Abstract: In China, as the major source of energy consumption and air pollutant emissions, the power industry is not only the principal force that bears the responsibility of national emission reduction targets but also a breakthrough that reflects the effectiveness of emission reduction. In this study, based on the integrated MARKAL-EFOM system (TIMES) model and scenario analysis method, a bottom-up energy system optimization model for the power industry was established, and four scenarios with different constraints were set up to predict and analyze the power demand and the energy consumption structure. Emission characteristics, emission reduction characteristics, and emission reduction cost of sulfur dioxide (SO$_2$), nitrogen oxide (NO$_X$), particulate matter 2.5 (PM$_{2.5}$), and mercury (Hg) were quantitatively studied. Finally, for the environmentally friendly development and optimal adjustment of power production systems in China, the control path in the power industry that is conducive to the emission reduction of air pollutants was obtained, which is of great significance for the ultimate realization of climate friendliness. The results demonstrate that from 2020 to 2050, the power demand of the terminal departments will increase, with the composition significantly changed. The focus of power demand will change from industry to the service industry gradually. If no additional targeted emission reduction or adjustment policies are added in the power industry, the primary energy and air pollutant emissions will increase significantly, putting great pressure on resources and the environment. For the emission reduction of air pollutants, the promotion effect of emission reduction measures, such as the implementation and promotion of non-fossil fuels, is restricted. The power industry can introduce and maximize the best available technologies while optimizing the structure of energy consumption to realize efficient emission reduction of air pollutants and energy conservation. In 2030, emissions will reach peak values with reasonable emission reduction cost. This has the additional effect of abating energy consumption and preventing deterioration of the ecological environment, which is of profound significance for the ultimate realization of climate friendliness.

Keywords: power industry; air pollutants; emission reduction path; TIMES model; emission reduction cost

1. Introduction

Air pollutants that are emitted along with fossil fuel combustion have an unpredictable impact on the atmospheric environment and climate conditions [1]. With the increasing knowledge of global
environmental protection, the control of air pollutants has attracted more and more attention from all levels of society [2]. As a secondary energy source, electricity occupies a decisive role in the development of China, with a huge demand in industrial production and homes [3]. The single power generating equipment of the coal-fired power plants has a large capacity, consuming a great quantity of fossil fuel [4]. In 2016, the coal-fired power plants consumed about 60% of the coal output [5], and the emissions of SO$_2$, NO$_X$, PM$_{2.5}$, and Hg produced by the power industry accounted for about 45%, 64%, 21%, and 50% of China’s total industrial emissions, respectively [6]. However, the fact that China’s energy consumption structure depends on fossil fuel will not change fundamentally in a short period of time. As the main source of energy consumption and air pollutant emissions in China, the power industry is not only the principal force that bears the responsibility of national emission reduction targets but also a breakthrough that reflects the effectiveness of emission reduction [7].

Therefore, the problem of air pollutant emissions being caused by the production process of the power industry needs to be solved urgently. It is necessary to study the air pollutant emission reduction path of the power industry under the constraints of pollutant emissions in China, putting forward specific measures as well as the corresponding implementation path and guarantee conditions, so as to effectively solve the current situation of the growing environmental deterioration and shortage of fossil energy [8]. This is also an inevitable choice for China in order to achieve sustainable development.

Countries around the world are suffering from the problem of air pollutants, so research on the emission reduction of air pollutants has been a burning issue. It is noted that the structure of energy consumption is closely related to the emissions of air pollutants [9,10]. At the same time, many researchers have also studied emission reduction from a technological perspective [11,12]. Wang evaluated air pollutant emissions at coal-fired power plants, taking the technological improvement of air pollution control devices as the key factor that has resulted in reductions in air pollutant emissions in China [13]. The analysis of the influencing factors of air pollutants is likewise a fundamental issue in emission reduction research [14–16]. Chen found that the concentration of population in cities is conducive to reducing the average cost of natural monopoly industries and gas emissions that cause pollution, as well as improving air quality [17]. In the research of air pollutant emission reduction control in the power industry, corresponding emission reduction improvement suggestions are proposed based on emission reduction technologies and equipment, or the emission reduction scenarios are simulated from the perspective of macro management [18]. However, the internal law of power industry operation has not been thoroughly studied from a system perspective [19]. Therefore, a systematic and in-depth study is required on the basic issues related to the air pollutant emission reduction mechanism and its influencing factors for the power industry in China.

In this study, an emission reduction path for China’s power industry was built to study the corresponding temporal evolution characteristics. Four scenarios with different constraints were established to predict and analyze the power demand and energy consumption structure from 2020 to 2050. The emission characteristics and emission reduction potential of air pollutants were quantitatively studied. Combined with emission reduction cost research, for the environmentally friendly development and optimal adjustment of China as well as global power production systems, the control path that is conducive to the emission reduction of air pollutants was achieved, which is of great significance for the ultimate realization of climate friendliness [20,21].

2. Research Method

2.1. TIMES Model

As a “bottom-up” analysis model, the TIMES model is the combination of market allocation of technologies model (MARKAL) and energy flow optimization model (EFOM) [22]. It takes detailed technologies or specific policies as the research points, which can be used to study the entire energy system of a country or region and analyze a specific sector, such as the transportation sector, residential sector, or steel sector. At present, the research on the TIMES model is mainly aimed at the whole
industry or region, and there are relatively few studies on emission reduction of air pollutants from the power industry in China [23–25]. In the field of energy and environment, this model shows superiority [26]. It can be utilized to analyze, calculate, and optimize the energy supply, conversion, and demand in an all-round way and is suitable for the research of pollutant emission reduction in the power industry [27]. Therefore, it was decided in this study to construct a system model from specific technical and policy perspectives.

2.2. TIMES Energy System Optimization Model for the Power Industry

In order to assess the ability of China’s power industry to meet its air pollutant emission target, a bottom-up TIMES energy system optimization model was established in this study, as shown in Figure 1.

![Figure 1. Structure of the power industry air pollutant emission reduction model.](image)

The established model is mainly divided into three parts: input, calculation process, and algorithm setting. Based on the assumption of China’s future population and economic parameters, the model calculates energy consumption and air pollutant emissions by simulating energy processing, conversion, and transportation from energy service demand.

In this study, 2015 was chosen as the base year to research the development and the emission characteristics of air pollutants. The planning period was set to be 2020 to 2050 and milestone years were set to be 2020, 2025, 2030, ..., 2050. The technology database not only considers the control technologies of air pollutants and the power generation technologies currently being utilized in China’s power industry but also the most advanced technologies available internationally at this moment [28]. It mainly includes traditional technologies such as ultra-supercritical power, circulating fluidized bed (CFB), and new technologies such as wind. For instance, CFB is currently the only low-grade fuel combustion technology with high efficiency and clean utilization that has achieved commercialization and large-scale application [29]. With the increasing emphasis on environmental protection in recent years, the pollutant emission of CFB boilers is facing increasing scrutiny [30]. Taking a 300 MW CFB boiler power plant as an example, every kilowatt of electricity produced will produce 0.077 mg/m³ SO₂, 0.022 mg/m³ NOₓ, and 0.0036 mg/m³ PM₂.⁵. In the first half of 2020, a total of 1528.97 mg/m³ SO₂, 6577.3 mg/m³ NOₓ, and 299.75 mg/m³ PM₂.5 was produced [31]. In a CFB boiler, methods for removing SO₂ include a wet flue gas desulfurization tower (WFGD), semi-dry method flue gas desulfurization, and activated carbon desulfurization, while denitration methods include selective catalytic reduction.
(SCR), selective non-catalytic reduction (SNCR), and SCR + SNCR. Measures to reduce PM$_{2.5}$ emissions include fabric filter (FF) and electrostatic precipitator (ESP). Hg is enriched in fly ash and captured by the precipitator in the CFB boiler, and the ESP and WFGD are the control methods [32–36]. In the database, technical parameters and reaction mechanisms of each technology are obtained, such as unit energy savings, emissions reduction, investment operation and maintenance (O&M) cost, current penetration rate, and applicable conditions [37–39]. The emissions of SO$_2$, NOx, PM$_{2.5}$, and Hg in the process of fuel consumption can be calculated.

The terminal departments are divided into construction, transportation, industry, and agriculture in the energy service demand forecasting module. Different methods are utilized to make predictions according to the characteristics of departments in different developmental stages. Among these varied methods, the elastic coefficient method is utilized to analyze the agricultural department [40]. The dynamic material flow analysis method is used to analyze the energy demand of cooling, heating, hot water, and cooking in different regions of the construction department [41], taking factors such as economic and social development, per capita construction area, and possible climate change into account. The econometric method and industrial life cycle curve method are adopted in the industrial department [42], while the Global Change Assessment Model—China (GCAM-China) method is mainly used to predict passenger and freight turnover in transportation department uses [43]. In addition, driven by the results of the energy service demand prediction module, by applying linear programming using the General Algebraic Modelling System (GAMS), the energy system module analyzes the impact of different policies or measures on the energy system by setting different resources, technologies, and environmental constraints [44].

In the emission assessment module of air pollutants, based on the activity level and the emission factors of the process flow, the results of the technology selection and energy selection optimized by the energy system analysis module are utilized, while the different energy processing links and corresponding removal processes in power production are fully considered to obtain the corresponding air pollutant emissions for the power industry and then, determine the peak level and peak time [45]. The main purpose of emission reduction cost analysis is to measure the economic feasibility of each scenario, and to provide a scientific basis for future power development strategy and technology selection through comparison with the reference (REF) scenario.

2.3. Assumptions and Scenarios

2.3.1. Assumptions

Based on existing planning and future forecasts, preliminary assumptions such as population, urbanization rate, GDP growth rate, and industrial structure were made in this study.

Among these assumptions, one is that the law of change of population (such as births and deaths) has relatively stable characteristics. Based on mathematical demography and the population equilibrium equation (Formula 1), this study predicted the future population of China grouped by urban–rural, gender, and age. The total fertility rate (TFR) model was used to calculate the newly born population:

\[ P_{F}(t+1, m+1) = P_{F}(t, m) - D_{F}(t, m) + I_{FI}(t, m) - I_{FO}(t, m) \]  

where $P_{F}(t,m)$ is the population at age $m$ in year $t$ (million); $D_{F}(t,m)$ is the population who died at age $m$ in year $t$ (calculated by the life table model) (million); $I_{FI}(t,m)$ is the population moving into the area (million); $I_{FO}(t,m)$ is the population moving out of the area (million); $I_{FI}(t,m)-I_{FO}(t,m)$ is the population of net migrants (million).
Based on the obtained population data, Keyfitz’s migration model for quantitatively describing population migration and urbanization is used \[46\]; this is shown in Formula (2). The calculation of the urbanization rate is shown in Formula (3):

\[
\begin{align*}
\frac{dP_r(t)}{dt} &= (r - m)P_r(t) \\
\frac{dP_u(t)}{dt} &= mP_r(t) + uP_u(t)
\end{align*}
\]

(2)

where \(P_r(t)\) and \(P_u(t)\) are the rural and urban populations, respectively, in year \(t\) (million); \(r\) is the natural growth rate of the rural population (%); \(u\) is the natural growth rate of the urban population (%); \(m\) is the rural population migration rate (net emigration rate) (%).

\[
\Phi(t) = \frac{P_u(t)}{[P_r(t) + P_u(t)]}
\]

(3)

Here, \(\Phi(t)\) is the urbanization rate.

Therefore, the basic assumptions of the model are calculated and demonstrated in detail in combination with the relevant research results at this stage \[47,48\], which are shown in Table 1.

**Table 1. Basic assumptions of the model.**

| Indexes                          | 2015   | 2020   | 2025   | 2030   | 2035   | 2040   | 2045   | 2050   |
|----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Population (million)            | 1400.4 | 1432.9 | 1447.1 | 1453.3 | 1445.9 | 1435.5 | 1401.2 | 1384.9 |
| Population (million)            | 55.3   | 59.0   | 62.3   | 66.2   | 69.5   | 71.4   | 73.2   | 75.9   |
| Urbanization Rate (%)           | 7.0    | 6.2    | 5.6    | 4.5    | 4.5    | 4.5    | 4.0    | 3.5    |
| Proportion of Primary Industry (%) | 9.8    | 6.9    | 6.3    | 5.9    | 5.6    | 5.2    | 4.9    | 4.3    |
| Proportion of Secondary Industry (%) | 42.3   | 40.7   | 38.1   | 36.7   | 35.0   | 33.4   | 31.9   | 30.2   |
| Proportion of Tertiary Industry (%) | 47.9   | 47.9   | 55.6   | 57.4   | 59.4   | 61.4   | 63.2   | 65.5   |

According to the current death and fertility level, China’s population size will gradually increase from 1400.4 million in 2015 to a peak value of 1453.3 million in 2030 and then, slowly decline, finally falling to 1384.9 million in 2050. China’s urbanization rate will increase year by year, from 55.3% in 2015 to 75.9% in 2050, with a gradually slowing growth rate. At the same time, the GDP growth rate shows a downward trend, which is 7.0% in 2015 and 3.5% in 2050. This is mainly related to the exhaustion and increasing prices of global resources. In addition, it can be found that from 2015 to 2050, the industrial structure of China will change significantly, and the proportion of primary industry and secondary industry will decrease from the initial 9.8% to 4.3% and 42.3% to 30.2%, respectively, and the proportion of tertiary industry will increase from 47.9% to 65.5%. This shows that with the further development of China’s industrialization process accompanied with energy-saving technology improvements, energy structure adjustment plays a decisive role in the air pollutant emission reduction control process.

2.3.2. Scenarios

In this study, to obtain the emission reduction path of air pollutants in China’s power industry, four scenarios were set according to the scenario analysis method, as shown in Figure 2.

The reference (REF) scenario: Starting from the base year, no additional targeted emission reduction or adjustment policies are added in the research process. The power industry operates in accordance with the existing energy policies, technological development, and regulations. Energy structure remains unchanged and still relies heavily on coal resources; no new technologies of power generation and emission reduction are introduced.
3. Results and Discussion

3.1. Power Demand

Based on the above assumptions, the power demand in China from 2015 to 2050 was studied. The results are presented in Table 2.

It is noted that the power demand in China shows an overall upward trend in this period, among which the demand in 2050 is 2.81 times of that in 2015. However, the growth rate decreases year by year, from 26.3% in 2020 to 5.4% in 2050. This is mainly due to the basic end of the industrial structure adjustment and urbanization process. This is consistent with Lin, who found that electricity...
demand growth is likely to continue to slow down in the near future, owing to ongoing economic structural change in China [49]. At the same time, the per capita power demand increases significantly from 4343 kW·h in 2015 to 12,338 kW·h in 2050. However, its growth rate shows a downward trend, which is 16.9% lower than that of 2020 in 2050. Although the power demand increases, energy-saving technologies and energy-saving awareness lead to a decreasing trend in the growth rate of power demand per capita year by year.

### Table 2. Power demand of China.

| Year | National Power Demand (billion kW·h) | Growth Rate of National Power Demand (%) | Per Capita Power Demand (kW·h) | Growth Rate of Per Capita Power Demand (%) |
|------|---------------------------------------|------------------------------------------|---------------------------------|------------------------------------------|
| 2015 | 6080                                  | / 1                                      | 4343                           | /                                        |
| 2020 | 7681                                  | 26.3                                     | 5364                           | 23.5                                     |
| 2025 | 9579                                  | 24.7                                     | 6620                           | 23.4                                     |
| 2030 | 11,591                                | 21.0                                     | 7977                           | 20.5                                     |
| 2035 | 13,539                                | 16.8                                     | 9369                           | 17.5                                     |
| 2040 | 14,953                                | 10.5                                     | 10,420                         | 11.2                                     |
| 2045 | 16,209                                | 8.4                                      | 11,569                         | 11.0                                     |
| 2050 | 17,075                                | 5.4                                      | 12,338                         | 6.6                                      |

1 null value.

The power demand of the terminal departments is presented in Figure 3, and corresponding growth rate change is given in Table 3. It is found that the overall power demand of terminal departments will increase to a different degree for a generation or more. However, its composition will change dramatically, and the focus will shift from the industry department to the construction and transportation departments slightly. The power demand proportion of industry will decrease significantly, from 71.9% in 2015 to 36.2% in 2050. Furthermore, the corresponding growth rate of demand also appears to show a downward trend, which will become negative after 2040, indicating that the power demand scale of the industrial department will shrink greatly. The reason for this phenomenon is that, with the improvement of technologies and process, efficiency of industrial production will improve and energy consumption will reduce significantly; on the other hand, under the continuous guidance of national policies, the industrial structure characterized by high pollution and energy consumption will gradually develop to become capital intensive and technology intensive. Due to the wide development and promotion of energy utilization and electric vehicle technology with the improvement of living standards, from 2015 to 2050, the proportion of the transportation department will increase from 13.8% to 31.8%. The proportion of electricity applied by the construction department will increase year by year, reaching 30.6% in 2050. With residents’ living standards improving, the ownership rate of home appliances will increase annually. The urban process results in a significant increase in power consumption of infrastructure. Meanwhile, in the construction department in 2030, the growth rate of power demand will come to its peak value of 50.3%. Moreover, the agricultural power demand proportion shows an overall downward trend, accounting for only 1.4% in 2050. Its corresponding growth rate also declines, from 17% in 2020 to only about 3% in 2050. This is primarily due to accelerated land circulation; the scale and intensive degree of land will be continuously improved. The progress of standardization, mechanization, modernization, and industrialization of agriculture will promote productivity gradually. With the improved efficiency of power consumption, power demand will decrease greatly.
3.2. Primary Energy Consumption

Primary energy consumption of the power industry under different scenarios is shown in Figure 4.

In the REF scenario, due to economic and social development, the primary energy consumption increases, with an average annual growth rate of about 2.5%. In 2050, it will attain the value of 98.83 EJ. At the same time, it can be seen that in this scenario, the energy structure remains unchanged and still relies on traditional coal power generation; no new technologies of power generation and emission reduction are introduced. Therefore, in 2050, coal consumption will reach 46.51 EJ, accounting for 47.1% of the total primary energy consumption. This shows that if the power system operates in accordance with the existing policies and technological development trends, it will bring enormous pressure on China’s future energy supply and pollutant emission control, so the energy consumption structure needs to be optimized.
The total amount and the structure of primary energy consumption in the other three scenarios improve to varying degrees. In 2050, the total energy consumption of the BAT, SER, and COC scenarios will decrease to 3.91, 7.38, and 10.98 EJ, respectively, compared with the REF scenario. Meanwhile, the proportion of non-renewable energy consumption decreases to varying degrees, dropping significantly by 10.8%, 19.4%, and 21.1%, respectively, from the base year, with clean energy being widely used. In these scenarios, the growth rates of aggregate energy consumption are less than that of GDP. On the one hand, the development and utilization of non-fossil energy can reduce the dependence on traditional energy while ensuring economic development; through the improvement and upgrading of technologies, energy consumption is greatly reduced. At the same time, it is possible to conclude that the SER scenario is more effective than the BAT scenario in terms of reducing energy consumption and improving consumption structure. In addition, under the BAT scenario, the largest introduction and promotion of the latest power generation technologies enable the IGCC to be developed and used rapidly. Natural gas will be consumed in large quantities because it can meet the calorific value requirements of the IGCC and is more economical. Therefore, in 2050, the consumption of natural gas will account for 10.1%, which is higher than in the other scenarios. Under the BAT scenario, coal consumption will still account for 44.9% in 2050, indicating that the power industry will not change its structural characteristics of being highly dependent on coal. This is explained by the fact that in this scenario, the control of air pollutants is mainly realized through the upgrading of technologies of power generation and end-of-pipe treatment, and the adjustment effect of energy structure is not observable, which further verifies the results obtained in the previous study. This is similar to Pan’s conclusions, which found that oil and gas will continuously play an important role in China’s economy in the coming three decades [50]. As a combination of SER and BAT scenarios, the COC scenario achieves the best balance in upgrading technologies and improving energy structure with the lowest primary energy consumption. Under this scenario, the renewable energy proportion in 2050 will reach 33.8%.
3.3. Emission Characteristics of Air Pollutants

Emission characteristics of air pollutants including emissions, emission reduction potential and emission reduction rate are shown in Figure 5 and Tables 4 and 5. According to the Kuznets curve, the economic growth of developing countries, which have relatively low levels of national income, will promote the increase in emissions of air pollutants. Therefore, in the REF scenario, from 2015 to 2045 in the power industry, the emissions of SO$_2$, NO$_X$, PM$_{2.5}$, and Hg show an overall growth trend. This shows that if the power industry does not adjust its energy consumption structure and optimize control technologies, it will bring great pressure on the emission control of air pollutants in China, which further verifies the results described above. In 2011, the Ministry of Environmental Protection in China promulgated and implemented air pollutant emission standards for coal-fired power plants, significantly reducing the emission limits of pollutants such as SO$_2$, PM$_{2.5}$, and NO$_X$. Therefore, relevant pollutant control devices in the power industry have been applied and promoted to a certain extent before 2015. In this study, the growth rate of PM$_{2.5}$, SO$_2$, and NO$_X$ emissions showed a gradual decrease tendency; emissions will peak in 2045, at 13.47, 15.01, and 4.89 Mt, respectively. As for the heavy metal pollutant Hg, which has gradually attracted public attention in recent years, there is no special removal device in the power plants at this stage. Instead, the existing flue gas purification device is utilized to coordinately remove Hg, but this method has a poor collaborative effect. It is still necessary to separately increase the special control equipment for Hg, such as ACI technology, so that the Hg emissions will continue to increase in the forecast period, reaching 224.81 t by 2050.

![Figure 5. Emissions of air pollutants in the power industry.](image-url)
Table 4. Emission reduction potential in power industry (Mt).

| Scenario | Air Pollutants | 2020  | 2025  | 2030  | 2035  | 2040  | 2045  | 2050  |
|----------|----------------|-------|-------|-------|-------|-------|-------|-------|
| BAT      | SO₂            | 0.48  | 0.44  | 2.09  | 1.83  | 5.11  | 7.84  | 7.93  |
|          | NOₓ            | 0.39  | 0.93  | 1.60  | 2.82  | 4.62  | 7.89  | 7.39  |
|          | PM₂₅           | 0.10  | 0.50  | 1.13  | 1.39  | 2.14  | 3.05  | 2.56  |
|          | Hg (10⁻⁵)      | 1.58  | 3.26  | 4.34  | 4.35  | 7.76  | 10.70 | 13.20 |
| SER      | SO₂            | 0.12  | 0.27  | 0.49  | 0.39  | 1.15  | 4.99  | 5.11  |
|          | NOₓ            | 0.14  | 0.34  | 0.25  | 0.42  | 0.34  | 4.37  | 4.25  |
|          | PM₂₅           | 0.09  | 0.19  | 0.17  | 0.36  | 0.28  | 1.40  | 1.22  |
|          | Hg (10⁻⁵)      | 0.47  | 1.68  | 1.79  | 2.27  | 2.44  | 5.83  | 9.35  |
| COC      | SO₂            | 0.60  | 0.64  | 2.66  | 4.48  | 7.49  | 10.00 | 9.18  |
|          | NOₓ            | 0.50  | 1.22  | 2.19  | 4.91  | 7.87  | 10.70 | 9.59  |
|          | PM₂₅           | 0.02  | 0.43  | 0.98  | 1.81  | 2.38  | 3.41  | 2.93  |
|          | Hg (10⁻⁵)      | 1.98  | 3.68  | 4.80  | 7.02  | 10.10 | 12.60 | 15.40 |

Table 5. Emission reduction rate in power industry (%).

| Scenario | Air Pollutants | 2020  | 2025  | 2030  | 2035  | 2040  | 2045  | 2050  |
|----------|----------------|-------|-------|-------|-------|-------|-------|-------|
| BAT      | SO₂            | 7.1   | 6.0   | 21.5  | 17.6  | 42.1  | 58.2  | 65.3  |
|          | NOₓ            | 4.7   | 10.1  | 15.3  | 23.8  | 35.4  | 52.6  | 55.4  |
|          | PM₂₅           | 4.3   | 16.9  | 31.0  | 34.9  | 50.1  | 62.4  | 62.8  |
|          | Hg             | 11.5  | 20.2  | 24.4  | 22.6  | 38.2  | 49.7  | 58.9  |
| SER      | SO₂            | 1.8   | 3.7   | 5.0   | 3.8   | 9.5   | 37.1  | 42.1  |
|          | NOₓ            | 1.7   | 3.7   | 2.4   | 3.6   | 2.6   | 29.1  | 31.9  |
|          | PM₂₅           | 3.9   | 6.4   | 4.7   | 9.1   | 6.6   | 28.6  | 29.9  |
|          | Hg             | 3.4   | 10.4  | 10.1  | 11.8  | 12.0  | 27.0  | 41.6  |
| COC      | SO₂            | 8.8   | 8.7   | 27.3  | 43.0  | 61.8  | 74.2  | 75.6  |
|          | NOₓ            | 6.0   | 13.3  | 20.9  | 41.5  | 60.3  | 71.5  | 71.9  |
|          | PM₂₅           | 0.9   | 14.5  | 26.9  | 45.5  | 55.7  | 69.7  | 71.8  |
|          | Hg             | 14.4  | 22.8  | 27.0  | 36.5  | 50.0  | 58.5  | 68.7  |

In the BAT scenario, to meet the strict national pollutant emission standards, in the power industry, on the one hand, the introduction and promotion of the best available emission reduction and power generation technologies will be maximized, and the new generation units will directly meet the requirements of mitigation; on the other hand, improvement and upgrading of the existing flue gas purification equipment and devices through methods such as desulfurization, denitrification, and dust removal will be promoted, with removal efficiency greatly improved. Therefore, the emission growth rate of SO₂, NOₓ, PM₂₅, and Hg will decrease gradually. In 2035, emissions will reach peak values of 8.58 Mt, 9.01 Mt, 2.59 Mt, and 149.06 t, respectively. It can be seen from the above that this is because before 2035, the national power demand is still in the development stage of high-level growth, and its average growth rate is practically 20%. During this period, thermal power generation continues to be the most important power generation mode. The large capacity of single equipment not only consumes a large amount of fossil fuel but also leads to a sharp increase in emissions. Therefore, emissions of pollutants in coal-fired power plants are relatively concentrated. However, with the innovation and promotion of technologies in this scenario, emission reduction measures show a slight effect. Although the absolute values of pollutant emissions increase, the annual increases in emissions are effectively controlled. In 2050, the emissions of these four pollutants will be 24%, 23%, 28%, and 21% lower than that of the base year, indicating that it can be significantly controlled in the BAT scenario.

In the SER scenario, the emissions of SO₂, NOₓ, PM₂₅, and Hg also show a trend of increasing, reaching peak values of 10.98 Mt, 12.72 Mt, 3.99 Mt, and 178.79 t, respectively, in 2040 and decreasing by 9.5%, 2.6%, 6.6%, and 12.0% compared with the REF scenario. This is because under this scenario, the power industry makes a significant energy structure adjustment, controlling the use of fossil
energy to the greatest extent. The application proportion of renewable and clean energy is added, and the promotion of clean energy to replace fossil fuel energy is accelerated. In 2050, the proportion of renewable energy utilization will be much greater than the REF and the BAT scenarios. The air pollutants produced by the power industry are mainly from the combustion of fossil fuel, so the improvement of renewable energy utilization efficiency is bound to help reduce the emissions. In 2050, the emissions of these four pollutants will be reduced to 7.03 Mt, 9.08 Mt, 2.86 Mt, and 131.27 t, respectively. Compared with the REF scenario, the level of pollutant emissions effectively improves but is higher than in the BAT scenario. This shows that the emission reduction effect obtained by improving the energy consumption structure is not clear. This is because the end-of-pipe treatment of pollutant emissions is directly taken as the improvement object in the BAT scenario. It is a lot easier and faster to achieve the emission reduction effect through upgrading the control process or equipment.

In the COC scenario, while energy structure is adjusted, the best available technologies are introduced and promoted to realize the dual goals of emission reduction and energy conservation. The application proportion of renewable energy is raised. Pollution control devices of traditional coal-fired generating units are optimized with the upgrading of technologies. The air pollutant emission reduction effect is more significant than the other scenarios. The emissions will achieve the peak values in 2030. The emissions of SO\(_2\), NO\(_X\), PM\(_{2.5}\), and Hg in 2050 are 2.96 Mt, 3.74 Mt, 1.15 Mt, and 70.33 t, respectively, a substantial reduction with the largest decline of all scenarios.

Based on the peak situation under each scenario, it can be found that if there is no interference in the power industry, the air pollutant emissions will reach the peak values as early as 2045. In the BAT, SER, and COC scenarios, not only are emissions significantly controlled but also, peak times are advanced and are 2035, 2040, and 2030, respectively. The corresponding emission peak values are COC, BAT, and SER scenarios in ascending order. Under the COC scenario, the average emission reduction rates are 42.8%, 40.8%, 40.7%, and 39.7%, which are far higher than the other scenarios.

Through the above scenario analysis results, it can be concluded that if the development is only carried out according to the REF scenario mode, environmental problems will continue to worsen. In order to effectively reduce the total emissions of air pollutants, it is necessary to optimize the energy structure, vigorously develop clean energy and renewable energy, control the proportion of coal in energy, and at the same time, improve the efficiency of front-end and end-of-pipe power generation of enterprises through policies and technologies.

3.4. Emission Reduction Characteristics of Air Pollutants

The emission reduction of air pollutants in the power industry is illustrated in Figure 6. It can be found that compared with the SER scenario, the BAT scenario can achieve better results in air pollutant emission reduction. The COC scenario has far greater emission reduction than the other scenarios, which further verifies the results obtained in the previous study. Combined with the emission characteristics obtained above, it is possible to conclude that with rapid economic development and continuous population growth, if the power industry continues to develop with the current trend, the emissions of air pollutants will increase significantly year by year. With further deterioration of the ecological environment, the sustainable development of China, and even the world, will not be achieved. It can be found from the research on the emission reduction law of air pollutants that only by adjusting energy consumption structure or improving pollutant control technologies can the emissions of air pollutants, which will reach peak values during the period 2035–2040, be alleviated to a certain extent. In contrast, under the COC scenario, emissions will peak in advance in 2030, and the emission reduction effect is far better than the other scenarios, which further verifies that the combination of consumption structure improvement and upgrading of best available technologies can achieve a better emission reduction effect.
The obtained emission reduction effect was categorized based on structural and technical effects, and the results are presented in Table 6. In the BAT scenario, the technical effect is more obvious than structural effect, while structural effect plays a more prominent role in the SER scenario. It can be observed that in the COC scenario, from 2020 to 2045, structural effect can play a greater role than technical effect in air pollutant emission reduction. However, the technical effect has a greater growth rate, which exceeds the structural effect in 2045 to 2050, reflecting a more obvious emission reduction effect.

3.5. Emission Reduction Cost of Air Pollutants

The upgrading of emission reduction technologies and the adjustment of energy structure will influence the emission reduction cost of the power industry obviously. The cost of emission reduction can promote green transformation in the power industry. However, its influence is extensive and far-reaching and involves all aspects of the economy, society, and people’s life. Consequently, the process of air pollutant emission reduction should consider not only the environmental impact but also the economic effect. A reasonable emission reduction cost not only significantly decreases the emissions of air pollutants but also reduces the impact on economy. Therefore, the unit and total emission reduction cost of four scenarios were studied, and the results are presented in Tables 7 and 8.

In the four scenarios, the upgrading degree of emission reduction technologies and the adjustment degree of energy structure are varied, so the corresponding emission reduction cost also shows a considerable difference. In the REF scenario, the unit emission reduction cost of SO$_2$, NO$_X$, PM$_{2.5}$, and Hg fluctuates slightly. The life cycle of emission reduction equipment in power plants is approximately 20 years. Therefore, unit emission reduction cost will fluctuate around the year 2035 due to the maintenance of relevant equipment, which is slightly higher than in the other years.

Under the BAT scenario, the power industry will rely heavily on fossil fuel such as coal as before, and in the initial stage of this scenario, it will need a large amount of capital to introduce and upgrade
best available technologies, so the cost of emission reduction is relatively high. The average unit cost of emission reduction in \( \text{SO}_2 \), \( \text{NO}_x \), \( \text{PM}_{2.5} \), and Hg is \( 1.80 \times 10^9 \), \( 6.68 \times 10^9 \), \( 6.86 \times 10^9 \), and \( 5.91 \times 10^{13} \) CNY/Mt, respectively. The concentration of Hg in flue gas is extremely low and is, therefore, difficult to grasp and remove. Therefore, the unit cost of Hg is far higher than for other pollutants, as high as \( 1.25 \times 10^{14} \) CNY/Mt in 2050.

Under the SER scenario, the unit emission reduction cost will increase annually from 2020 to 2040, reaching the peak value in 2040 and eventually, \( 3.26 \times 10^9 \) CNY/Mt in 2050. Emission reduction is primarily achieved through the substitution of clean energy for fossil energy in this scenario. The cost of clean energy power generation technologies includes not only the introduction of technologies but also the transformation of existing devices. In the initial stage of energy structure adjustment, it will take a large amount of investment to carry out infrastructure construction and upgrading. Therefore, the overall cost of emission reduction is far higher than that of the other scenarios and five times that of the BAT scenario. After 2040, with the gradual improvement of energy structure and matured non-fossil fuel utilization technologies, the cost will slowly come down.

| Year | Item | The BAT Scenario | The SER Scenario | The COC Scenario |
|------|------|------------------|------------------|------------------|
|      |      | Structural Effect | Technical Effect | Structural Effect | Technical Effect | Structural Effect | Technical Effect |
| 2020 | \( \text{SO}_2 \) | 0.86 | 2.20 | 1.94 | 0.76 | 2.54 | 0.64 |
|      | \( \text{NO}_x \) | 1.63 | 4.20 | 4.02 | 1.56 | 4.75 | 1.19 |
|      | \( \text{PM}_{2.5} \) | 0.36 | 0.92 | 0.91 | 0.35 | 0.95 | 0.24 |
|      | Hg (10^{-5}) | 0.63 | 1.63 | 0.82 | 0.32 | 2.12 | 0.53 |
| 2025 | \( \text{SO}_2 \) | 1.25 | 3.07 | 2.95 | 1.20 | 3.39 | 1.13 |
|      | \( \text{NO}_x \) | 2.04 | 4.99 | 4.57 | 1.87 | 5.49 | 1.83 |
|      | \( \text{PM}_{2.5} \) | 0.44 | 1.07 | 0.85 | 0.35 | 1.08 | 0.36 |
|      | Hg (10^{-5}) | 1.06 | 2.60 | 1.47 | 0.60 | 3.06 | 1.02 |
| 2030 | \( \text{SO}_2 \) | 1.45 | 3.39 | 2.27 | 0.97 | 3.79 | 1.62 |
|      | \( \text{NO}_x \) | 2.25 | 5.25 | 4.31 | 1.85 | 5.66 | 2.43 |
|      | \( \text{PM}_{2.5} \) | 0.53 | 1.24 | 0.57 | 0.24 | 1.14 | 0.49 |
|      | Hg (10^{-5}) | 1.47 | 3.43 | 1.64 | 0.70 | 3.75 | 1.61 |
| 2035 | \( \text{SO}_2 \) | 1.62 | 3.60 | 2.61 | 1.17 | 5.51 | 2.36 |
|      | \( \text{NO}_x \) | 2.64 | 5.88 | 4.22 | 1.90 | 7.43 | 3.18 |
|      | \( \text{PM}_{2.5} \) | 0.61 | 1.36 | 0.65 | 0.29 | 1.67 | 0.72 |
|      | Hg (10^{-5}) | 1.52 | 3.38 | 1.94 | 0.87 | 5.30 | 2.27 |
| 2040 | \( \text{SO}_2 \) | 2.65 | 5.64 | 2.94 | 1.39 | 6.40 | 4.27 |
|      | \( \text{NO}_x \) | 3.31 | 7.02 | 4.11 | 1.94 | 8.15 | 5.43 |
|      | \( \text{PM}_{2.5} \) | 0.90 | 1.91 | 0.64 | 0.30 | 1.83 | 1.22 |
|      | Hg (10^{-5}) | 2.73 | 5.80 | 2.18 | 1.03 | 6.55 | 4.37 |
| 2045 | \( \text{SO}_2 \) | 3.42 | 6.94 | 5.03 | 2.48 | 6.21 | 6.31 |
|      | \( \text{NO}_x \) | 3.97 | 8.07 | 5.71 | 2.81 | 7.38 | 7.50 |
|      | \( \text{PM}_{2.5} \) | 1.06 | 2.16 | 1.05 | 0.52 | 1.81 | 1.77 |
|      | Hg (10^{-5}) | 3.71 | 7.53 | 4.24 | 2.09 | 6.52 | 6.60 |
| 2050 | \( \text{SO}_2 \) | 3.55 | 6.88 | 5.02 | 2.59 | 5.26 | 6.42 |
|      | \( \text{NO}_x \) | 4.05 | 7.85 | 5.78 | 2.98 | 6.35 | 7.76 |
|      | \( \text{PM}_{2.5} \) | 1.05 | 2.05 | 1.16 | 0.60 | 1.56 | 1.91 |
|      | Hg (10^{-5}) | 4.61 | 8.94 | 6.37 | 3.28 | 7.09 | 8.66 |
Table 7. Unit emission reduction cost of air pollutants (CNY/Mt).

| Scenario | Year | SO₂  | NOₓ  | PM₂.₅ | Hg    |
|----------|------|------|------|--------|-------|
| REF      | 2020 | 6.45 × 10⁷ | 5.48 × 10⁸ | 6.01 × 10⁸ | 3.82 × 10¹¹ |
|          | 2025 | 5.95 × 10⁷ | 5.65 × 10⁸ | 5.98 × 10⁸ | 4.02 × 10¹¹ |
|          | 2030 | 6.14 × 10⁷ | 5.35 × 10⁸ | 5.88 × 10⁸ | 3.92 × 10¹¹ |
|          | 2035 | 6.56 × 10⁷ | 5.72 × 10⁸ | 6.28 × 10⁸ | 4.15 × 10¹¹ |
|          | 2040 | 6.42 × 10⁷ | 5.41 × 10⁸ | 6.09 × 10⁸ | 4.01 × 10¹¹ |
|          | 2045 | 5.85 × 10⁷ | 5.13 × 10⁸ | 5.87 × 10⁸ | 3.86 × 10¹¹ |
|          | 2050 | 5.65 × 10⁷ | 5.01 × 10⁸ | 5.42 × 10⁸ | 3.24 × 10¹¹ |
|          | Average | 6.15 × 10⁷ | 5.39 × 10⁸ | 5.93 × 10⁸ | 3.86 × 10¹¹ |
| BAT      | 2020 | 1.63 × 10⁹ | 6.82 × 10⁹ | 7.04 × 10⁹ | 4.80 × 10¹² |
|          | 2025 | 1.86 × 10⁹ | 7.41 × 10⁹ | 7.62 × 10⁹ | 9.89 × 10¹² |
|          | 2030 | 2.05 × 10⁹ | 7.94 × 10⁹ | 8.12 × 10⁹ | 1.15 × 10¹³ |
|          | 2035 | 1.42 × 10⁹ | 6.33 × 10⁹ | 6.58 × 10⁹ | 5.76 × 10¹³ |
|          | 2040 | 1.72 × 10⁹ | 5.99 × 10⁹ | 6.01 × 10⁹ | 9.21 × 10¹³ |
|          | 2045 | 2.01 × 10⁹ | 6.41 × 10⁹ | 6.68 × 10⁹ | 1.13 × 10¹⁴ |
|          | 2050 | 1.88 × 10⁹ | 5.83 × 10⁹ | 5.94 × 10⁹ | 1.25 × 10¹⁴ |
|          | Average | 1.80 × 10⁹ | 6.68 × 10⁹ | 6.86 × 10⁹ | 5.91 × 10¹³ |
| COC      | 2020 | 5.26 × 10⁹ | 2.20 × 10¹⁰ | 2.27 × 10¹⁰ | 1.55 × 10¹³ |
|          | 2025 | 9.13 × 10⁹ | 3.67 × 10¹⁰ | 3.73 × 10¹⁰ | 4.85 × 10¹³ |
|          | 2030 | 5.56 × 10⁹ | 2.18 × 10¹⁰ | 2.13 × 10¹⁰ | 3.09 × 10¹³ |
|          | 2035 | 1.55 × 10⁹ | 6.71 × 10⁹ | 7.11 × 10⁹ | 6.16 × 10¹³ |
|          | 2040 | 2.27 × 10⁹ | 7.79 × 10⁹ | 7.93 × 10⁹ | 1.20 × 10¹⁴ |
|          | 2045 | 2.09 × 10⁹ | 6.73 × 10⁹ | 7.01 × 10⁹ | 1.20 × 10¹⁴ |
|          | 2050 | 1.69 × 10⁹ | 5.31 × 10⁹ | 5.23 × 10⁹ | 1.11 × 10¹⁴ |
|          | Average | 3.94 × 10⁹ | 1.53 × 10¹⁰ | 1.55 × 10¹⁰ | 7.25 × 10¹³ |
| SER      | 2020 | 1.64 × 10¹⁰ |                 |                 |       |
|          | 2025 | 2.73 × 10¹⁰ |                 |                 |       |
|          | 2030 | 3.57 × 10¹⁰ |                 |                 |       |
|          | 2035 | 4.41 × 10¹⁰ |                 |                 |       |
|          | 2040 | 5.11 × 10¹⁰ |                 |                 |       |
|          | 2045 | 4.23 × 10¹⁰ |                 |                 |       |
|          | 2050 | 3.26 × 10¹⁰ |                 |                 |       |
|          | Average | 3.56 × 10¹⁰ |                 |                 |       |

Table 8. Total emission reduction cost of air pollutants (CNY).

| Year | REF  | BAT  | SER  | COC  |
|------|------|------|------|------|
| 2020 | 3.85 × 10⁹ | 5.39 × 10¹⁰ | 1.57 × 10¹¹ | 1.75 × 10¹¹ |
| 2025 | 4.28 × 10⁹ | 7.20 × 10¹⁰ | 3.22 × 10¹¹ | 3.65 × 10¹¹ |
| 2030 | 3.71 × 10⁹ | 8.45 × 10¹⁰ | 3.64 × 10¹¹ | 2.43 × 10¹¹ |
| 2035 | 3.85 × 10⁹ | 7.70 × 10¹⁰ | 4.78 × 10¹¹ | 1.05 × 10¹¹ |
| 2040 | 3.70 × 10⁹ | 1.01 × 10¹¹ | 6.02 × 10¹¹ | 1.42 × 10¹¹ |
| 2045 | 2.38 × 10⁹ | 1.32 × 10¹¹ | 7.45 × 10¹¹ | 1.67 × 10¹¹ |
| 2050 | 2.69 × 10⁹ | 1.24 × 10¹¹ | 5.91 × 10¹¹ | 1.30 × 10¹¹ |

Total emission reduction cost corresponding to the COC scenario is ranked between the BAT scenario and the SER scenario. However, from a long-term standpoint, in 2050, the unit emission reduction cost of this scenario is the lowest when compared with the figures for BAT and SER scenarios, which are 1.69 × 10⁹, 5.31 × 10⁹, 5.23 × 10⁹, 1.11 × 10¹⁴ for SO₂, NOₓ, PM₂.₅, and Hg, respectively. Combined with the previous research results, it can be found that in the long run, the COC scenario can achieve a more reasonable emission reduction cost.
4. Conclusions

Given its urbanization and economic development, the power demand of China has shown a trend of continuous growth annually, developing at a speed that is higher than the growth of GDP. During the period of 2015–2050, the power demand of terminal departments will increase to a different degree, but its composition will change significantly, with the focus gradually shifting from industry to construction and transportation.

If the current policy and technology development trends are maintained in the power industry, the energy structure remains unchanged, and no new technologies of power generation and emission reduction are introduced, the primary energy and air pollutant emissions will rise dramatically. By 2050, the primary energy consumption of China’s power industry will reach 98.83 EJ, and the emissions of SO$_2$, NO$_X$, PM$_{2.5}$, and Hg will be as high as 12.14 Mt, 13.33 Mt, 4.08 Mt, and 224.81 t, respectively, which puts heavy pressure on China’s pollutant control and energy balance.

For the emission reduction of air pollutants, the promotion effect of emission reduction measures, such as the implementation and promotion of non-fossil fuels, is restricted. In view of China’s limited fossil resources, with the planned gradual stability of energy consumption, non-fossil energy development will have a tendency to diversify. Energies with huge reserves and low air pollutant emissions such as nuclear, wind, and solar will gradually become the supporting force for the development of non-fossil energy, if the cost can be further reduced and obstacles such as grid connection can be overcome.

The power industry can introduce and maximize the best available technologies while optimizing the structure of energy consumption to realize efficient emission reduction in air pollutants and energy conservation. In 2030, under the COC scenario, the emissions of SO$_2$, NO$_X$, PM$_{2.5}$, and Hg will reach peak values of 7.07 Mt, 8.28 Mt, 2.66 Mt, and 129.98 t, respectively, with reasonable emission reduction cost. This has the additional effect of abating energy consumption and preventing deterioration of the ecological environment, which is of profound significance for the ultimate realization of climate friendliness.

In order to further study the application of the bottom-up analysis model on the emissions of China, in the future, we will further explore the collaborative removal of CO$_2$ and air pollutants in the power industry and other industries to obtain the most economical and effective emission reduction measures.

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