon emission reduction in 2020 is only caused by economic decline, not technological progress. Therefore, in the Post COVID-19 Era, it is more necessary to re-evaluate the low-carbon policy and guard against the uncontrolled growth of fossil energy.

3. The paper provides several countermeasures to the two events. Carbon tax or other low carbon policies may be effective strategies to deal with long-term low energy prices, but need to pay attention to households’ impact. The recycling method should be applied if necessary. Another way to effectively restore the factor input and safely return to work is essential in the post-COVID-19 era. Only in this way could the negative economic impact of the pandemic be effectively alleviated.

4. Methodology and data source

4.1. CEEEA/CGE model

A CGE model named CEEEA (China Energy-Economy-Environment Analysis) model is utilized in this paper [33], which could easily explore the environment, energy, and economic impact of the events we want to simulate. The CGE model is widely used to analyze policy or events’ impact [34–36]. The CGE model in this paper consists of five blocks: production block, income-expenditure block, trade block,
energy-environment block, and macroscopic-closure & market-clearing block. The framework of the CEEEA model is shown in Appendix C.

4.1.1. Production block

The basic structure of the production block is shown in Fig. 2. At the top level, the production technology is specified by a Leontief function of quantities of factor input and intermediate input (excluding energy input). Factor input is nested by labor input and KE input (the bundle of capital and energy input). KE input is a constant elasticity of substitution (CES) function of capital input and energy input. The aggregated energy input is specified by a CES function of electricity and fossil energy. The fossil energy is again nested by the CES function of primary fossil energy and refined oil. The nest patterns in the primary fossil energy input bundle and non-solid energy input bundle are like fossil energy input. Electricity input is a CES function of thermal power and nonthermal power generation. The latter consists of hydropower and other renewable energies, including nuclear power, wind power, and solar power. All of them are following the CES functions. The elasticity of all sectors is shown in Fig. 2. However, there is an exception that the elasticity of the CES function in primary fossil energy input is zero in energy processing sectors such as the electricity and petroleum processing industry, which is set according to AIM/GGE [37] and Lou (2015) [38]. The primary fossil energy aggregation in energy processing sectors is based on Leontief production technology, not CES production technology.

The domestic output in the production block will link to the income-expenditure block, forming the income of enterprises. It also links the block to a trade block. Enterprises need to determine the share of their products in the domestic or international market. The input of coal, crude oil, and natural gas compose CO2 emissions after considering the carbon dioxide emission factor. These primary fossil energy inputs are the linkage between production block and energy-environment block.

4.1.2. Trade block

The trade block mainly depicts international trade and is displayed in Figure 3. The general CGE model assumes that the products produced in the same industry are identical, homogeneous. If such an assumption is directly put into the model, it will make it impossible to have both imports and exports of the same kind of goods in the model. However, both import and export exist in one country in reality. Therefore, like most CGE studies, this paper introduces the Armington assumption. The Armington assumption means that the residents and enterprises in the model do not directly consume and use imported goods or domestic goods. They consume Armington commodities composed of imported goods and corresponding domestic produced goods for domestic consumption through the CES production function [39]. Another, the model assumes that manufacturers need to determine the supply share in the domestic market and in the international market. They need to sell the goods according to the target market’s characteristics, and finally, transport the goods to the two markets. This paper uses the constant transformation elasticity (CET) function to describe the conversion process.

CEEA model is a multi-sector and multi-household CGE model with a single country. The rest of the world is considered a whole economic entity. The use of the multi-regional CGE model is bound to simplify the relevant information of industry and residents. The main focus of this paper is the comprehensive impact on China, so the single region CEEA model is better than the multi-regional CGE model in this topic.

Domestic consumptions (or the consumption of Armington commodity) is the consumption of all domestic activities. There must be market-clearing conditions in such a commodity market. Thus, the commodity is the linkage between the international trade block and the macroscopic-closure & market-clearing block. Moreover, as consumption is the expenditure of users and income of sellers, it also links to income-expenditure block. The gap between import and export forms a trade surplus, which is a macroscopic-closure condition, linking to the macroscopic-closure & market-clearing block.

4.1.3. Income-expenditure block

The income-expenditure block describes the economic relationship among economic entities in society, displayed in Fig. 4. The main activities of the economy are composed of government, domestic enterprises, urban and rural residents, and the rest of the world. Except for the government, other subjects pursue maximization: enterprises pursue profit maximization, and the two kinds of residents pursue utility maximization. Therefore, the behavior preference of economic entities described in this paper is determined by maximization behavior. By selling labor and capital, residents get remuneration from enterprises. Added by government transfer payment, households’ income is used for consumption, savings, and direct tax. The income of enterprises obtained by selling commodities is used for intermediate input for production, payment of indirect taxes, and savings. The government collects income through direct tax, indirect tax, and tariff, and all the income is used for government consumption, government savings, and transfer payment. Foreign enterprises sell goods produced abroad to domestic residents, enterprises, and governments. The foreign enterprises also purchase domestic goods and paying tariffs. The gap between income and expenditure is trade deficits.

The block expresses all the cash flow between activities and the relationship between revenue and expenditure in activities. Thus, this block links every other block except for the energy-environment block. Most of them are already introduced in the previous subsections, including the link to production block, trade block, and part of macroscopic-closure & market-clearing block. Government balanced budget is one of the macroscopic closure conditions. Thus, the government’s behavior is also a linkage between macroscopic-closure & market-clearing block and this block.
4.1.4. Energy-environment block

The energy-environment block is used to link the energy input data in the input–output table with the actual energy consumption data of the industry, as well as to describe the relationship between energy consumption and carbon dioxide emissions, as shown in Fig. 5. In this paper, referring to Fujimori’s method [37], the energy balance table is constructed, and the intermediate energy input in the input–output table is associated with the actual energy consumption through the linear equations. Then the carbon dioxide emission factor is used to calculate the carbon dioxide emissions of the energy consumption. As this paper does not consider carbon pricing, the block only links to the production block.

4.1.5. Macroscopic-closure & market-clearing block

Macroscopic-closure & market-clearing block includes some of the basic assumptions in the CEEEA model. As for macro closure, this paper mainly considers three balance rules: government balance budget, foreign trade balance, and investment savings balance. These three rules have been introduced in the revenue and expenditure block and will not be repeated here. The model assumes that all savings are converted into investments, and the total investment is equal to the total endogenous savings. Therefore, this model is savings-driven. The market-clearing condition is used to express the balance between the supply and demand of all markets in the model. This paper sets up two clearing conditions (Fig. 6): one is the clearing of the product market: all the Armington composite commodities are used for consumption, saving, and intermediate investment in the production of the residents and the government. The other is the clearing of the factor market: the income of labor and capital obtained by rural residents and urban residents is equal to the endowment of the labor force and capital input of the whole society in a given period of time.

4.2. Data source and social accounting Matrix

China Input-Output Table (CIOT) is used to construct a Social Accounting Matrix (SAM), which is primary data for the CGE model [40]. To analyze energy issues, we construct an energy balance table, and the data of this table is from China Statistical Yearbook [41]. Compared with Global Carbon Budget 2017 [42], we declare that the CO₂ emission we discuss is only from energy consumption, without biological breath, microbial decomposition, carbon sinks, and carbon emissions from land.
Table 2
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                                                   |
| REP   | Refined oil                                                                 |
| CMC   | Chemicals                                                                   |
| MTL   | Metal smelting and rolling products                                         |
| MTP   | Metal products                                                              |
| ThP   | Thermal power generation                                                   |
| HpP   | Hydropower generation                                                       |
| WdP   | Wind power generation                                                      |
| NcP   | Nuclear generation                                                          |
| SdP   | Solar power generation                                                     |
| TRA   | Transportation, warehousing, and postal services                            |
| CST   | Construction                                                                |
| RST   | Real Estate                                                                 |
| A_C   | Accommodation and Catering                                                 |
| OTH   | Other industry                                                              |
| SER   | Services                                                                   |
| RUR   | Rural residents                                                            |
| CTZ   | Urban residents                                                            |
| GOV   | Government                                                                 |

Notes: The unit of capital stock is billion CNY in 2017, as the model data is based on the 2017 input-output table.

Table 3
AEEI, capital depreciation rate, and capital stock of each sector in the CGE model.

| Sector’s Abbr. | Depreciation rate | Capital stock | AEEI |
|----------------|-------------------|---------------|------|
| Agriculture, forestry, animal husbandry and fishery 5.0% 4516 2.5% |
| Coal mining and washing industry 6.2% 1550 0.6% |
| Petroleum exploitation 6.5% 1174 0.6% |
| Natural gas exploitation 6.5% 263 0.6% |
| Refined oil 6.5% 1353 0.6% |
| Chemicals 5.5% 6364 1.5% |
| Metal smelting and rolling products 5.5% 7085 2.5% |
| Metal products 5.5% 1527 2.0% |
| Thermal power generation 4.8% 6423 2.5% |
| Hydropower generation 4.8% 2029 2.5% |
| Wind power generation 4.8% 500 3.5% |
| Nuclear generation 4.8% 156 2.8% |
| Solar power generation 4.8% 29 3.5% |
| Transportation, warehousing and postal services 5.2% 9654 3.3% |
| Construction 5.5% 2993 0.6% |
| Real Estate 5.2% 30,069 1.0% |
| Accommodation and Catering 5.2% 2047 1.0% |
| Other industry 5.5% 26,229 1.6% |
| Services 4.5% 38,443 2.3% |

Notes: The unit of capital stock is billion CNY in 2017, as the model data is based on the 2017 input-output table.

5. Scenario design

5.1. Assumptions in simulation

In this paper, the scenario design follows certain assumptions, specifically for the time trend and the scope of the pandemic influence time trend. In January, China made a first-class response to the epidemic situation. After the Spring Festival, all provinces extended their holidays. In mid-April, graduation classes in some middle schools officially and carefully opened. At the same time, no university officially opened, but the rate of returning to work for workers is relatively high. The resumption rate of small and medium-sized enterprises in China is 84%\(^1\). The impact of the pandemic on China started in January, increased significantly at the end of January, peaked in February, and gradually weakened after March. The impact on some specific industries will last for a long time and will not end until June or even longer. Therefore, this paper assumes the influence curve according to this trend. Also, since the long-term international impact of the pandemic is still uncertain, this paper focuses on analyzing the impact of the pandemic on China in 2020. Moreover, this paper does not provide accurate data prediction but recognizes principal contradiction and secondary contradiction.

For the scope of influence in the scenario of decreasing oil prices in this paper, it is assumed that the international oil price will fall sharply and be cut in half. In the scenario related to the COVID-19 pandemic, the paper assumes that the consumption behavior of residents changed, and the capital and labor input of enterprises are affected by the epidemic. Specifically, to limit mobility, the government suggests that some residents can only stay at home to work and attend meetings. In addition to the economic downturn, the demand for public transport, refined oil, accommodation, catering, and real estate has decreased significantly\(^2\). However, due to the rigid demand for public transport, it was not affected by nearly 100% reduction like accommodation and catering in the most difficult February. However, with the resumption of work and the difficult international pandemic situation, the recovery speed of public transport is far less than that of the accommodation and catering industries. At the same time, due to the pandemic, many workers can only work at home or work flexibly (to the office from time to time, instead of from 9o‘clock to 17o‘clock on working days). Even employees in some industries can only stay in their city and do nothing. Although the government actively resumed work and production after the extended holiday, the labor supply and the efficiency of capital use were still partially affected by the epidemic. Therefore, this paper assumes that the negative impact of the epidemic on China’s labor and capital supply will be from 30% and 20% in January to 50% and 40% in February. After that, with the rapid recovery of supply after the resumption of work and production, there were only 15% and 10% supply gaps in March, gradually reducing to 0%. The impact of household consumption and enterprise factor input considered in this paper is shown in Fig. 7.

Throughout the year, China’s demand for public transport, refined oil, accommodation, catering, and real estate will decrease by about \(\text{TFP endogenous, run the model from the base year to the current year by the real GDP and estimate AEEI or TFP \cite{43,44}. The method can make the model’s GDP results precisely full in the actual GDP; however, this kind of method usually assumes that the total factor productivity of each industry is the same. This paper wants to distinguish the different development levels of different sectors, so we directly exogenous AEEI each year. AEEI in the CGE model is considered in this study according to the relevant literature \cite{45} and Medium and Long-term Energy Saving Special Planning \cite{46}. Table 3 depicts the value of the parameter of AEEI in each sector. Labor endowment, an exogenous variable, is determined by the National Population Development Plan (2016–2030) \cite{47}.}

1. http://www.myical.com/news/100596171.html (accessed in July 2020)
20% to 25%, labor supply by about 10%, and capital supply by about 7% via the COVID-19 pandemic. It should be noted that the impact of the pandemic on China is different. Therefore, it is impossible to exhaust the assumptions and accurately quantify the relevant assumptions due to the uncertainty in many aspects. However, to ensure the accuracy of the conclusion, this paper considers the consumption side and the supply side and makes assumptions on the significant impacts of the epidemic situation.

Also, the impact of the basic assumptions may be relatively significant. It is mainly because the general equilibrium model is challenging to simulate short-term human speculation and the potential "retaliatory" rebound of the economy. If we want to analyze such issues further, we need more data to support these additional assumptions. Therefore, this paper does not consider this kind of subjective initiative. Although the value of the influence conclusion may be larger than the actual situation, the relationship between scenarios and the basic logic of the conclusion will not change. The purpose of this paper is not data prediction, like how many percentages the epidemic will reduce the economy, but logical analysis and policy implications. Therefore, ignoring such initiatives will not affect the logic and conclusion of this paper.

5.2. Scenarios

Considering the impact of the pandemic, COVID-19, and international oil prices on China’s economy, this paper constructs the OIL scenario and the COVID scenario, respectively. To analyze the impacts of consumption structural change and supply change caused by COVID-19, this paper constructs the CSMP (consumption) scenario and INP (input) scenario. To model the actual scenario in 2020, this paper constructs a scenario named ALL scenarios to simulate the combined effect of COVID-19 and international oil prices. The scenario design of this paper is shown in Table 4.

### Table 4

| Scenario | Descriptions |
|---------|--------------|
| BAU     | Business as Usual. Scenario with no COVID-19 and oil price impact. |
| COVID   | COVID-19. Scenario with only COVID-19 impact. |
| OIL     | International oil price. Scenario assuming international oil price will be cut in half in 2020. |
| CSMP    | Consumption. Scenario simulating changes in consumer behavior due to the COVID-19 pandemic. |
| INP     | Consumption. Scenario simulating changes in labor and capital input due to the COVID-19 pandemic. |
| ALL     | All effects accounted. Scenario simulating the comprehensive impact of COVID-19 and oil price. |

6. Results and discussions

6.1. GDP

The GDP changes in 2020 under different scenarios are illustrated in Fig. 8. It should be noted that the GDP output value of all scenarios is discussed at a constant price in 2012. It is found that the change of consumption structure has a minor impact on the economy (an increase of 0.058%); another is the sharp drop found in the scenario of cutting international oil prices in half, China’s economy fell instead of increasing (a decrease of 0.957%). This is mainly because the domestic oil mining industry has been dramatically impacted, while the profits of other industries from reducing international crude oil are not enough to make up for the losses of the domestic oil exploitation industry. The specific information is given in section 6.2. We find that COVID-19 has a far more profound impact on the economy than the collapse of international crude oil prices.

Here we also found the culprit of the economic downturn. In the COVID scenario, GDP reduced by 9.431%. If we analyze the impact of the supply side and the consumption side, we found that the change rates will be 9.484% and +0.058%. That is, the supply of factors has become a significant problem affecting China’s economy. The result also confirms why China’s government is active in promoting enterprises to resume work and resume production.

6.2. Commodity market

Fig. 9 and Fig. 10 show the changes in commodity prices and domestic output. The result indicates that the impact of the COVID-19 on commodity prices is relatively low, and the decline in most bulk commodities prices was less than 3%. Regardless of speculative behavior, the pandemic will decrease 0.49% – 3.03% in commodity prices. Agriculture is the least affected, accounting for 0.49%, and the real estate industry is the most affected, accounting for 3.03%. However, due to the
double reasons for the falling international crude oil price and the vast dependence of China’s crude oil on foreign countries, the domestic crude oil price leads the price reduction (43.63% – 44.18%). Due to the production linkage, the price of natural gas followed the price reduction (by about 4.18% – 5.22%). As the main downstream of the crude oil industry, the refined oil market will have also experienced a large-scale price reduction (27.61% – 28.37%). Another, the downstream of refined oil will also experience price reduction, such as the chemical industry and transportation industry (7.22% – 8.24% and 7.22% – 8.32%).

Different from commodity prices, industry output is sensitive to both COVID-19 and oil prices. The sharp drop in oil price has dramatically reduced the output of the domestic crude oil extraction industry (63.02% – 66.04%), and the power generation industry has been affected by the substitution effect, resulting in a decrease in output of the
power generation industry (0.81% – 2.78% in the COVID scenario). The oil processing industry will usher in the spring of output, and its downstream industries also have a slight increase in output. The different performance of the industries is the reason for the low impact of the oil price slump on GDP. In contrast, the pandemic has a comprehensive impact on China’s whole industry. The pandemic has suppressed the development of all industries, causing 6.99% (Hydro-power) to 17.24% (Accommodations and catering) loss, especially for transportation, accommodation, and catering. The reduction of domestic output has made the COVID-19 pandemic a major reason for the reduction of economic growth.

6.3. The purchasing power of residents

Fig. 11 shows the changes in residents’ purchasing power in different scenarios. The results show that the COVID-19 significantly cut residents’ purchasing power (from 7.12% to 7.24%), while the sharp drop in oil price increases the purchasing power of residents to some extent (2.38% to 3.02%). The slump of international oil prices makes gasoline and diesel prices drop, so the residents get to benefit from it. At the same time, because the prices of all the commodities would reduce, the residents benefit again and finally improve the residents’ real purchasing power. By splitting the impact of the COVID scenario to the CSMP scenario and the INP scenario, it is shown that residents’ consumption habits have little impact on the purchasing power, and the primary source of the decline in purchasing power caused by the pandemic is income stagnation caused by enterprises shut down and layoffs. The opposite effect of oil price and COVID-19 pandemic on the purchasing power of residents will eventually make the actual purchasing power of residents decrease by 4.51% – 4.96% in 2020.

6.4. Import and export

Fig. 12 and Fig. 13 show the changes in China’s import and export of all kinds of goods. A simple sharp drop in international oil prices will lead to a large-scale increase in crude oil imports, while China’s oil exports will fall by 95.16%, even though they are already exceptionally low. Low oil price brings high oil consumption. It will also cause strategic oil storage behaviors of the oil-importing countries. These behaviors will increase the short-term oil demand to a certain extent and somehow increase the oil price. Also, with the alleviation of the epidemic situation, the international oil demand will gradually increase. Therefore, the international oil price may not be maintained at the ultra-low price for a long time, as shown in Fig. D.2. If the pandemic control is better than expected, the change rates of oil import and export may be overestimated. However, in any case, maintaining the ultra-low price for a long time will undoubtedly cause financial problems in other high-cost oil extraction industries, including American shale oil. It may lead to losses or even bankruptcy. Besides, the increase in exports of petroleum processing products may also benefit from ultra-low oil prices. Apart from the slump of oil prices, this paper also found that the COVID-19 pandemic affects China’s economy and has a more significant impact on international trade. The import and export of major industries were affected (reducing from 5.23% to 21.74%).
6.5. The share of primary energy consumption

Fig. 14 shows a different share of primary energy consumption in these counterfactual scenarios. In the BAU scenario, coal, oil, and gas share is 69.71%, 19.64%, and 4.17%, respectively. The share of renewables is 6.47% in the BAU scenario. Note that the CEEEA model runs from 2012 to 2020, and we do not let power generation be exogenous variables or give an exogenous subsidy to renewables. Instead, we only set the annual variation of electricities on AEEI so that the power generation could be slightly lower than reality in the BAU scenario. We can find that COVID-19 may have a minor positive impact on renewables. The share of renewables in the COVID scenario will be 6.55% instead of 6.47% in the BAU scenario. It may be due to the fact that the epidemic has made it difficult to make good use of factors, with the decline in total energy consumption. At the same time, the renewables with higher intelligence levels and relatively low marginal costs would suffer fewer negative impacts. However, the pandemic reduces the demand and oil price, which makes the results different. In the scenario of plummeted oil prices, oil consumption will increase distinctly, and the share of renewable energy will significantly reduce from 6.47% to 5.38%. Therefore, the COVID-19 pandemic will reduce the demand for crude oil and reduce its price, which is an excellent challenge for the renewable energy industry.

6.6. CO₂ emissions

Fig. 15 shows the changes in China’s CO₂ emissions under different scenarios. Under the BAU scenario, the carbon emissions in 2020 will be...
The ALL-CT scenario, the first countermeasure, is to increase the cost of fossil fuels consumption. We assume that a carbon tax of 100 CNY/ton is imposed on all sectors except services. The countermeasure is to adjust the price gap between oil and renewables. It is the ALL-CT scenario, which is a scenario considering a carbon tax and the situations in the ALL scenario.

The ALL-TR scenario, the second countermeasure, however, considers that the carbon tax may lead to a decline in economic performance and the reduction of social welfare. After considering the tax recycling scheme, we assume that the households will get transfer payments through the tax recycling scheme to reduce the negative impact of the carbon tax on households. Everyone shares the transfer payment equally. It is the ALL-TR scenario, which is a scenario considering tax recycling and the situations in the ALL-CT scenario.

The ALL-PFP scenario, the third countermeasure, aims to the negative impact of COVID-19 on the economy. We assume that a 10% tax reduction for all enterprises and expansionary fiscal policy is implemented. To be specific, about 20% of the government’s expenditure will be increased to resist the economic crisis caused by the pandemic, and 10% of indirect tax will be cut to support the enterprises. Such a scenario simulates the Proactive Fiscal Policy (PFP). It is the ALL-PFP scenario, which is a scenario considering tax cutting and the situations in the ALL-TR scenario.

The ALL-RtW scenario, the final countermeasure, assists enterprises in resume production as soon as possible. We assume that 50% of the missing job is back due to the active government’s efforts. Such a scenario considers increasing available factor endowment and the situation in the ALL-TR scenario.

Table 5 displays the impacts of these countermeasures on GDP, CO\(_2\) emissions, and social welfare. All of the value presented in the Table is the percentage changes of the index relative to the index in BAU scenario. We find that carbon tax can significantly reduce CO\(_2\) emissions and have a slight negative impact on GDP and social welfare. To reduce the negative impact on social welfare, tax recycling is implemented. We find that such a tax recycling scheme has a strong positive impact on social welfare, especially on rural welfare. Then we consider an expansionary fiscal policy and find the policy does not significantly help alleviate the economic impact of the pandemic but also increases carbon emissions. Finally, if policymakers try to let the people return to work, the negative impact of COVID-19 can be mitigated significantly. However, the emission mitigation dividend of the carbon tax will be reduced by expansionary fiscal policy and recovery of the job market.

### Table 5

| Impacts of countermeasures on macro index (compared with the BAU scenario). | BAU | ALL | ALL-CT | ALL-TR | ALL-PFP | ALL-RtW |
|---|---|---|---|---|---|---|
| GDP emissions | 0.00% | -9.48% | -9.90% | -9.94% | -9.78% | -5.50% |
| CO\(_2\) emissions | 0.00% | 8.84% | 0.04% | 0.10% | 2.71% | 7.68% |
| Rural welfare | 0.00% | -4.96% | -6.40% | 0.03% | 1.66% | 5.58% |
| Urban welfare | 0.00% | -4.51% | -6.05% | -4.31% | -2.62% | 1.34% |

10.88 billion tons, while in the OIL scenario, the carbon emissions will be up to 12.95 billion tons. The collapse of international oil prices will significantly promote global carbon emissions. The results are similar to Malliet et al. (2020) [49]. Meanwhile, the global energy pattern will have a significant change, and the competitiveness of the renewable energy industry will be greatly weakened. Therefore, climate policy and efforts need to be re-evaluated. Another, the spread of the pandemic has a significant effect on the reduction of carbon emissions. In the COVID scenario, the carbon emission is 9.97 billion tons, which is 8.39% lower than in the BAU scenario. Under the dual influence of oil price and the COVID-19 pandemic, the carbon emissions of some industries have decreased to a certain extent. However, the emissions of oil import and processing-related industries have increased more, so the total energy consumption and total carbon emissions may have increased with the assumption that international oil prices will reduce by 50% in the whole year of 2020. However, the international oil price has increased in recent months, the emission of 2020 may not appear as an increasing trend.

7. Countermeasures

From the above analysis, we find that the COVID-19 pandemic and the reduction of international oil prices may significantly impact economic growth. The economic slowdown will reduce the motivation for people to pursue long-term goals. Moreover, the comparative advantage of oil over renewable energy has been improved significantly. The two events are much more harmful to the low-carbon economy. The increasing fossil fuels consumption and the reduction of GDP lead to carbon intensity. Holding such a perspective, we design countermeasures to reduce pandemic and economic impact.

![Fig. 15. changes in CO\(_2\) emissions.](image-url)
The conclusions in this section have significant implications for the post-pandemic era.

1. We have identified that the decline of CO$_2$ emissions caused by the pandemic is short-term, caused by the decline of economic activities rather than the victory of low-carbon policies or activities. The decline of oil prices will promote the rise of energy demand in turn. Moreover, the sustained low oil price may significantly increase CO$_2$ emissions. Carbon tax and other emission reduction policies may be effective weapons to deal with low energy prices. However, we need to pay attention to the affordability of households, and the recycling scheme of the carbon tax may be conducive to the implementation of such policies.

2. We have identified the leading cause of economic weakness during the pandemic period: the decline of factor activity level or the decline of factor input. Therefore, effectively restoring the factor input and safely returning to work is essential in the post-COVID-19 era. Only in this way could the negative economic impact of the pandemic be effectively alleviated.

8. Conclusions and policy implication

8.1. Conclusions

The impacts of the two significant events of the COVID-19 pandemic and the slump of the international oil price are analyzed by this paper using CEEEA/CGE model. The impact of COVID-19 is analyzed from two aspects of the consumption side and the supply side. The impacts of the pandemic and the price slump on China’s economy and emissions are studied. It is found that the pandemic and oil prices affect China’s economy and emissions in different ways and directions. This paper draws some interesting and practical conclusions from the interactions and primary and secondary relations of these impacts.

The slump of international oil prices is neither a bad thing nor a good thing for China, with a high dependence on import oil. The impact of low oil prices on GDP is less than that of the pandemic. The continuing low international oil price positively impacts China’s oil processing, transport, chemical industry, and even households. The reduction of international oil prices would cause a chain of reductions in commodity prices. It will greatly reduce the price of gasoline and diesel oil, which would lead to an inevitable rise in the purchasing power of residents. However, domestic crude oil extraction enterprises will suffer a huge economic loss due to the high production cost when facing ultra-low oil prices. If the low oil price lasts for a long time, many enterprises have to face problems, like bankruptcy, which has the risk of causing fluctuations in the financial market and even in the economy.

Meanwhile, the low oil price will cause speculation in crude oil and higher crude oil consumption, resulting in higher carbon dioxide emissions in the short term. Low oil price is also a heavy strike to renewable energy enterprises. Environmental policies and low carbon transition policies may need to be reassessed.

COVID-19 has a far more significant impact on China’s environment and economy than international oil prices do. From a clear point of view, the change of residents’ consumption behavior caused by the pandemic has little impact on the economy. It is just a certain degree of change in the structure of consumption and production. However, due to the “shut down” of the enterprises caused by the pandemic and the short-term “disconnection” of upstream and downstream industrial chains, the production factors of enterprises cannot be fully utilized and put into production, which is a massive blow to the economy. It is also the reason why China tries to reduce the mobility of residents and to carry out community management (it will change the consumer behavior of residents to a certain extent, but maybe a good way to control the spread of the pandemic) while vigorously helping enterprises to resume productivity (to restore the industrial chain and make full use of production factors). Also, from the consumption side, part of the production factors used by enterprises is an essential part of residents’ income, so the economy’s stagnation brings about short-term unemployment and the decrease of residents’ purchasing power. Contrary to the conclusion of the sharp drop in international oil prices, China’s total import and export trade has also declined on a large scale due to the pressure of the economic downturn. At the same time, enterprises’ demand for energy and carbon emissions has also decreased, and carbon dioxide emissions will be reduced at a relatively significant level.

Overall, the impact of international oil prices on the oil industry’s output, crude oil import and export, and the petrochemical industry is far more significant than the impact of the COVID-19 pandemic. The impact on carbon emissions may also be more remarkable than the impact of the pandemic on carbon emissions. As far as the international oil price is low, China’s emissions may increase instead of reducing. It is a fatal blow to the domestic oil production industry. The impact of the COVID-19 pandemic on other industries, especially the service sector, is far greater than that of international oil prices. The impact on the total economic output is much greater than the impact of international oil prices. Therefore, if the country wants to ensure economic growth, the most important thing is to restore the domestic industrial chain, ensure employment, and to limit large population movements.

8.2. Policy implications

According to the conclusion of this paper, in the face of the low international oil price and the COVID-19 pandemic all over the world, the policy implications of this paper for Post COVID-19 Era are as follows:

1. Support the resumption of the production of enterprises rather than simple expansionary fiscal policy. We find that the economic loss caused by factor input loss is far more significant than that caused by the change of demand structure. The conclusion of this paper directly supports the policy of limited resumption of work and employment, that is, supporting the resumption of work with controlling the flow and gathering of population. Another, we can also support enterprises by tax reduction in different industrial chains, encourage the mode of work shifting. Attention should be paid more to small and micro-enterprises. Most enterprises are facing problems such as broken sales channels and difficulties in upstream supply. Pay attention to the supply chain, which is the core work after the enterprises return to work.

2. Implement different economic recovery policies in different regions, especially in different industries. In the short term, after the pandemic, the demand for “hoarding” will decrease. As a result, rigid consumption will be stable. After reopening the closed service industry, such as tourism and film, there may be retaliatory rebounds, and it is necessary to prevent personnel gathering. The development of wholesale, retail, and express industries needs to support the “housing economy” in the short and medium term to prevent the spread of the pandemic and restore economic vitality.

3. Re-evaluating low carbon policies and a more stringent carbon mitigation strategy are needed. Renewables may encounter a massive loss if the oil price is too low, as well as an electric vehicle. Therefore, supportive policies for renewable energy need to be reassessed. Climate negotiations may only be completed based on economic growth. When it comes to the economic downturn, emission reduction may become an issue less to talk about [50-52]. During the economic downturn, can we keep the negotiation results of the climate conference and negotiate after the economy recovers, instead of holding the climate conference at the wrong time.

8.3. Limitations

The oil price has rebounded after the decline due to the recovery of the economic level. Thus, the results in this paper that the combined effect of oil price and the pandemic will significantly increase CO$_2$
emissions do not seem to have a vital reference significance. However, the mechanism analysis and countermeasures are the main innovation of this paper.

In addition, the impact of behavioral changes on households is mainly simulated by setting assumptions. How the lifestyle and work style change in the post-COVID-19 era needs further observations to do more serious studies.

Data Availability Statement
All the data in this paper open accessed to the public, such as the input output table in China (http://data.stats.gov.cn/ifnormal.htm?u= http://files/html/quickSearch/trcc/trcc01.html&h = 740), data on energy consumption is from the National Bureau of Statistics in China (http://www.stats.gov.cn/tjsj/).

CRediT authorship contribution statement
Zhijie Jia: Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. Shiyan Wen: Software, Data curation, Writing – original draft. Boqiang Lin: Conceptualization, Software, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements
This paper is supported by Business Administration Plateau Discipline Fund of Minjiang University (Grant No. 5010100403), and National Natural Science Foundation of China (No. 72074184).

Appendix A. Data in the model.
The balanced SAM, which is used in the CEEEA model, is shown in Table A.1. Here Activity indicates different sectors, CAP indicates Capital input, LAB indicates labor input, IDT indicates indirect tax, TRF indicates tariffs, RUR indicates rural residents, CTZ indicates urban residents, GOV indicates government, INV indicates investment, and ROW indicates the rest of the world.

| Activity | CAP | LAB | IDT | TRF | RUR | CTZ | GOV | INV | ROW | Total |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Activity | 126,614 |     |     |     |     |     |     |     |     | 195,760 |
| CAP     | 9112 |     |     |     |     |     |     |     |     | 9112 |
| LAB     | 35,573 |     |     |     |     |     |     |     |     | 35,573 |
| IDT     | 9053 |     |     |     |     |     |     |     |     | 9053 |
| TRF     | 298 |     |     |     |     |     |     |     |     | 298 |
| RUR     |     | 2457 |     |     |     |     |     |     |     | 2457 |
| CTZ     |     | 6655 |     |     |     |     |     |     |     | 6655 |
| GOV     |     |     | 9053 | 298 | 788 | 2215 |     |     |     | 12,355 |
| INV     |     |     |     | 1032 | 18,665 | 4118 |     |     |     | 22,194 |
| ROW     |     |     |     |     |     |     |     |     | 15,109 | 15,109 |

Appendix B. Detailed information on the CEEEA model in this paper
Mathematical expression

**Production block**

\[
RNW_i = \alpha^{m} \left( \delta_{m}^{m} - \delta_{m}^{m} \right) NcP_{i}^{m} + \delta_{m}^{m} \left( \frac{WdP_{i}^{m}}{NcP_{i}^{m}} \right) \left( \frac{1 - \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}}{\delta_{m}^{m} \delta_{m}^{m}} \right) SoP_{i}^{m} \right)^{1/\delta_{m}^{m}} \\
(\text{B.1})
\]

\[
PNC_{i}^{m} = \frac{\delta_{m}^{m} \left( \frac{WdP_{i}^{m}}{NcP_{i}^{m}} \right) \left( \frac{1 - \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}}{\delta_{m}^{m} \delta_{m}^{m}} \right) SoP_{i}^{m}}{1 - \delta_{m}^{m} \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}} \left( \frac{SoP_{i}^{m}}{NcP_{i}^{m}} \right) \left( \frac{1 - \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}}{\delta_{m}^{m} \delta_{m}^{m}} \right) \\
(\text{B.2})
\]

\[
PNC_{i}^{m} = \frac{\delta_{m}^{m} \left( \frac{WdP_{i}^{m}}{NcP_{i}^{m}} \right) \left( \frac{1 - \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}}{\delta_{m}^{m} \delta_{m}^{m}} \right) SoP_{i}^{m}}{1 - \delta_{m}^{m} \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}} \left( \frac{SoP_{i}^{m}}{NcP_{i}^{m}} \right) \left( \frac{1 - \delta_{m}^{m} - \delta_{m}^{m} \delta_{m}^{m}}{\delta_{m}^{m} \delta_{m}^{m}} \right) \\
(\text{B.3})
\]

\[
RNW,PRNW_{i} = NcP_{i}^{m} + WdP_{i}^{m} + SoP_{i}^{m} + PSoP_{i}^{m} \\
(\text{B.4})
\]

\[
NTP_{i} = \delta_{m}^{m} \left( \frac{HyP_{i}^{m}}{RNW_{i}^{m}} \right) \left( \frac{1 - \delta_{m}^{m}}{1 - \delta_{m}^{m}} \right) \\
(\text{B.5})
\]

\[
NTP,PNTP_{i} = HyP_{i}^{m} + PRNW_{i}^{m} + RNW,PRNW_{i}^{m} \\
(\text{B.7})
\]
\[ ELE_i = \alpha_i^{E} (\delta_i^{E} Th_i^{PE} + (1 - \delta_i^{E}) NTP_i^{PE})^{1/\delta_i^{E}} \]  
(B.8)

\[ PT_{Th_i} = \frac{\delta_i^{E}}{1 - \delta_i^{E}} (\text{NTP}_i)_{Th_i}^{(1-\delta_i^{E})} \]  
(B.9)

\[ ELE,PEL_i = Th_i,PT_{Th_i} + NTP,PT_{NTP_i} \]  
(B.10)

\[ NOS_i = \alpha_i^{NOS} (\delta_i^{NOS} \text{OIL}_i^{PE} + (1 - \delta_i^{NOS}) \text{GAS}_i^{PE})^{1/\delta_i^{NOS}} \]  
(B.11)

\[ POH_i = \frac{\delta_i^{NOS}}{1 - \delta_i^{NOS}} (\text{GAS}_i^{NOS})^{(1-\delta_i^{NOS})} \]  
(B.12)

\[ NOS,PNO_i = \text{OIL,POH}_i + \text{GAS,PGAS}_i \]  
(B.13)

\[ PFE_i = \alpha_i^{PFE} (\delta_i^{PFE} \text{COAL}_i^{PE} + (1 - \delta_i^{PFE}) \text{NOS}_i^{PE})^{1/\delta_i^{PFE}} \]  
(B.14)

\[ PCOAL_i = \frac{\delta_i^{PFE}}{1 - \delta_i^{PFE}} (\text{NOS}_i)_{\text{COAL}}^{(1-\delta_i^{PFE})} \]  
(B.15)

\[ PFE,PPFE_i = \text{COAL,PCOAL}_i + \text{NOS,PNO}_i \]  
(B.16)

\[ Fossil_i = \alpha_i^{\text{Fossil}} (\delta_i^{\text{Fossil}} \text{PEL}_i^{\text{Fossil}} + (1 - \delta_i^{\text{Fossil}}) \text{REF}_i^{\text{Fossil}})^{1/\delta_i^{\text{Fossil}}} \]  
(B.17)

\[ PFE,PRE_i = \frac{\delta_i^{\text{Fossil}}}{1 - \delta_i^{\text{Fossil}}} (\text{REF}_i)_{\text{PFE}}^{(1-\delta_i^{\text{Fossil}})} \]  
(B.18)

\[ Fossil,PFossil_i = PFE,PPFE_i + REF,PRE_i \]  
(B.19)

\[ ENE_i = \alpha_i^{\text{ENE}} (\delta_i^{\text{ENE}} ELE_i^{\text{ENE}} + (1 - \delta_i^{\text{ENE}}) \text{Fossil}_i^{\text{ENE}})^{1/\delta_i^{\text{ENE}}} \]  
(B.20)

\[ PELE_i = \frac{\delta_i^{\text{ENE}}}{1 - \delta_i^{\text{ENE}}} (\text{Fossil}_i)_{\text{ENE}}^{(1-\delta_i^{\text{ENE}})} \]  
(B.21)

\[ ENP,PELE_i = ELE,PELE_i + Fossil,PFossil_i \]  
(B.22)

\[ CE_i = \alpha_i^{\text{CE}} (\delta_i^{\text{CE}} ENE_i^{\text{CE}} + (1 - \delta_i^{\text{CE}}) \text{CAP}_i^{\text{CE}})^{1/\delta_i^{\text{CE}}} \]  
(B.23)

\[ PENE_i = \frac{\delta_i^{\text{CE}}}{1 - \delta_i^{\text{CE}}} (\text{CAP}_i)_{\text{PEN}}^{(1-\delta_i^{\text{CE}})} \]  
(B.24)

\[ CE,PCP_i = ENP,PELE_i + CAP,PCAP_i \]  
(B.25)

\[ VAE_i = \alpha_i^{\text{VAE}} (\delta_i^{\text{VAE}} CE_i^{\text{VAE}} + (1 - \delta_i^{\text{VAE}}) \text{LAB}_i^{\text{VAE}})^{1/\delta_i^{\text{VAE}}} \]  
(B.26)

\[ PCE_i = \frac{\delta_i^{\text{VAE}}}{1 - \delta_i^{\text{VAE}}} (\text{LAB}_i)_{\text{PCE}}^{(1-\delta_i^{\text{VAE}})} \]  
(B.27)

\[ VAE,PAE_i = CE,PCP_i + \text{LAB,PLAB}_i \]  
(B.28)

\[ INT_{ij} = \delta_{ij}^{PE} Z_{ij} \]  
(B.29)

\[ VA_{E_{ij}} = \delta_{ij}^{VAE} Z_{ij} \]  
(B.30)

\[ PZ_{ij} = \delta_{ij}^{PE} VAE_{ij} + \sum_i \delta_{ij}^{PE} \sum_i P Q_i \]  
(B.31)

Income-expenditure block

(B.32)

\[ SG = \left( \sum_i T D_i + \sum_i T Z_i + \sum_i T M_i \right) \]  
(B.33)
\[ \begin{align*}
X_{G_i} &= \frac{\mu_i}{PQ_i} \left( \sum_j TD_j + \sum_j TZ_j + \sum_j TM_i - SG \right) \\
\text{XP}_{i,j} &= \frac{\beta_{ij}^{\text{PQ}}}{PQ_i} \left( \sum_i \left( \gamma_i^{\text{LAB}} \cdot \text{PLAB}_i + \gamma_i^{\text{CAP}} \cdot \text{PCAP}_i \right) - SP_i - TD_i \right) \\
TD_i &= \tau_d \sum_i \left( \gamma_i^{\text{LAB}} \cdot \text{PLAB}_i + \gamma_i^{\text{CAP}} \cdot \text{PCAP}_i \right) \\
TZ_i &= \tau_P \cdot \text{PZ}_i \\
TM_i &= \tau_m \cdot \text{PM}_i,
\end{align*} \]

\textbf{Trade block}

\[ \begin{align*}
PE_i &= \varepsilon_i \cdot \text{PWE}_i \\
\text{PM}_i &= \varepsilon_i \cdot \text{PWM}_i \\
\sum_i \text{PWE}_i \cdot E_i + SF &= \sum_i \text{PWM}_i \\
Q_i &= \gamma_i (\delta_m \cdot M_i + \delta_d \cdot D_i)^{1/\xi} \\
M_i &= \left[ \frac{\gamma_i \delta_m \cdot PQ_i}{(1 + \gamma_i \delta_m \cdot PM_i)} \right]^{\frac{1}{\xi}} Q_i \\
D_i &= \left[ \frac{\gamma_i \delta_d \cdot PQ_i}{PD_i} \right]^{\frac{1}{\xi}} Q_i \\
Z_i &= \theta_i \left( \xi_E \cdot E_i^{\delta} + \xi_D \cdot D_i^{\delta} \right)^{\frac{1}{\delta}} \\
E_i &= \left[ \delta_i \cdot \xi_E \cdot [(1 + \tau_i) \cdot PZ_i] \right]^{\frac{1}{\xi}} Z_i \\
D_i &= \left[ \delta_i \cdot \xi_D \cdot [(1 + \tau_i) \cdot PZ_i] \right]^{\frac{1}{\xi}} Z_i
\end{align*} \]

\textbf{Energy-Environment block}

\[ \begin{align*}
\text{EM}_i &= \gamma^{\text{coal}} \cdot \text{ENE}_\text{COAL}_i + \gamma^{\text{oil}} \cdot \text{ENE}_\text{OIL}_i + \gamma^{\text{gas}} \cdot \text{ENE}_\text{GAS}_i \\
\text{ENE}_\text{COAL}_i &= \chi^{\text{coal}} \cdot \text{COAL}_i \\
\text{ENE}_\text{OIL}_i &= \chi^{\text{oil}} \cdot \text{OIL}_i \\
\text{ENE}_\text{GAS}_i &= \chi^{\text{gas}} \cdot \text{GAS}_i
\end{align*} \]

\textbf{macroscopic-closure & market-clearing block}

\[ \begin{align*}
X_{V_i} &= \frac{\lambda_i}{PQ_i} \left( \sum_j SP_j + SG + eSF \right) \\
Q_i &= \sum_i \text{XP}_{i,j} + X_{G_i} + X_{V_i} + \sum_j \text{INT}_{i,j} \\
\sum_i \text{LAB}_i &= \sum_j \text{FF}_{i,j}^{\text{LAB}} \\
\sum_i \text{CAP}_i &= \sum_j \text{FF}_{i,j}^{\text{CAP}}
\end{align*} \]
Objective function

\[
T_{OUT} = \sum \left( \prod X P_{ij} \right)
\]  

(Objective function B.56)

Descriptions of key variables

As there are many variables in the CEEEA model, this paper only introduces several parts of the key variables. Most of them are endogenous variables but ignore the introduction of several parameters, most of which are exogenous parameters, such as \( \alpha_{ele}^{i} \), \( \delta_{ele}^{i} \) and \( \rho_{ele}^{i} \) in lots of CES functions. The key variables (most of them are endogenous variables) are shown in Table B.1.

Table B1
Descriptions of key variables.

| Variables | Descriptions |
|-----------|--------------|
| \( NcP_i \) | Nuclear power input |
| \( WdP_i \) | Wind power input |
| \( SoP_i \) | Solar power input |
| \( RNW_i \) | Other renewable energy input |
| \( HyP_i \) | Hydropower input |
| \( NTP_i \) | Nonthermal power input |
| \( ThP_i \) | Thermal power input |
| \( ELE_i \) | Electricity input |
| \( OIL_i \) | Oil input |
| \( GAS_i \) | Gas input |
| \( NOS_i \) | Non-solid primary fossil energy input |
| \( COAL_i \) | Coal input |
| \( PFE_i \) | Primary fossil energy |
| \( REF_i \) | Refined oil input |
| \( FOSSIL_i \) | Fossil energy input |
| \( ENR_i \) | Energy input |
| \( CE_i \) | Capital-energy input |
| \( CAP_i \) | Capital input |
| \( LAB_i \) | Labor input |
| \( VAE_i \) | Value-added and energy input |
| \( INT_{ij} \) | Intermediate input |
| \( Z_j \) | Domestic output |
| \( PNcP_i \) | Price of Nuclear power input |
| \( PWdP_i \) | Price of Windpower input |
| \( PSoP_i \) | Price of Solar power input |
| \( PRNW_i \) | Price of Other renewable energy input |
| \( PHyP_i \) | Price of Hydropower input |
| \( PNTP_i \) | Price of Nonthermal power input |
| \( PThP_i \) | Price of Thermal power input |
| \( PELE_i \) | Price of Electricity input |
| \( POIL_i \) | Price of Oil input |
| \( PGAS_i \) | Price of Gas input |
| \( PNOS_i \) | Price of Non-solid primary fossil energy input |
| \( PCOAL_i \) | Price of Coal input |
| \( PPFE_i \) | Price of Primary fossil energy |
| \( PREF_i \) | Price of Refined oil input |
| \( PFossili_i \) | Price of Fossil energy input |
| \( PENE_i \) | Price of Energy input |
| \( PCE_i \) | Price of Capital-energy input |
| \( PCAP_i \) | Price of Capital input |
| \( PLCAP_i \) | Price of Labor input |

(continued on next page)
Equations (B.1) to (B.4) are a CES production function bundle aggregating three kinds of renewable energy input. The first is a CES production function, the second and the third are the first-order condition of the CES function, and the last is an equation to balance the value. From equation (B.1) to (B.28), all CES function bundles are in production block at different nest levels. Equations (B.29) to (B.31) describe the output bundle by the Leontief production function. Equations (B.29) and (B.30) are the relationships between output and intermediate input, and between output and VAE input. Equation (B.31) is a simplified value identity equation. Bringing Equations (B.29) and (B.30) into Equation (B.31) can get an identity equation similar to the equation (B.4).

Income and expenditure block describes the behaviors of household savings (B.32), government savings (B.33), government consumption (B.34), household consumption (B.35), direct tax (B.36), indirect tax (B.37), and tariff (B.38).

Equations (B.39) and (B.40) describe the relationship between domestic and international prices. As international trade is not what we focus on, this paper follows the small country assumption. Equation (B.41) expresses the trade deficit. Equations (B.42) to (B.44) are Armington’s assumptions, which describe the behavior of consuming import goods and consuming domestic goods. Equation (B.42) is a CES function, and the following two equations are the first-order conditions of it. Like the former equation bundle, equations from (B.45) to (B.47) describe the behavior of how domestic enterprises distribute their product to the domestic market and international market. Among them, equation (B.45) is a CET function, and equations (B.46) and (B.47) are the first-order condition of equation (B.45).

Equations (B.48) and (B.51) describe the relationship among fossil fuel consumption, CO₂ emissions, and factor inputs in the production block. Equation (B.48) describes the emissions. Equations (B.49) to (B.51) describe the relationship between energy cost (value) in SAM and actual energy consumption in each industry.

Equation (B.52) is a mathematical expression of macroscopic closure. Equations (B.53), (B.54), and (B.55) are mathematical expressions of market clearing. Equation (B.56) is the utility function, which is also the objective function.

### Table B1 (continued)

| Variables | Descriptions |
|-----------|--------------|
| PVAE<sub>i</sub> | Price of Value-added and energy input |
| PD<sub>j</sub> | Price of domestic output |
| SP<sub>j</sub> | Savings of residential |
| SG<sub>j</sub> | Savings of the government |
| XP<sub>j</sub> | Consumption of the residents |
| XG<sub>j</sub> | Consumption of the government |
| D<sub>j</sub> | Direct tax |
| T<sub>j</sub> | Indirect tax |
| TM<sub>j</sub> | Tariffs |
| E<sub>j</sub> | Export |
| D<sub>j</sub> | Domestic goods for domestic consumption |
| M<sub>j</sub> | Import |
| Q<sub>j</sub> | Armington commodity |
| SF<sub>i</sub> | Trade deficit |
| Pr<sub>i</sub> | Price of export |
| PD<sub>i</sub> | Price of domestic goods for domestic consumption |
| PM<sub>i</sub> | Price of import |
| PQ<sub>i</sub> | Price of Armington commodity |
| ε<sub>i</sub> | Local currency exchange rate |
| PWE<sub>i</sub> | Price of export in USD |
| PWM<sub>i</sub> | Price of import in USD |
| EM<sub>i</sub> | CO₂ emissions |
| ENE<sub>i</sub> | Coal consumption (Unit: million tonnes of coal equivalent) |
| ENE<sub>i</sub> | Oil consumption (Unit: million tonnes of coal equivalent) |
| ENE<sub>i</sub> | Gas consumption (Unit: million tonnes of coal equivalent) |
| XV<sub>i</sub> | Investment |
| FF<sub>lab</sub> | The endowment of labor |
| FF<sub>cap</sub> | The endowment of capital |
| TOTUU | Total utility |
Appendix C. The framework of CEEEA/CGE model

Appendix D. Descriptive figures

See Fig. D1 and Fig. D2

Fig. D1. COVID-19 in China: cumulative diagnosis, newly diagnosed and hospitalized patients (data source: National Health and Health Council).
Fig. D2. The petroleum spot price in Brent and WTI (data source: CEIC database).
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