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Impacts of Clean Energy Substitution for Polluting Fossil-Fuels in Terminal Energy Consumption on the Economy and Environment in China

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Abstract: China has initiated various dedicated policies on clean energy substitution for polluting fossil-fuels since the early 2010s to alleviate severe carbon emissions and environmental pollution and accelerate clean energy transformation. Using the autoregressive integrated moving average (ARIMA) regression, we project the potentials of substituting coal and oil with clean energy for different production sectors in China toward the year 2030. Based on the projections, a dynamic multi-sectoral computable general equilibrium model, CHINAGEM, is employed to examine: the impacts of future clean energy substitution on China's energy production, outputs of non-energy sectors, macro-economy, and CO_2 emissions. First, we found that most production sectors are projected to replace polluting fossil-fuels with clean energy in their terminal energy consumption in 2017–2030. Second, clean energy substitution enables producing green co-benefits that would enable improvements in energy production structure, reductions in national CO_2 emissions, and better real GDP and employment. Third, technological progress in non-fossil-fuel electricity could further benefit China's clean and low-carbon energy transformation, accelerating the reduction in CO_2 emissions and clean energy substitution. Furthermore, the most beneficiary are energy-intensive and high carbon-emission sectors owing to the drop in coal and oil prices, while the most negatively affected are the downstream sectors of electricity. Through research, various tentative improvement policies are recommended, including financial support, renewable electricity development, clean energy utilization technology, and clean coal technologies.

Keywords: clean energy substitution; polluting fossil-fuels; energy consumption; economic impacts; carbon-emission reduction

1. Introduction

China's energy production and consumption structures have long been dominated by coal and oil, which are the main air pollution and carbon-emission sources [1–3]. Burning gas also produces carbon emissions, it however, compared to coal and oil, can produce far less SO_2, NOx, CO, and dust [4–6]. Therefore, gas is viewed as a type of clean energy from the perspective of environmental pollution as a whole [7,8]. The proportions of coal and oil in the total energy production reached 77% and 9% in 2016, respectively, whereas the overall proportion of clean energy (i.e., gas and electricity) accounted for merely 14%. In that year, the shares of coal and oil in total energy consumption were as high as 62% and 19%, respectively, in contrast to the shares of gas and electricity which were 6% and 13%, respectively [9]. In addition, more than 80% of energy commodities were consumed by production sectors [10]. The fossil-fuel dominated energy structure has thereby led to severe carbon emissions and air pollution problems, because more than 95% of national CO_2 emissions could be attributed to coal and oil combustion [11]. After the Paris Agreement, China's government promised to reduce its carbon emissions by raising the proportions of gas and electricity in the total energy consumption to 15% and 20% by 2030, respectively. Achieving this goal demands continuous massive efforts in accelerating clean transformation of China's energy consumption in coming decades.

To meet the goal of alleviating severe carbon emissions and environmental pollution and accelerating clean transformation of energy consumption, China has initiated a series of policies on clean energy substitution for polluting fossil-fuels (i.e., coal and oil) since the early 2010s. In 2013, the State Council issued the "Air Pollution Prevention and Control Action Plan" and implemented the "coal to gas" and "coal to electricity" projects to control air pollution in Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta city clusters [12]. National Development and Reform Commission (NDRC) publicized the "Guiding Opinions on Promoting Electricity Substitution" in 2016 to substitute coal and oil of 130 million tons of coal equivalent (tce) with electricity in terminal energy consumption, which would enhance the electrification of production sectors [13]. The "13th Five-Year Plan for Energy Development" released by NDRC in 2016 reemphasized the clean transformation of energy consumption, aiming to optimize the energy consumption structure via clean energy substitution for polluting fossil-fuels [14]. Affected by clean energy substitution projects, Beijing, Shaanxi, and Zhejiang provinces achieved 2.56, 3.99, and 8.16 billion KWh of electricity substitution till 2017, respectively, equivalent to a reduction in coal and oil consumptions by 4.16, 1.28, and 3.3 million tce through a series of policy incentives, such as financial subsidies to power the grid and production equipment renovation and electricity price support [15].

Whereas most quantitative research concentrated on China's energy structure from the perspective of production, an increasing number of studies have realized the importance of research problems on the consumption-side of the energy structure. Those studies include projections of China's future energy demand utilizing econometric models, such as those by Yuan et al., Yuan et al., and Gao et al. [16–18]. A few others empirically analyzed the impacts of clean energy substitution based on both the econometric and computable general equilibrium (CGE) model. In the studies, the coal-to-gas substitution was firstly investigated to reveal the trend of replacing coal by gas in terminal energy consumption [19,20]. Subsequently, dedicated attention has been paid to examining the electricity substitution for polluting fossil-fuels (i.e., coal-to-electricity and oil-to-electricity substitution), according to Lin et al., Wu et al., and Zhang et al. [21–23].

Despite increasing efforts laid on projecting China's future energy demand toward 2030, the existing studies have rarely focused on the central problem of the future energy consumption structure of production sectors. Some studies have attempted to project China's total energy demand or the demand for a specific energy product [16,17,24], yet few have projected the structure of the future energy demand [25–28]. Upon the same base year of 2016, studies agree that China's proportion of coal in energy consumption would fall rapidly to 55.2–60.0% by 2020 and 45.4–50.19% by 2030, and the proportion of oil would decline by 5.9–10.3 percent points by 2020 and 21.6–25.8 percent points by 2030. Simultaneously, the proportions of gas and electricity would rise to 11.1–16.2% and 22.2–25.1% by 2030, respectively. Nevertheless, those studies on predicting sheerly the future national energy demand are not favored to offer a projection of the future energy consumption structure of production sectors.

Most studies have claimed to identify the positive economic and environmental effects of China's energy production transformation using the CGE model [29–31]. These studies, which normally focused on identifying energy consumption changes, have however exposed a disagreement in the economic and environmental impacts [32–36]. Existing studies agree that clean transformation of energy production, especially for renewable energy development, would effectively reduce carbon emissions and produce green co-benefits in elevating economic growth and employment [29–31]. Chen et al. and Niu et al. found that clean energy substitution in terminal energy consumption could effectively cut down carbon emissions [32,33]. However, Lin et al. and Wu et al. demonstrated that the CO_2 abatement by clean energy substitution is limited because fossil-fired electricity generation would also emit a large amount of CO_2 [21,22]. Furthermore, previous studies suggested opposite analytical results for economic impacts of clean energy substitution. Some proved that clean energy substitution could increase the net values added from both energy and non-energy sectors, as well as total employment [34,35]; others declared that clean energy substitution would cause damage to China's energy production, trade, and economic activities [19,36]. Much attention needs to be paid to assessing the impacts of future clean energy substitution on energy production, the economy, and the environment in China by merits of the CGE model.

The purpose of this study is to empirically examine the impacts of future clean energy substitution on energy production, the economy, and the environment. To achieve this goal, we first project the potentials of substituting polluting fossil-fuels with clean energy for different production sectors in China toward 2030 using the autoregressive integrated moving average (ARIMA) regression. Thereafter, a dynamic multi-sectoral CGE model, named CHINAGEM, is employed to study the impacts of future clean energy substitution on China's energy production, the outputs of non-energy sectors, macro-economy, and CO_2 emissions, based upon the projections. The study contributes to the current research realm in the following aspects: (1) a methodological approach is developed via coupling ARIMA with the CHINAGEM model, in which the ARIMA regression takes on forecasting changes in production sectors' future energy consumption structure, and the CHINAGEM model is responsible for evaluating the impacts of clean energy substitution on the economy and environment. (2) The impacts of clean energy substitution are assessed from both the consumption and supply side of energy commodities. (3) The impacts on energy production, outputs of non-energy sectors, macro-economy, and CO_2 emissions are empirically examined.

The remainder of this study is organized into three sections. Section 2 introduces the methodology and simulation model. Section 3 discusses the estimation results by the ARIMA regression and the simulation results by the CHINAGEM model for the impacts of clean energy substitution on the energy production, outputs of non-energy sectors, macro-economy, and CO_2 emissions. The last section concludes the study with policy implications.

2. Methodology and Data

The potentials of substituting coal and oil with clean energy for different production sectors are projected using the ARIMA regression during the period of 2017 to 2030. Subsequently, based on the projections, we employed the CHINAGEM model to evaluate the impacts of future clean energy substitution on China's energy production, outputs of non-energy sectors, macro-economy, and CO_2 emissions. A brief description of the ARIMA regression and CHINAGEM model is introduced as follows.

2.1. ARIMA Regression

Here, the future changes in consumptions of four terminal energy sources (i.e., coal, oil, gas, and electricity) are projected for each production sector separately using the ARIMA regression. Then, the projections on the shares of terminal energy consumption are obtained to represent the potentials of clean energy substitution. ARIMA regression is widely used in projecting future energy consumption and is regarded as an efficient method for long-term forecast [37–42]. ARIMA regression requires the sequence to be stationary, at least after being differentiated. Thus, the formula of ARIMA (p, d, q) regression for a differentiated sequence is specified as follows:

$$\Delta y_t = \beta_0 + \sum\nolimits_{i=1}^{p} \beta_i \Delta y_{t-i} + \varepsilon_t + \sum\nolimits_{i=1}^{q} \theta_i \varepsilon_{t-i} \quad (1)$$

where t represents time; Δy_t and Δy_{t-i} are the current and lag value of differentiated terminal energy consumption of each production sector, respectively; ε_t and ε_{t-i} are the current and lag value of error terms, respectively; β_i are the autocorrelation coefficients; θ_i are the autocorrelation coefficients of error terms; p is the autoregressive order; d is the degree of differencing; and q is the moving-average order.

Generally, there are six steps for the ARIMA regression—data collection, identification, order determination, parameter estimation, model verification, and projection. For the first step, the annual data on terminal energy consumption (i.e., coal, oil, gas, and electricity) for seven production sectors (i.e., agriculture, mining and quarrying, manufacturing, energy and water industry, construction, transportation, and other services) are obtained from the Energy Statistics Yearbook of China (1992−2018). The data of 1991–2016 are used for ARIMA parameter estimation, and the data of 2017 are used to validate the projection accuracy of the ARIMA regression. The changing trend of terminal energy consumption in each production sector in China is shown in Appendix C (Figure A2). After data collection, we obtain the stationarity of the original data using the Augmented Dickey-Fuller (ADF) test, autocorrelation function (ACF), and partial autocorrelation function (PAF) diagram. To save space, we do not display all results of the ACF and PAF tests, but we have applied them to validate the ADF test results. Based on the time series diagram (Appendix C, Figure A2) and ADF stationarity test results (Appendix C, Table A4), all original sequences are not stationary and could not be used for ARIMA regression without being differentiated.

The differentiated approach is used to smoothen the non-stationary time series, and the degree of differencing, d, is determined by the ADF unit root test. The results indicate that over a half of the time series are stationary after first-order differencing. However, the data on coal consumption for transportation, gas consumption for agriculture, manufacturing, transportation, and other services, as well as electricity consumption for manufacturing, energy and water industry, transportation, and other services are stationary after second-order differencing (Appendix C, Table A5). Then, the autoregressive order, p, and the moving-average order, q, are determined based on the truncating and trailing features of ACF and PAF tests in the differentiated sequences. Based on the identified orders, the ARIMA regressions are specified, and the statistical significance of parameters is tested. The results of the ARIMA models are shown in Appendix C (Table A6), and most of them have rather high R^2 values, indicating good fitness of regressions. After the specification of ARIMA (p, d, and q) regressions, we finally determined the orders by re-checking the randomness of the residual sequences, which should be white noise sequences. The randomness of the residual sequences could be tested by the ACF, PAF, and ADF tests (Appendix C, Table A7). The last step of ARIMA regression is to project the terminal energy consumption of different production sectors from 2017 to 2030. The fitness between the original differentiated series and the projected differentiated series is compared in Appendix C (Figure A3), which indicates that the fitted values from ARIMA regression for the period of 1991–2016 are very close to the official statistics.

2.2. CGE Model

With the changes in future terminal energy consumption of different production sectors projected by the ARIMA regression, a dynamic multi-sectoral CGE model is used to simulate and analyze the economic and environmental impacts of clean energy substitution. For examining the economic and environmental effects of different policies, a class of multi-criteria evaluation models were often adopted [43–45], yet few applied a CHINAGEM-alike model to fathom the economic and environmental effects caused by clean energy substitution for polluting fossil-fuels.

The CHINAGEM model is a dynamic CGE model of China, developed by the Center of Policy Studies, Victoria University [46]. The theoretical framework of the CHINAGEM model is introduced in Feng et al. [47]. In the CHINAGEM model, clean energy substitution would directly cause the decreases in the demand for polluting fossil-fuels but raise the demand for clean energy, which in turn reduces prices of polluting fossil-fuels and increases prices of clean energy. Stimulated by rising prices of clean energy, the clean energy sectors would expand their power generation. Simultaneously, the production of coal and oil sectors would fall down due to decreasing prices. Then the outputs of non-energy sectors are impacted by not only the changes of energy commodity prices, but also the impacts transmitted through the input-output chain of production sectors. Finally, the output changes of production sectors would lead to different results of employment and economic growth. Meanwhile, carbon emissions would change owing to the consumption change of energy commodities.

To save space, only the nested structure of energy commodities consumed by production sectors in the CHINAGEM model is introduced here. For dynamic simulations, the CHINAGEM model employs several mechanisms including physical capital accumulation, financial asset/liability accumulation, and lagged adjustment processes in the labor market.

2.2.1. Nested Structure of Energy Consumption for Production Sectors

In the CHINAGEM model, the nested constant elasticity of substitution (CES) functions are used to describe the substitution between different energy consumptions for each production sector (Figure 1, Panel A). According to the principle of cost minimization, the producers determine the optimal energy input.

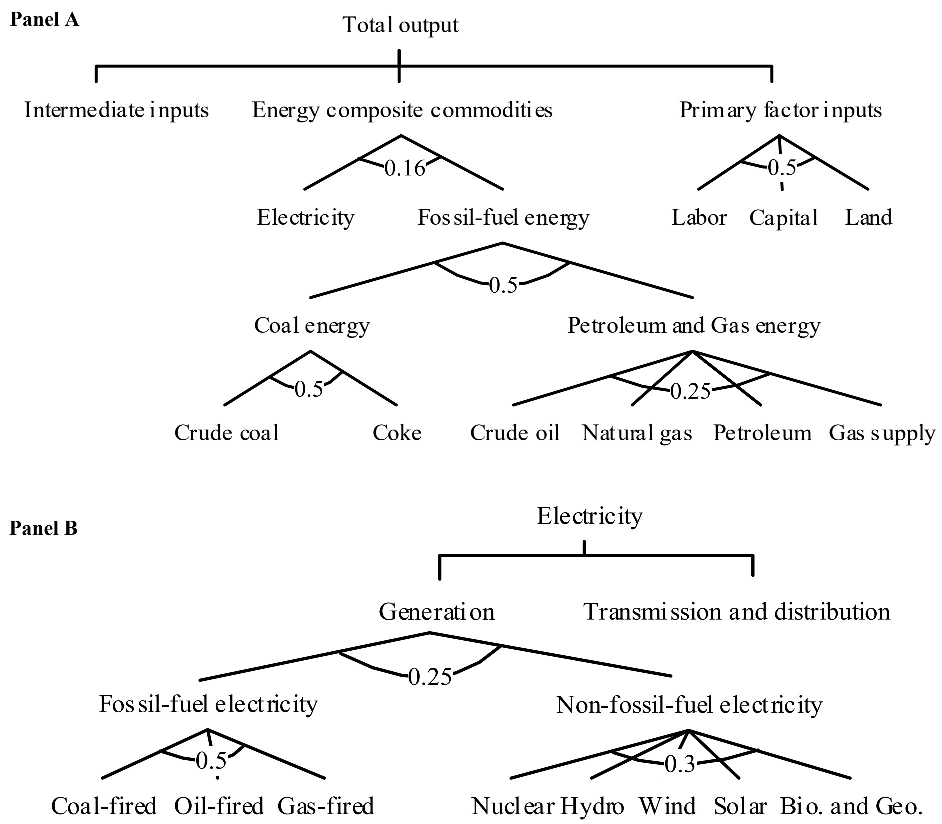

Figure 1. Nested structure of energy consumption for production sectors in the CHINAGEM model. **Note:** Panel A is for the nested structure of energy commodities; Panel B is for the nested structure of electricity sectors.

On the top of the nested structure, other intermediate inputs, energy composite commodities, and primary factor inputs are assumed to be fixed in proportion with the production sectors' activity level (Figure 1, Panel A). The Leontief function, a special CES function with a substitution elasticity of 0, is used. At the lower level of the nested structure, the energy composite commodities include electricity and fossil-fuel energy described by the CES function with a substitution elasticity of 0.16. Then, fossil-fuel energy includes coal, petroleum, and gas with a substitution elasticity of 0.5. On the bottom of the nested structure, coal includes crude coal and coke with a substitution elasticity of 0.5, and petroleum and gas comprises crude oil, natural gas, petroleum, and gas supply with a substitution elasticity of 0.25.

To simulate the substitution between different electricity sectors, the nested structure of electricity consumption for production sectors is developed. The electricity sector is split into eight electricity generation sectors with different power sources, including coal-fired power, oil-fired power, gas-fired power, nuclear power, hydropower, wind power, solar power, and biomass and geothermal power, and one sector for power transmission and distribution (Figure 1, Panel B). On top of the nested structure of electricity, the Leontief function is employed to assume electricity utilization to be in proportion with the service for electricity transmission and distribution. Then, we categorize electricity generation sectors into fossil-fuel and non-fossil-fuel electricity, with a substitution elasticity of 0.25. The former includes coal-fired power, oil-fired power, and gas-fired power, and the substitution among these types of electricity is described by the CES function with a substitution elasticity of 0.5. The substitution elasticity of non-fossil-fuel electricity is assumed to be 0.3.

2.2.2. Data and Closure

To establish the database of the CHINAGEM model, we use China's 2012 input-output table with 139 original production sectors (A schematic representation of the CHINAGEM model database is illustrated by Appendix A (Table A1)). Since there is only one electricity sector in the official input-output table, the original electricity sector is split to eight electricity-generating sectors with different power sources and one sector of power transmission and distribution based on the data from China Electric Power Statistics Yearbook (2013). Similarly, the sector of crude oil and gas is split into two separate sectors, crude oil and crude gas. Thus, 146 production sectors are obtained (Appendix A, Table A2). The Armington elasticities of commodities are transferred from the Global Trade Analysis Project (GTAP) V9 database by mapping the CHINAGEM 146 sectors to GTAP 57 sectors with the sectorial matching concordance in Table A3, Appendix A. Other elasticities of demand and supply equations are from previous studies [48].

For the dynamic simulation of the CHINAGEM model, we adopt short-term macro-economic closure for each year. Specifically, because of the almost fixed nominal wage contracts, the wages are assumed to be fixed, and the employment of production sectors is determined by real wages. The capital of the production sectors is assumed to be fixed, and the return of capital is allowed to change. The investment of each production sector is determined by the rate of return. The government expenditure is fixed in proportion with household expenditure.

2.2.3. Simulation Scenario Design

To study the economic and environmental impacts of clean energy substitution, we establish a baseline scenario and three policy scenarios. The baseline scenario is calibrated from 2012 to 2050 without additional shocks regarding clean energy substitution, which is considered as a business-as-usual scenario. To achieve this, the projections on the growth in real GDP, population, and labor, as well as the changes in shares of agriculture, industry, and service are shocked in the CHINAGEM model. The impacts of future clean energy substitution are simulated from 2017 to 2030. Three policy scenarios are designed covering both the consumption and supply side of energy commodities as follows. The impacts of clean energy substitution are given by the difference between the baseline scenario and policy scenarios.

1. Scenario 1: The primary purpose of implementing clean energy substitution is to reduce severe air pollution by substituting polluting fossil-fuels with clean energy in terminal energy consumption of production sectors. Therefore, this scenario considers the replacement of polluting fossil-fuels by gas and electricity with all types of power sources, including fossil-fuel electricity and non-fossil-fuel electricity. The changes in proportions of polluting fossil-fuels and clean energy in terminal energy consumption of production sectors are obtained from the projections of ARIMA regression from 2017 to 2030.
2. Scenario 2: Fossil-fuel electricity still accounts for a large proportion of power generation in China. However, the generation of fossil-fuel electricity requires a great amount of fossil-fuels and emits severe carbon dioxide. Hence, much attention should be paid to increasing the proportion of electricity with renewable sources in terminal energy consumption to maximize the environmental benefits of clean energy substitution. Since 2013, China has firmly encouraged enterprises to utilize more clean energy from the consumption side via the renewable energy portfolio and

green electricity trading policies [49,50], which increased the utilization of renewable electricity by production sectors. As a result, Scenario 2 simulates the effects of substituting polluting fossil-fuels with non-fossil-fuel electricity as well as gas.

3. Scenario 3: National Energy Administration (NEA) has advocated to promote technological advancement and reduce the cost of renewable energy by adoption of innovative development mode [51]. Accordingly, upon the policy analyzed Scenario 2, Scenario 3 further considers that the production technology for non-fossil-fuel electricity is improved to increase the supply of non-fossil-fuel electricity. It assumes that the production efficiency of non-fossil-fuel electricity would improve by 1% every year during the period of 2017 to 2030.

3. Results

3.1. ARIMA Projection Results

Except for the energy and water industry, the proportion of electricity in terminal energy consumption of production sectors clearly exhibits a rising trend during the period of 1991 to 2030, yet the proportions of coal and oil have been persistently decreasing (Figure 2). Meanwhile, the share of gas in terminal energy consumption of most sectors has also been rising.

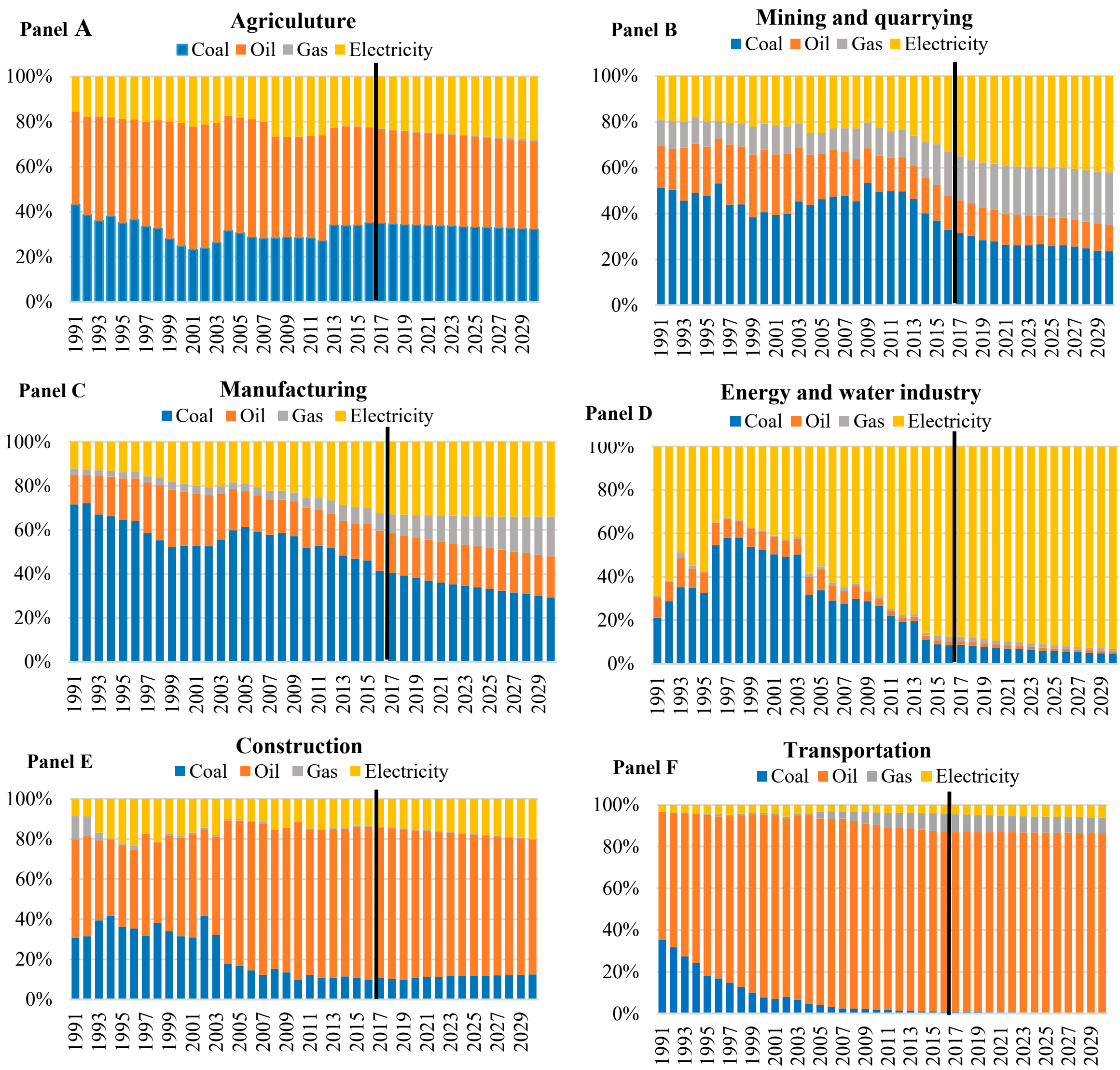

Figure 2. *Cont.*

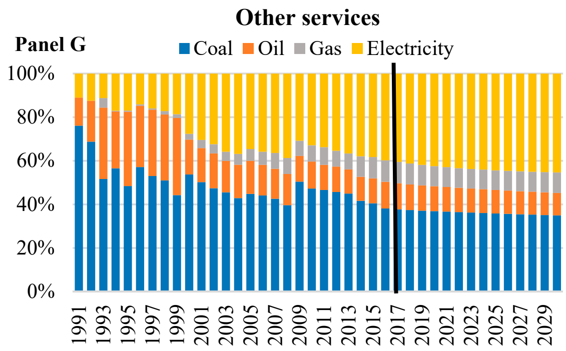

Figure 2. Official data and projections on terminal energy consumption of production sectors in 1991–2030. Source: Data of energy consumption in 1991–2016 are from the Energy Statistics Yearbook of China; data in 2017–2030 are projected by the ARIMA regression.

The production sectors, which highly depended on coal over the past decades, including mining and quarrying, manufacturing, and other services, show an obvious trend of replacing coal by electricity in terminal energy consumption toward 2030. The mining and quarrying sector is projected to have the largest potential in coal-to-electricity substitution among all production sectors. When its shares of coal and oil in terminal energy consumption would fall significantly from 32.94% and 14.72% in 2016 to 23.61% and 11.41% in 2030 respectively, the shares of electricity and gas would increase to the levels of 41.98% and 23.01% by 2030, respectively (Figure 2, Panel B). Similarly, the share of coal in terminal energy consumption of manufacturing sectors is projected to have the largest reduction due to coal-to-gas substitution among all production sectors. Specifically, the share of coal in its terminal energy consumption would decline significantly from 41.32% in 2016 to 29.33% in 2030 (Figure 2, Panel C). Meanwhile, the share of gas would increase rapidly from 7.99% in 2016 to 18.02% in 2030, and the shares of oil and electricity would increase slightly to 18.64% and 34.01% by 2030, respectively. Unlike the above two sectors, other services would replace fossil-fuels by electricity because the shares of coal, oil, and gas in its terminal energy consumption would decline to 34.9%, 10.3%, and 9.40% by 2030, respectively. Simultaneously, its share of electricity would rise from 39.8% in 2016 to 41.98% in 2030 (Figure 2, Panel G).

Construction and transportation, which highly depended on oil, have a large disparity in the trend of substituting oil with electricity in their terminal energy consumption. Construction has the most potential in the oil-to-electricity substitution among all production sectors. When the share of oil in its terminal energy consumption would fall significantly from 76.25% in 2016 to 67.20% in 2030, the share of electricity is projected to significantly increase to 19.91% by 2030, but the shares of coal and gas would change slightly (Figure 2, Panel E). However, the share of electricity in the terminal energy consumption of transportation is projected to moderately increase from 4.31% in 2016 to 6.18% in 2030 because of the penetration of electric vehicles and electrified railways, and the shares of coal, oil, and gas would slightly decline to 0.5%, 85.99%, and 7.30% by 2030, respectively (Figure 2, Panel F).

Compared with the above sectors, the structures of energy consumption would be relatively stable for the agriculture and energy and water industry during the period of 2017 to 2030. The energy consumption of the agricultural sector is dominated by oil and coal. When the shares of oil and coal in its terminal energy consumption are projected to decrease significantly from 42.19% and 35.15% in 2016 to 38.84% and 32.27% in 2030, respectively, the shares of electricity and gas would increase to the levels of 28.00% and 0.89% by 2030, respectively (Figure 2, Panel A). As for energy and water industry, whose terminal energy consumption is dominated by electricity and gas, only gas would have a larger share toward 2030 (increase from 45.83% in 2016 to 47.7% in 2030), and the shares of coal, oil, and electricity would have relatively slow decreases (Figure 2, Panel D).

3.2. Simulation Results of the CGE Model

3.2.1. Impacts on Energy Production

As a whole, it is obvious that clean energy substitution would significantly benefit the clean and low-carbon energy transition in China, for it could effectively lower the production of coal and oil and simultaneously raise the production of clean energy, especially for renewable energy (Figure 3).

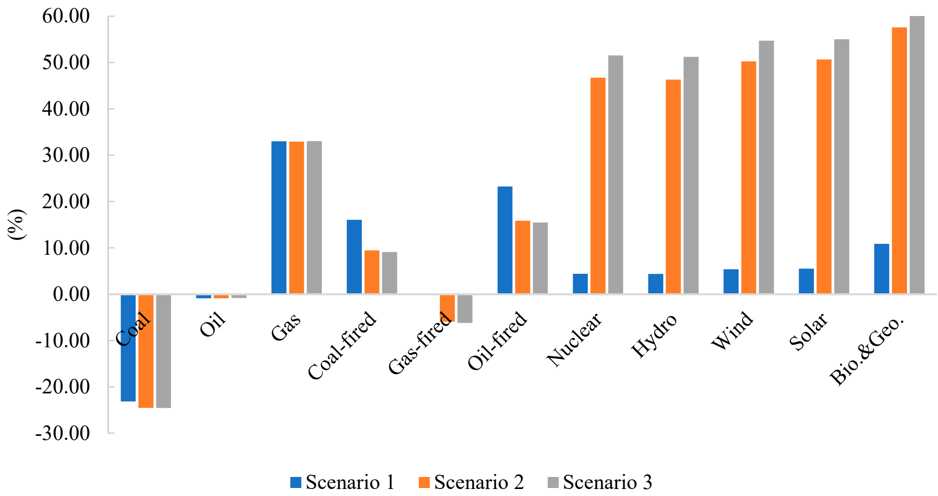

Figure 3. Accumulative impact of clean energy substitution on energy commodity production in 2017–2030. Note: The percentage represents the changes in the policy scenarios relative to the baseline scenario. Source: The CHINAGEM simulation.

Under Scenario 1, clean energy substitution could effectively reduce the production of coal and oil and largely increase the production of clean energy. The outputs of coal and oil would decline by 23.15% and 0.87%, respectively; gas is projected to have a sharp increase by more than 30% (Figure 3). Meanwhile, except for gas-fired electricity, the output of electricity with different power sources would increase by 4.41–23.24% from 2017 to 2030. Among electric power sources, oil-fired electricity would have the largest increase in output by 23.24%, followed by coal-fired electricity with an output increase of 16.07%. Nuclear power and renewable electricity would have smaller increases in output. Although electricity with all types of power sources is used to replace polluting fossil-fuels, the decreasing price of coal and oil, resulting from the reduction in coal and oil consumptions of the production sectors, would significantly lower the generation cost of coal-fired and oil-fired electricity, causing a larger output increase than other electricity sources. In contrast to coal-fired and oil-fired electricity, the output of gas-fired electricity would have a slight decrease (0.18%) among electricity sectors. The increase of gas in terminal energy consumption would raise the price of gas, thus increasing the generation cost of gas-fired electricity and hindering its output expansion.

Compared with Scenario 1, Scenario 2 shows a much higher increase in the output of non-fossil-fuel electricity by substituting polluting fossil-fuels with non-fossil-fuel electricity sources and gas in terminal energy consumption. The outputs of nuclear power and renewable electricity would have much larger increases by over 45% in Scenario 2, resulting from substituting coal and oil with non-fossil-fuel electricity and gas (Figure 3). Meanwhile, coal-fired and oil-fired electricity would have increases in output of 9.44% and 15.86%, respectively, which are lower than those in Scenario 1, derived from the reduction in coal and oil prices. Since the smaller output increases in coal-fired electricity, compared with Scenario 1, the output of coal would have a larger decrease (24.52%) under Scenario 2.

Moreover, if the production technology of non-fossil-fuel electricity is improved, the outputs of non-fossil energy would increase further in Scenario 3. The progress in production technology could lower the generation cost of non-fossil-fuel electricity, and reduce the prices of non-fossil-fuel electricity with respect to fossil-fired electricity. Therefore, nuclear power and renewable electricity would have increases in output of over 50% (Figure 3), moderately larger than Scenario 2. Meanwhile, the output of fossil-fired electricity would decrease further. Therefore, technological progress in non-fossil-fuel electricity could further benefit China's clean and low-carbon energy transformation as well as clean energy substitution.

3.2.2. Impacts on Outputs of Non-Energy Sectors

The impacts of clean energy substitution on the outputs of non-energy production sectors are much more different, depending on how the non-energy sectors are interlinked with energy sectors along the upstream and downstream input-output chain. Of the 135 non-energy sectors, 48 sectors would experience output reduction, and the rest would have output expansion, affected by clean energy substitution (Appendix B, Figure A1). To save space, we only examine the changes in output of the top eight non-energy section most positively and negatively affected by clean energy substitution (Table 1).

Table 1. Accumulative changes in output of the most positively and negatively affected sectors in 2017–2030 (%).

Sectors	Scenario 1	Scenario 2	Scenario 3
The most positively affected sectors			
Gas supply	22.52	22.34	22.48
Thermal supply	6.53	6.50	6.61
Coking	5.79	5.75	5.80
Ferrer production	4.92	4.84	4.98
Brick material	4.40	4.35	4.42
Power transmission and distribution	4.36	4.43	4.53
Steel production	4.24	4.16	4.24
Construction	4.10	4.04	4.11
The most negatively affected sectors			
Radar and broadcast equipment	−2.50	−2.58	−2.61
Fishery	−2.39	−2.45	−2.51
Communication equipment	−2.07	−2.13	−2.15
Electrical parts	−2.01	−2.10	−2.09
Textile production	−1.72	−1.78	−1.80
Computer	−1.55	−1.60	−1.61
Leather	−1.39	−1.46	−1.48
Rail transportation	−0.91	−1.06	−1.00

Source: The CHINAGEM simulation.

Most of the sectors benefited by clean energy substitution are energy-intensive sectors with high carbon-emission. Under Scenario 1, the output of gas supply would have the largest increase by 21.78% because of the rising gas consumption of production sectors. Similarly, the increase in output of power transmission and distribution would achieve a level of 4.36% because of the fixed proportion between electricity and power transmission and distribution. The output of thermal supply would also have a large increase by 6.53%, followed by that of coking (5.79%), ferrer production (4.92%), brick material (4.40%), steel production (4.24%), and construction (4.10%) (Table 2, column 1). The decreasing prices of coal and oil, resulting from clean energy substitution, could stimulate the production expansion of the energy-intensive sectors because coal and oil are regarded as their major inputs. Similar to Scenario 1, the outputs of energy-intensive sectors would have large increases in Scenario 2 and Scenario 3.

The most negatively affected sectors are mainly downstream sectors of electricity. The output of radar and broad equipment would have the biggest reduction (2.50%), followed by that of fishery (2.39%), communication equipment (2.07%), electrical parts (2.01%), textile production (1.72%), computer (1.55%), leather (1.39%), and rail transportation (0.91%) under Scenario 1. As these sectors highly depended on electricity for their production, the increase in electricity prices, caused by the rising electricity consumption of production sectors, would raise the production cost of these sectors and consequently reduce their production. Moreover, the rising cost would worsen the term of trade in China, which would further reduce the production of these export-oriented sectors, such as textile products, electrical equipment, and electrical parts. Similar to Scenario 1, the most negatively affected sectors are those that highly depend on electricity in Scenario 2 and Scenario 3.

3.2.3. Impacts on the Macro-Economy

In addition to the impacts on energy production and sectors' outputs, clean energy substitution would also have significant impacts on China's macro-economy. Affected by clean energy substitution, China's real GDP would grow by 2.71–2.81% from 2017 to 2030 (Figure 4). Over 60% of sectors would experience an increase in output affected by clean energy substitution, which would raise their employment and contribute to real GDP growth from the income side. The employment in the labor market would increase by 1.14–1.18% during 2017–2030. Interestingly, compared with Scenario 1 (2.78%), the substitution of polluting fossil-fuels with non-fossil-fuel electricity and gas would have smaller positive impacts on economic growth under Scenario 2, which could lead the real GDP to increase by 2.71%. However, if the production technology of non-fossil electricity could be improved, a larger GDP increase could be obtained (2.81%, Scenario 3).

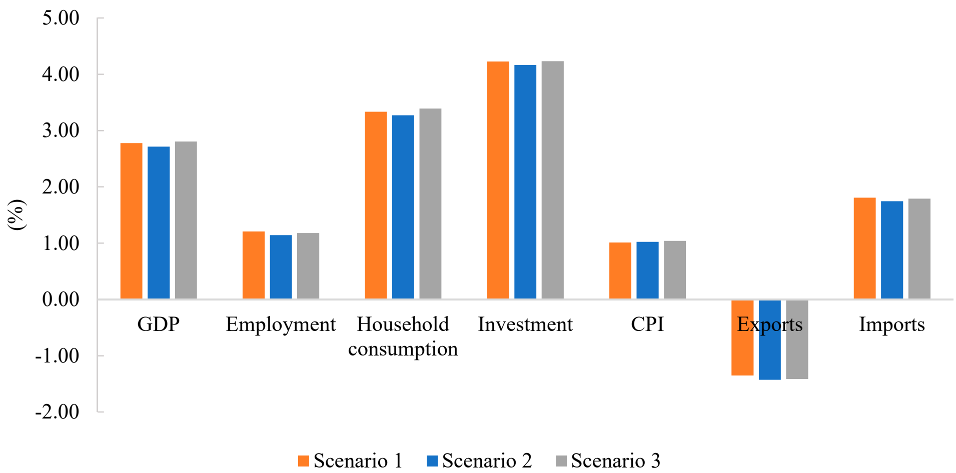

Figure 4. Impacts of clean energy substitution on the macro-economy in 2017–2030. Source: The CHINAGEM simulation.

Furthermore, economic growth would lead to higher household consumption (3.27–3.39%). As the decline of polluting fossil-fuels would reduce the prices of investment commodities, most of which are highly energy-intensive goods, the investment would increase by 4.16–4.23% from 2017 to 2030. In addition, the consumer price index (CPI) would rise by 1.01–1.04% because of clean energy substitution. Even though clean energy substitution would lead to the reduction of polluting fossil-fuels, the economic growth would raise the household's income and consumptions, consequently causing the CPI to increase. Simultaneously, the increasing CPI would worsen China's term of trade, leading to a decrease in exports by 1.35–1.43% and increase in imports by 1.74–1.81%.

3.2.4. Impacts on CO_2 Emissions

Except for the economic and sectoral impacts, clean energy substitution has also impacted on China's CO_2 emission, as it would change energy structure from both the production and consumption side. Carbon emissions could be calculated with a method of multiplying different fossil-fuels used by production sectors and households with their CO_2 emission factors. The CO_2 emission factors of fossil-fuels are from IPCC [52]. Notably, in this study, we did not consider CO_2 emitted in the production and conversion process. Without clean energy substitution, China's CO_2 emissions would increase from 11.08 billion tons in 2016 to 19.29 billion tons in 2030 (Table 2), with an average annual growth rate of 4.36%.

Table 2. National CO_2 emissions under different scenarios in 2017–2030 (billion tons).

Year	Baseline	Scenario 1	Scenario 2	Scenario 3
2017	11.08	11.08	11.08	11.08
2018	11.67	11.85	11.82	11.82
2019	12.29	12.42	12.36	12.36
2020	12.92	12.93	12.86	12.86
2021	13.55	13.42	13.33	13.33
2022	14.18	13.94	13.84	13.84
2023	14.80	14.43	14.32	14.31
2024	15.43	14.89	14.76	14.76
2025	16.06	15.34	15.20	15.20
2026	16.70	15.79	15.64	15.64
2027	17.34	16.25	16.09	16.09
2028	17.99	16.7	16.53	16.53
2029	18.64	17.16	16.98	16.97
2030	19.29	17.61	17.42	17.42

Source: The CHINAGEM simulation.

Compared with the baseline scenario, Scenario 1 suggests that clean energy substitution could effectively cut down China's CO_2 emissions. In Table 2, CO_2 emissions would reduce to 17.61 billion tons in 2030, if polluting fossil-fuels are assumed to be substituted by gas and electricity with all types of power sources (Scenario 1), which is 1.68 billion tons smaller than that under the baseline. The environmental benefits of clean energy substitution, which is cutting down CO_2 emissions, are derived from the reduction of coal and oil and the increase in clean energy. More importantly, the accumulative CO_2 emissions would reduce by 8.12 million tons during 2017–2030. If polluting fossil-fuels are assumed to be substituted by gas and non-fossil-fuel electricity, the CO_2 emissions would reduce further to 17.42 billion tons in 2030, resulting from the output reduction of fossil-fired electricity which could further reduce the consumption of coal and oil (Scenario 2). The accumulative reduction of CO_2 emissions would achieve a level of 9.72 million tons during 2017–2030. The changes in CO_2 emissions under Scenario 3 would be similar to those under Scenario 2.

As CO_2 emissions could be cut down effectively by clean energy substitution, China is expected to reach its carbon emission peak ahead of schedule if the share of clean energy in terminal energy consumption of production sectors increases. However, it is worthy to note that the reduction in CO_2 emissions has been weakened by the rebound effect because the economic growth caused by clean energy substitution would increase the consumption of energy commodities and raise CO_2 emissions. Moreover, the decreasing prices of coal and oil could stimulate the expansion of high energy-intensive sectors, consequently raising consumptions of polluting fossil-fuels in these sectors. Therefore, more attention should be paid to the expansion of those high energy-intensive sectors when clean energy substitution policies are implemented.

4. Conclusions and Discussions

China's energy production and consumption structures have long been dominated by the exploitation of coal and oil, which are main air pollution and carbon emitters. To meet the goal of alleviating severe carbon emissions and environmental pollution and accelerating clean transformation of energy consumption, China has initiated a series of policies on clean energy substitution for polluting fossil-fuels since the early 2010s. As a result, the proportions of gas and electricity in China's terminal energy consumption have risen gradually over the past years. This study first projects the potentials of substituting coal and oil with clean energy for different production sectors in China toward 2030, using the ARIMA regression. Thereafter, a dynamic multi-sectoral CGE model, CHINAGEM, is employed to study the impacts of future clean energy substitution on China's energy production, outputs of non-energy sectors, macro-economy, and CO_2 emissions, based upon the projections. Three policy scenarios are designed to analyze the energy-economic-environmental impacts of the substitution of polluting fossil-fuels with gas and electricity, the substitution of polluting fossil-fuels with gas, as well as non-fossil-fuel electricity, and technological progress in non-fossil-fuel electricity.

The major conclusions of this study are summarized as follows. First, most production sectors are projected to replace polluting fossil-fuels with clean energy in their terminal energy consumption from 2017 to 2030. Among these production sectors, the mining and quarrying sector is projected to have the greatest potential of coal-to-electricity substitution because the proportion of electricity in its terminal energy consumption would rise to 41.98% by 2030. Meanwhile, manufacturing is projected to have the greatest potential of coal-to-gas substitution, and the proportion of gas in its terminal energy consumption would rise from 7.99% in 2016 to 18.02% in 2030.

Second, clean energy substitution would bring economic and environmental co-benefits with clean energy transformation. Under Scenario 1, the output of gas would significantly increase by 32.98% during 2017–2030, and that of electricity with different power sources would rise by 4.38% to 23.24%. At the same time, the outputs of coal and oil are projected to decline by 23.15% and 0.87% relative to the baseline scenario. In response to the changes in energy consumption and production, national CO_2 emissions would significantly reduce by 1.68 billion tons during 2017 to 2030. In addition, real GDP and employment would increase by 2.78% and 1.21%, respectively. If polluting fossil-fuels are substituted by gas and non-fossil-fuel electricity (Scenario 2), the output of renewable electricity would have a larger increase, over 45%, and that of coal would decline further, accompanied with the reduction in CO_2 emissions.

Third, technological progress in non-fossil-fuel electricity could further benefit China's clean and low-carbon energy transformation, accelerating the reduction in CO_2 emissions, as well as clean energy substitution. Furthermore, the most benefited are energy-intensive and high carbon-emission sectors owing to drop in coal and oil prices, while the most negatively affected are the downstream sectors of electricity. It is worthy to note that the reduction in CO_2 emissions may be weakened by the rebound effect because of the economic expansion affected by the implementation of clean energy substitution, which is that the expansion of high energy-intensive sectors would raise their energy consumption, including both fossil-fuel and non-fossil-fuel energy. Therefore, more attention should be paid to the expansion of those high energy-intensive sectors when clean energy substitution is implemented.

Through research, a series of tentative improvement policies are recommended as follows. First, financial support including electricity price, investment, and equipment electrification subsidies is required for the production sectors to accelerate their substitution of polluting fossil-fuels with clean energy. Second, more supporting policies about the development of renewable electricity should be issued, such as feed-in tariff, carbon tax, carbon trading market, and renewable energy portfolio, to lower the prices of renewable electricity and increase the utilization of renewable electricity by the production sectors. Third, the technology for clean energy utilization of the production sectors should be effectively improved by increasing investment in research and development and production equipment renovation. Moreover, to alleviate air pollution caused by burning coal, the application of clean coal technologies, such as desulfurization, deamination, and dust removal, needs to be implemented.

Author Contributions: H.C. and Q.C. raised the research questions and designed the experiments; L.H. collected data and established the models; L.H., J.C., B.Y. and T.H. wrote the paper; H.C. and Q.C. checked the language of the whole article and made modifications. All authors read and approved the final manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1 The Structure of the CHINAGEM Database

We build the database from the 2012 Input-output table for China. Table A1 is a schematic representation of the CHINAGEM database. By splitting the electricity sector in the original input-output table to eight power generation sectors and one sector of power transmission and distribution, and splitting crude gas and oil to crude gas and crude oil, it has 146 commodities (*Com*) and industries (*Ind*) from 2 sources (*Src*, import or domestic). The main matrices are *BAS*, *TAX*, *MAR*, *LAB*, *CAP*, *LND* and *PTAX*. Among these matrices, *USE* and *TAX* are 3-dimensional matrices, they each have a size of $146\times 2\times 146$ ($Com\times Src\times Ind$). The Margin Matric is the only 4-dimensional matrix. We define nine commodities/industries as margins, they are whole sale and retail, rail transport, road transport, water transport, air transport, pipeline, transport services, warehousing, and insurance. Hence the Margin matrix has a size of $9\times 146\times 2\times 146$ ($Mar\times Com\times Src\times Ind$). The remaining matrices are 1-dimensional matrices of size 146 (*Ind*).

Table A1. A schematic representation of the CHINAGEM database.

	Dimension	Producer (*Ind*)	Household (*1*)	Investor (*1*)	Government (*1*)	Export (*1*)
Basic flows	*C*S*	*BAS*	*BAS*	*BAS*	*BAS*	*BAS*
Taxes	*C*S*	*TAX*	*TAX*	*TAX*	*TAX*	*TAX*
Margins	*M*C*S*	*MAR*	*MAR*	*MAR*	*MAR*	*MAR*
Labor	*1*	*LAB*				
Capital	*1*	*CAP*				
Land	*1*	*LND*				
Production tax	*1*	*PTAX*				
Other cost	*1*	*OCT*				

Appendix A.2 The Production Sectors of CHINAGEM Model

The 146 production sectors of the CHINAGEM model are shown in Table A2.

Table A2. The 146 production sectors of the CHINAGEM model.

No.	Sectors	No.	Sectors
1	Crops	74	Agricultural equipment
2	Forest	75	Special equipment
3	Livestock	76	Automobile
4	Fishery	77	Automobile parts
5	Agricultural service	78	Rail equipment
6	Coal mineral production	79	Ships
7	Crude oil	80	Other transportation equipment
8	Crude gas	81	Generators
9	Ferrer ore	82	Power T&D equipment
10	Non-Ferrer ore	83	Electrical wires
11	Other mineral production	84	Battery
12	Other mineral service	85	Home electronical equipment
13	Grain mill	86	Other electronical equipment
14	Feed process	87	Computer
15	Vegetable oil	88	Communication equipment
16	Sugar production	89	Radar and broadcast equipment
17	Meat production	90	Video and TV equipment
18	Fish production	91	Electrical parts
19	Non-staple food production	92	Other electrical equipment
20	Convenient food production	93	Meters
21	Dairy production	94	Other manufacture
22	Condiment production	95	Scrap
23	Other food	96	Machine repair

Table A2. *Cont.*

No.	Sectors	No.	Sectors
24	Wines	97	Coal-fired electricity
25	Other beverage	98	Gas-fired electricity
26	Tobacco	99	Oil-fired electricity
27	Cotton textile	100	Nuclear electricity
28	Wool textile	101	Hydropower
29	Silk textile	102	Wind power
30	Knit and weave	103	Solar power
31	Textile production	104	Biomass and geothermal power
32	Clothes	105	Power transmission and distribution
33	Leather	106	Thermal supply
34	Shoes	107	Gas supply
35	Lumber	108	Water supply
36	Furniture	109	Construction
37	Paper production	110	Retail
38	Printing	111	Rail transportation
39	Cultural and sport production	112	Road transportation
40	Petroleum refine	113	Water transportation
41	Coke	114	Air transportation
42	Basic chemistry	115	Pipe transportation
43	Fertilizer	116	Logistics
44	Pesticide	117	Storage
45	Painting dyes	118	Post
46	Synthetic material	119	Hotel
47	Special chemistry	120	Restaurant
48	Daily chemistry	121	Information service
49	Medicine	122	Software service
50	Chemistry fiber	123	Financial service
51	Rubber production	124	Capital service
52	Plastic production	125	Insurance
53	Cement	126	Real estate
54	Cement production	127	Lease
55	Brick material	128	Business service
56	Glass	129	Research
57	China	130	Technology service
58	Fireproof material	131	Technology expansion service
59	Non-metal production	132	Water service
60	Steel and iron	133	Ecological service
61	Steel production	134	Public facility management
62	Ferrer production	135	Household service
63	Non-Ferrer casting	136	Other service
64	Non-Ferrer rolling	137	Education
65	Metal production	138	Health
66	Boilers	139	Social work
67	Metal process machine	140	Journalism and publication
68	Carrying equipment	141	Broadcast, film and TV
69	Pumper and other machine	142	Culture and arts
70	Cultural equipment	143	Sports
71	General equipment	144	Recreation
72	Mineral equipment	145	Public security
73	Chemistry equipment	146	Public administration

Appendix A.3 The Sectorial Matching Concordance

The sectorial matching concordance is shown in Table A3.

Table A3. The sectorial matching concordance between GTAP model and CHINAGEM model.

Sectors in GTAP Model			Sectors in CHINAGEM Model
No.	Code	Description	No.
1	pdr	Paddy rice	1
2	wht	Wheat	1
3	gro	Other grains	1
4	v_f	Veg & fruit	1
5	osd	Oil feeds	1
6	c_b	Cane & beet	1
7	pfb	Plant fibres	1
8	ocr	Other crops	1
9	ctl	Cattle	3
10	oap	Other animal products	3
11	rmk	Raw milk	3
12	wol	Wool	3
13	frs	Forestry	2
14	fsh	Fishing	4, 5
15	coa	Coal	6
16	oil	Oil	7
17	gas	Gas	8
18	omn	Other mining	9, 10, 11, 12
19	cmt	Cattle meat	17
20	omt	Other meat	17
21	vol	Vegetable oils	15
22	mil	Milk	21
23	pcr	Processed rice	13, 14
24	sgr	Sugar	16
25	ofd	Other food	18, 19, 20, 22, 23
26	b_t	Beverages and tobacco products	24, 25, 26
27	tex	Textiles	27, 28, 29, 30, 31
28	wap	Wearing apparel	32, 34
29	lea	Leather	33
30	lum	Lumber	35, 36
31	ppp	Paper & paper products	37, 38, 39
32	p_c	Petroleum & coke	40, 41
33	crp	Chemical rubber products	42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52
34	nmm	Non-metallic minerals	53, 54, 55, 56, 57, 58, 59
35	i_s	Iron & steel	60, 61, 62
36	nfm	Non-ferrous metals	63, 64
37	fmp	Fabricated metal products	65
38	mvh	Motor vehicles and parts	68, 69, 76, 77, 78
39	otn	Other transport equipment	79, 80
40	ele	Electronic equipment	85, 86, 87, 88, 89, 90
41	ome	Other machinery & equipment	70, 81, 82, 83, 84, 91, 92, 93
42	omf	Other manufacturing	66, 67, 71, 72, 73, 74, 75, 94, 95, 96
43	ely	Electricity	97, 98, 99, 100, 101, 102, 103, 104, 105
44	gdt	Gas distribution	106, 107
45	wtr	Water	108
46	cns	Construction	109
47	trd	Trade	110, 119, 120
48	otp	Other transport	111, 112, 115
49	wtp	Water transport	113
50	atp	Air transport	114
51	cmn	Communications	116, 117, 118
52	ofi	Other financial intermediation	123, 124
53	isr	Insurance	125
54	obs	Other business services	121, 122, 126, 127, 128, 129, 130, 131
55	ros	Recreation & other services	140, 141, 142, 143, 144
56	osg	Other services (Government)	132, 133, 134, 137, 138, 139, 145, 146
57	dwe	Dwellings	135

Appendix B

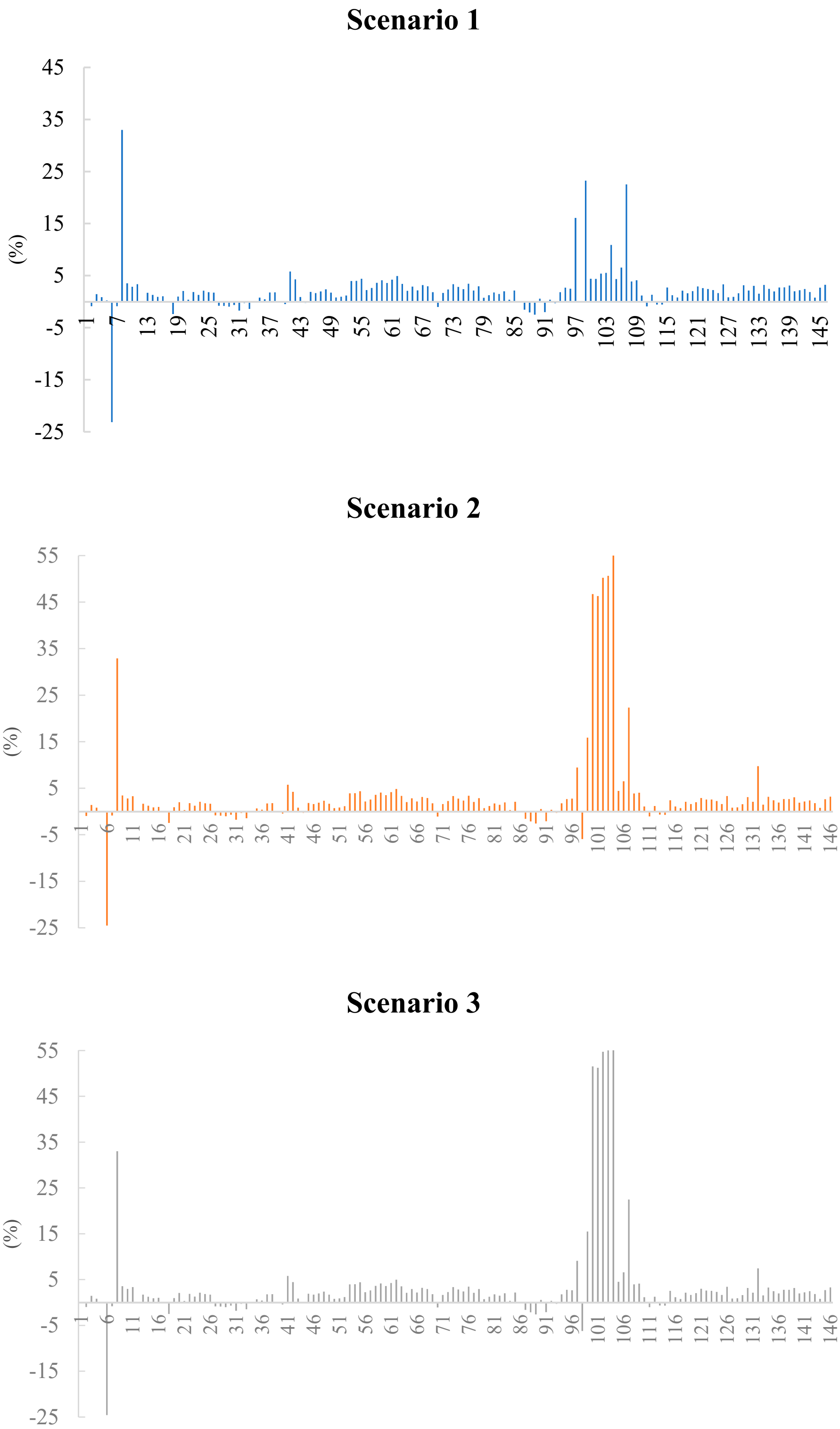

Figure A1. The cumulative impacts of clean energy substitution on the outputs of production sectors. **Source:** The CHINAGEM simulation.

Appendix C

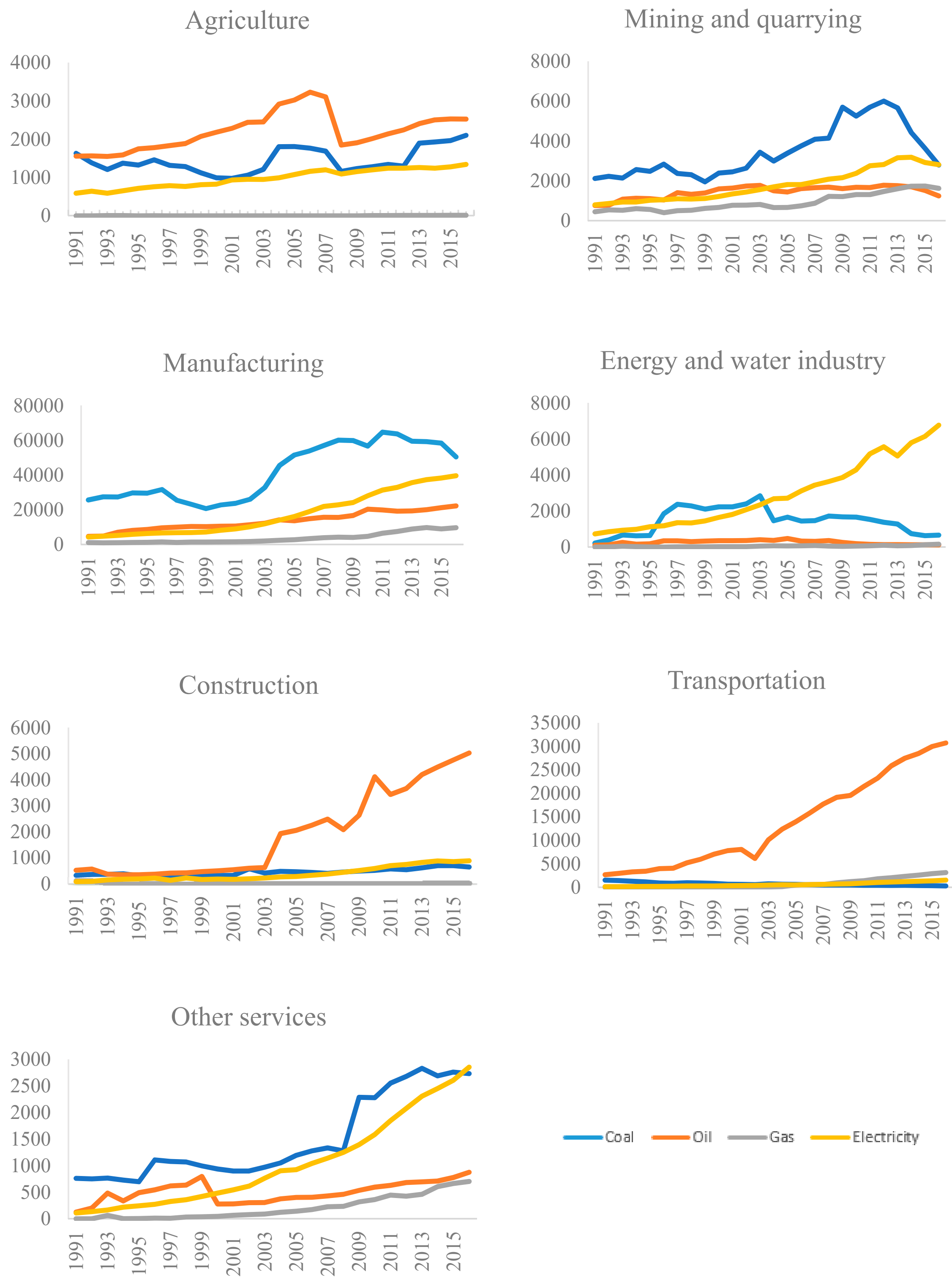

Figure A2. The changing trend of terminal energy consumption for production sectors in China from 1991 to 2016 (10^4 tons of coal equivalent (tce)). **Source:** The Energy Statistics Yearbook of China (1992–2017).

Table A4. ADF stationarity test for original series of terminal energy demand for production sectors in China.

Sector	Energy Commodity	t-Statistic	Prob.*
Agriculture	Coal	−1.266923	0.6283
	Oil	−1.733843	0.4029
	Gas	−0.005266	0.9495
	Electricity	−0.684714	0.8331
Mining and quarrying	Coal	−1.279212	0.6228
	Oil	−2.407349	0.1499
	Gas	0.026049	0.9526
	Electricity	1.783099	0.9994
Manufacturing	Coal	−1.243439	0.6381
	Oil	−0.484508	0.8786
	Gas	3.898705	1.0000
	Electricity	−0.988104	0.7389
Energy and water industry	Coal	−1.904277	0.3250
	Oil	−1.700393	0.4189
	Gas	0.009993	0.9510
	Electricity	2.927249	1.0000
Construction	Coal	−0.350402	0.9029
	Oil	0.515356	0.9838
	Gas	−1.125199	0.6856
	Electricity	−1.118196	0.6895
Transportation	Coal	−2.852566	0.1967
	Oil	1.496762	0.9988
	Gas	3.619652	1.0000
	Electricity	0.586410	0.9990
Other services	Coal	−0.123968	0.9339
	Oil	−1.912347	0.3216
	Gas	4.001430	1.0000
	Electricity	0.529219	0.9988

Source: The ARIMA regression.

Table A5. ADF Stationarity test for differentiated series of terminal energy demand for production sectors in China.

Sector	Energy Commodity	t-Statistic	Prob.*
Agriculture	Coal	−4.382152	0.0023
	Oil	−4.185833	0.0036
	Gas	−9.106804	0.0000
	Electricity	−5.025878	0.0006
Mining and quarrying	Coal	−3.978660	0.0058
	Oil	−4.026766	0.0052
	Gas	−4.060885	0.0048
	Electricity	−4.133398	0.0204
Manufacturing	Coal	−2.682921	0.0915
	Oil	−4.616368	0.0014
	Gas	−4.169695	0.0049
	Electricity	−6.843205	0.0000
Energy and water industry	Coal	−4.817209	0.0008
	Oil	−5.711939	0.0001
	Gas	−4.630552	0.0013
	Electricity	−5.500325	0.0003

Table A5. *Cont.*

Sector	Energy Commodity	t-Statistic	Prob.*
Construction	Coal	−8.032724	0.0000
	Oil	−5.503997	0.0002
	Gas	−3.411236	0.0207
	Electricity	−12.31219	0.0000
Transportation	Coal	−6.163410	0.0001
	Oil	−4.307724	0.0027
	Gas	−6.880683	0.0000
	Electricity	−6.547434	0.0000
Other services	Coal	−4.739897	0.0015
	Oil	−6.021559	0.0000
	Gas	−5.734466	0.0002
	Electricity	−5.367821	0.0002

Source: The ARIMA regression.

Table A6. The ARIMA regression results for differentiated series of terminal energy demand for production sectors.

Dependent Variable: DAC1 (1st-order Differentiated Variable of Coal Consumption for Agriculture)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(3)	−0.632	0.171	−3.694	0.001
MA(3)	0.964	0.053	18.101	0.000
R-squared	0.171	Prob(F-statistic)		0.000
Dependent Variable: DAO1 (1st-order Differentiated Variable of Oil Consumption for Agriculture)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(2)	0.542	0.190	2.854	0.010
MA(2)	−0.956	0.050	−18.969	0.000
R-squared	0.227	Prob(F-statistic)		0.000
Dependent Variable: DAG2 (2nd-order Differentiated Variable of Gas Consumption for Agriculture)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.162	0.037	4.395	0.000
AR(1)	−0.841	0.057	−14.869	0.000
MA(2)	−1.000	0.038	−26.525	0.000
R-squared	0.820	Prob(F-statistic)		0.000
Dependent Variable: DAE1 (1st-order Differentiated Variable of Electricity Consumption for Agriculture)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	31.741	3.532	8.987	0.000
AR(1)	0.523	0.224	2.333	0.030
MA(1)	−1.000	0.246	−4.068	0.001
R-squared	0.260	Prob(F-statistic)		0.042
Dependent Variable: DM & QC1 (1st-order Differentiated Variable of Coal Consumption for Mining and Quarrying)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(2)	0.400	0.227	1.762	0.093
MA(5)	−0.819	0.097	−8.449	0.000
R-squared	0.467	Prob(F-statistic)		0.000
Dependent Variable: DM & QO1 (1st-order Differentiated Variable of Oil Consumption for Mining and Quarrying)				

Table A6. *Cont.*

Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(1)	0.295	0.169	1.748	0.097
AR(2)	−0.650	0.151	−4.308	0.000
MA(1)	−0.234	0.107	−2.181	0.042
MA(2)	0.896	0.055	16.173	0.000
R-squared	0.198	Prob(F-statistic)		0.000
Dependent Variable: DM&QG1 (1st-order Differentiated variable of Gas Consumption for Mining and Quarrying)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	63.559	11.110	5.721	0.000
AR(1)	0.468	0.175	2.679	0.015
MA(1)	−0.574	0.076	−7.597	0.000
MA(2)	0.554	0.076	7.302	0.000
MA(3)	−0.917	0.036	−25.207	0.000
R-squared	0.517	Prob(F-statistic)		0.006
Dependent Variable: DM&QE1 (1st-order Differentiated variable of Electricity Consumption for Mining and Quarrying)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	105.149	13.902	7.564	0.000
AR(1)	0.587	0.206	2.848	0.010
MA(1)	−0.446	0.225	−1.988	0.061
MA(2)	−0.470	0.218	−2.156	0.044
R-squared	0.225	Prob(F-statistic)		0.057
Dependent Variable: DMC1 (1st-order Differentiated variable of Coal Consumption for Manufacturing)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(5)	−0.483	0.205	−2.354	0.031
MA(4)	0.569	0.188	3.031	0.008
MA(5)	0.387	0.197	1.969	0.066
R-squared	0.413	Prob(F-statistic)		0.000
Dependent Variable: DMO1 (1st-order Differentiated variable of Oil Consumption for Manufacturing)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	691.109	152.233	4.540	0.000
AR(1)	−0.731	0.140	−5.210	0.000
MA(1)	1.142	0.063	18.007	0.000
MA(3)	−0.539	0.035	−15.227	0.000
R-squared	0.393	Prob(F-statistic)		0.017
Dependent Variable: DMG2 (2nd-order Differentiated variable of Gas Consumption for Manufacturing)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	52.626	3.469	15.171	0.000
AR(4)	−0.980	0.286	−3.425	0.004
MA(1)	−1.433	0.041	−34.760	0.000
MA(3)	0.480	0.022	21.683	0.000
R-squared	0.770	Prob(F-statistic)		0.000
Dependent Variable: DME2 (1st-order Differentiated variable of Electricity Consumption for Manufacturing)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(1)	−0.959	0.208	−4.618	0.000
AR(2)	−0.543	0.156	−3.473	0.003
MA(1)	1.111	0.126	8.856	0.000
MA(3)	−0.560	0.091	−6.188	0.000
R-squared	0.514	Prob(F-statistic)		0.051

Table A6. *Cont.*

Dependent Variable: DPC1 (1st-order Differentiated variable of Coal Consumption for Energy and Water Industry)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(2)	−0.448	0.191	−2.347	0.029
MA(2)	0.987	0.067	14.780	0.000
R-squared	0.308	Prob(F-statistic)		0.000
Dependent Variable: DPO1 (1st-order Differentiated variable of Oil Consumption for Energy and Water Industry)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	−23.725	6.410	−3.701	0.002
AR(1)	−0.227	0.122	−1.858	0.080
AR(3)	0.601	0.092	6.508	0.000
MA(3)	−0.957	0.037	−25.946	0.000
R-squared	0.617	Prob(F-statistic)		0.001
Dependent Variable: DPG1 (1st-order Differentiated Variable of Gas Consumption for Energy and Water Industry)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(3)	−0.666	0.211	−3.152	0.005
MA(3)	0.847	0.064	13.182	0.000
R-squared	0.006	Prob(F-statistic)		0.000
Dependent Variable: DPE2 (2nd-order Differentiated Variable of Electricity Consumption for Energy and Water Industry)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	14.729	3.982	3.699	0.002
AR(1)	−0.547	0.252	−2.177	0.045
AR(2)	−0.555	0.237	−2.343	0.032
AR(3)	−0.457	0.234	−1.957	0.068
MA(1)	−1.000	0.203	−4.938	0.000
R-squared	0.734	Prob(F-statistic)		0.000
Dependent Variable: DCC1 (1st-order Differential Variable of Coal Consumption for Construction)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	17.676	5.654	3.126	0.005
AR(1)	−0.426	0.205	−2.076	0.050
MA(5)	−0.891	0.049	−18.037	0.000
R-squared	0.577	Prob(F-statistic)		0.000
Dependent Variable: DCO1 (1st-order Differential Variable of Crude oil Consumption for Construction)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(1)	−0.959	0.172	−5.570	0.000
AR(2)	−0.627	0.162	−3.860	0.001
MA(1)	1.966	0.105	18.674	0.000
MA(2)	1.465	0.108	13.510	0.000
R-squared	0.445	Prob(F-statistic)		0.000
Dependent Variable: DCG1 (1st-order Differential Variable of Crude gas Consumption for Construction)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(1)	−0.321	0.165	−1.943	0.065
MA(1)	0.924	0.083	11.075	0.000
R-squared	0.491	Prob(F-statistic)		0.000

Table A6. *Cont.*

Dependent Variable: DCE2 (1st-order Differential Variable of Electricity Consumption for Construction)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(2)	0.395	0.193	2.041	0.055
MA(1)	−1.034	0.048	−21.474	0.000
R-squared	0.624	Prob(F-statistic)		0.000
Dependent Variable: DTC2 (2nd-order Differentiated Variable of Coal Consumption for Transportation)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(3)	−0.346	0.157	−2.201	0.040
MA(1)	−1.000	0.030	−33.155	0.000
R-squared	0.701	Prob(F-statistic)		0.044
Dependent Variable: DTO1 (1st-order Differentiated Variable of Oil Consumption for Transportation)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	1486.252	162.030	9.173	0.000
AR(1)	0.769	0.098	7.854	0.000
MA(1)	−0.959	0.040	−23.868	0.000
R-squared	0.257	Prob(F-statistic)		0.000
Dependent Variable: DTG2 (2nd-order Differentiated Variable of Gas Consumption for Transportation)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	3.862	0.781	4.944	0.000
AR(1)	−1.385	0.137	−10.109	0.000
AR(2)	−1.094	0.137	−7.994	0.000
MA(1)	0.596	0.210	2.840	0.012
MA(2)	−0.557	0.156	−3.581	0.003
MA(3)	−0.984	0.152	−6.493	0.000
R-squared	0.641	Prob(F-statistic)		0.003
Dependent Variable: DTE2 (1st-order Differentiated Variable of Electricity Consumption for Transportation)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(2)	−0.451	0.228	−1.976	0.062
MA(1)	−0.470	0.215	−2.190	0.041
R-squared	0.319	Prob(F-statistic)		0.000
Dependent Variable: DRC1 (1st-order Differentiated Variable of Coal Consumption for Other Services)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	153.019	28.683	5.335	0.000
AR(2)	0.409	0.221	1.849	0.086
MA(1)	−0.449	0.246	−1.820	0.090
MA(2)	−0.481	0.240	−2.007	0.065
R-squared	0.279	Prob(F-statistic)		0.000
Dependent Variable: DRE2 (2nd-order Differentiated Variable of Electricity Consumption for Other Services)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
AR(2)	0.443	0.214	2.069	0.052
MA(2)	−0.876	0.061	−14.481	0.000
R-squared	0.141	Prob(F-statistic)		0.000

Table A6. *Cont.*

Dependent Variable: DRO1 (1st-order Differentiated Variable of Oil Consumption for Other Services)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	40.117	13.348	3.005	0.007
AR(2)	0.640	0.112	5.722	0.000
MA(2)	−1.000	0.132	−7.600	0.000
R-squared	0.329	Prob(F-statistic)		0.019
Dependent Variable: DRG2 (2nd-order Differentiated Variable of Gas Consumption for Other Services)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	3.591	0.460	7.801	0.000
AR(1)	−0.449	0.209	−2.147	0.046
AR(2)	−0.413	0.134	−3.089	0.006
MA(1)	−1.000	0.202	−4.952	0.000
R-squared	0.739	Prob(F-statistic)		0.000

Source: The ARIMA regression.

Table A7. ADF stationarity test of residual series for production sectors in China.

Sector	Energy Commodity	t-Statistic	Prob.*
Agriculture	Coal	−4.098440	0.0051
	Oil	−4.346252	0.0028
	Gas	−5.838931	0.0001
	Electricity	−4.426841	0.0022
Mining and quarrying	Coal	−3.955062	0.0066
	Oil	−4.125973	0.0045
	Gas	−4.750180	0.0010
	Electricity	−4.905932	0.0011
Manufacturing	Coal	−2.787728	0.0787
	Oil	−5.733958	0.0001
	Gas	−3.953653	0.0078
	Electricity	−4.664891	0.0015
Energy and water industry	Coal	−4.492589	0.0020
	Oil	−5.528755	0.0002
	Gas	−4.149220	0.0046
	Electricity	−4.594561	0.0019
Construction	Coal	−5.074255	0.0005
	Oil	−4.713244	0.0012
	Gas	−7.172407	0.0000
	Electricity	−4.877345	0.0009
Transportation	Coal	−6.006844	0.0001
	Oil	−4.828614	0.0009
	Gas	−4.416807	0.0025
	Electricity	−4.442505	0.0024
Other services	Coal	−3.685462	0.0149
	Oil	−4.601862	0.0016
	Gas	−4.055596	0.0063
	Electricity	−4.763266	0.0012

Source: The ARIMA regression.

Figure A3. *Cont*.

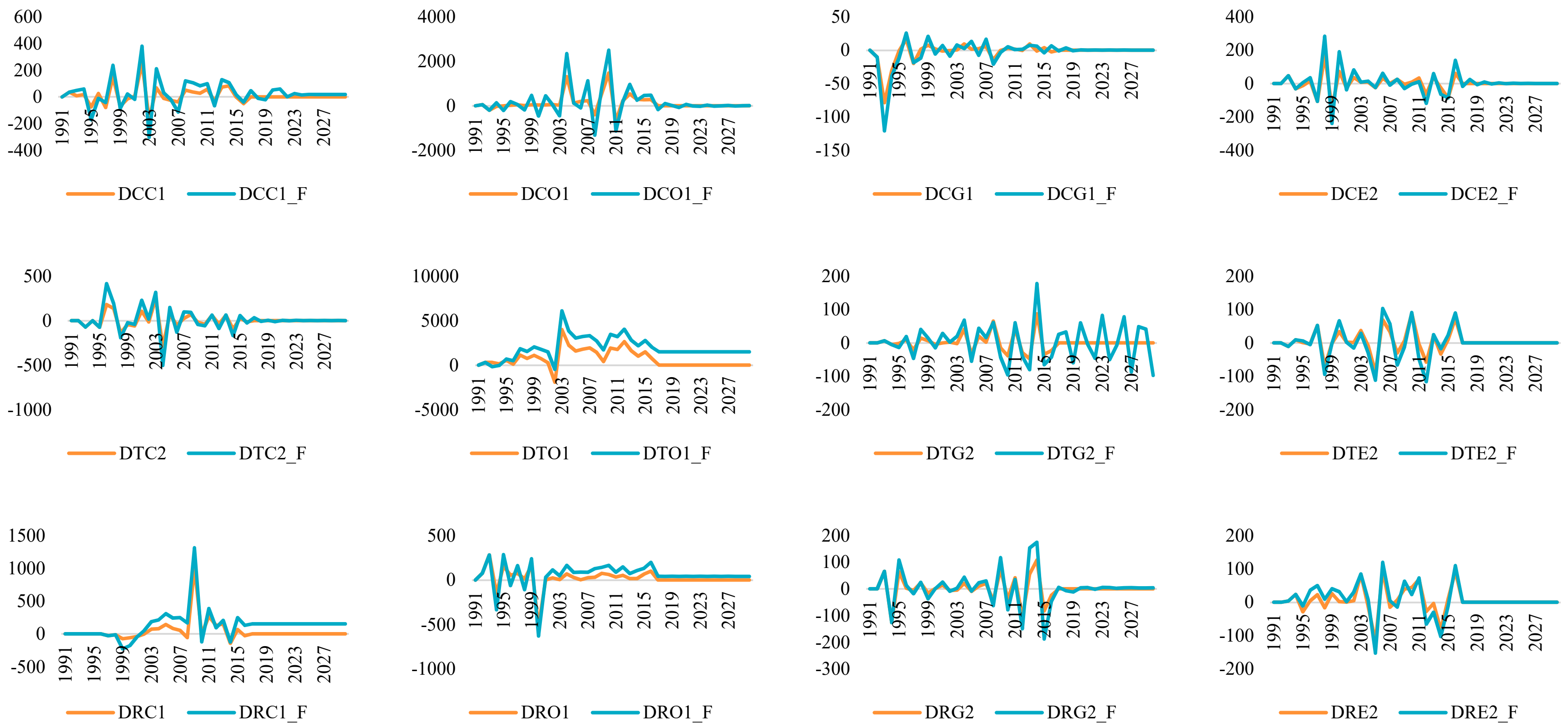

Figure A3. The fitness graphs of the original series and the projected series of terminal energy consumption for each production sector (10^4 tce). **Note:** The yellow lines represent the original series, and the blue ones represent the projected series. **Source:** Authors' calculation.

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