sustainability

MDPI

Article

Collaborative Optimization of Emissions and Abatement Costs for Air Pollutants and Greenhouse Gases from the Perspective of Energy Structure: An Empirical Analysis in Tianjin

Xiaran Zhang [1], Xiaoxia Rong [2], Meng Cai [1] and Qingchun Meng [1,*]

[1] School of Management, Shandong University, Jinan 250100, China
[2] School of Mathematics, Shandong University, Jinan 250100, China
* Correspondence: meqich@sdu.edu.cn

Received: 6 June 2019; Accepted: 15 July 2019; Published: 16 July 2019

check for updates

Abstract: Both air pollution and greenhouse effect have become important issues with regard to environmental protection both in China and across the world. Consumption of energy derived from coal, oil, and natural gas forms the main source of China's major air pollutants, SO_2 and NO_X, as well as the major greenhouse gas CO_2. The energy structure adjustment approach provides a sensible way, not only to achieve climate change mitigation and air pollutant reduction, but also to reduce abatement costs. In this paper, a multi-objective optimization method was adopted in order to analyze the collaborative optimization of emissions and abatement costs for both air pollutants and greenhouse gases. As a typical industrial city and economic center with fossil fuels as its main energy source, Tianjin of China is used as the research sample to prove that this method can mitigate air pollutants and greenhouse gas emissions and reduce abatement costs. Through demonstration, the results show that the optimization method proposed can reduce SO_2, NO_X, and CO_2 emissions by 27,000 tons, 33,000 tons, and 29,000 tons, respectively, and the abatement costs will be reduced by 620 million yuan by adjusting the energy structure of Tianjin. The proposed method also suggests that China can achieve reductions of abatement cost and greenhouse gas and air pollutant emissions under the proposed energy structure. The results indicate that collaborative optimization would help China and other countries cope with climate change while improving domestic air quality.

Keywords: collaborative optimization; emission reduction; abatement cost; energy structure; multi-objective optimization

1. Introduction

Currently, China faces dual pressures from air pollution and greenhouse gas emissions. China's regional air pollution problems are very serious: More than one-fifth of the country's land has experienced extraordinarily high levels on the "smog index". A "top-down", mandatory commitment to the carbon emission reduction model dictated by the Kyoto Protocol is now gradually being transformed into a "bottom-up", "Nationally Determined Contributions" (NDC) mechanism of the Paris Agreement [1]. China expects the future of carbon emissions per unit of GDP to fall by 60–65% by 2030 compared to 2005. Due to the severity of domestic air pollution, combined with the commitment to join the international community in implementing an independent policy to reduce greenhouse gas emissions, both the "13th Five-Year Plan for Controlling Greenhouse Gas Emissions" and the "13th Five-Year Plan for Ecological Environmental Protection" issued by the State Council mention "enhanced coordinated control of carbon emissions and atmospheric pollutant emissions".

The collaborative governance of air pollutants and greenhouse gases is an excellent choice and policy outlet for China during a critical stage in its economic transformation.

According to "China statistical yearbook on environment 2017", the total investment in treatment of environmental pollution reached 921.98 billion yuan in 2016. Among the three main areas of environmental pollution—air, water, and soil—the current investment related to air pollution is the highest. For example, in the industrial sector, 68.5% of the total investment in pollution treatment was spent on the treatment of waste gas (SO_2, NO_X, smoke, dust, etc.). In the short term, the cost of greenhouse gas reductions is derived from potential GDP loss caused by production cutbacks [2]. Irrespective of both the financial constraints and the needs of economic development, only focusing on reducing emissions will not prove conducive to the long-term development of collaborative governance [3,4]. Therefore, it is necessary to consider the costs paid to reduce air pollutants and greenhouse gas emissions, namely abatement costs [5]. This paper proposes a cooperative optimization-based approach to reduce emissions and abatement costs. Its underlying goal is to reduce both air pollutant and greenhouse gas emissions and cut down abatement costs simultaneously in order to achieve a coordinated balance.

While previous studies have been devoted to the collaborative governance of air pollutants and greenhouse gases in the context of technological improvements and macro control, in the long run, the energy structure, which is the ratio between one energy type consumption and the total energy consumption [6], holds the key to achieving collaborative governance [7]. The main air pollutants of China such as SO_2, and NO_X, and greenhouse gas CO_2 are produced from the consumption of fossil fuel-based energy sources, including coal, oil, and natural gas, which also offer the potential for collaborative governance [8]. When equal amounts of coal, oil, and natural gas are consumed, the emissions of SO_2, NO_X, and CO_2 vary greatly. For example, 1 kg of oil is consumed to produce 5.77–36.25 grams of NO_x, while equal amounts of coal and natural gas yield 1.88–8 grams and 0.736–2.085 grams of nitrogen oxides, respectively. The difference in the method of use, even for the same amount of energy, will affect the emission ratio of SO_2, NO_X and CO_2. For example, due to advanced desulfurization facilities in industrial sectors, the amount of SO_2 produced by coal combustion is lower than that of other sectors in society. However, higher temperatures result in a larger amount [9].

According to the differences in both the energy type and the combustion mechanism, the collaborative optimization method proposed in this research primarily concerns the arrangement of different energy sources (coal, oil, natural gas) in different sectors without disrupting production. This is an attempt to minimize the emissions of air pollutants and greenhouse gasses, while also reducing abatement costs and achieving both environmental and economic benefits. By taking Tianjin as an example, the effectiveness of the collaborative optimization method is also verified. The main contributions are as follows:

(i) The model for collaborative optimization of emissions and abatement costs is established. On the basis of analyzing the common constraints of different modes of energy consumption, the optimization of multiple targets, including reductions in air pollutant and greenhouse gas emissions, as well as abatement cost reductions, is realized by adopting a multi-objective optimization method.

(ii) A perspective of energy structure is proposed in order to solve the problem of collaborative optimization. According to the type and combustion mechanism of a given form of energy, limited energy (coal, oil, natural gas) is arranged reasonably into different social sectors, so as to achieve collaborative optimization on the premise of meeting social needs.

(iii) The collaborative optimization scheme of Tianjin is proposed. The relevant parameters of the collaborative optimization model are determined using the actual data, such as the yearbook of Tianjin. The collaborative optimization scheme, as well as the specific energy structure adjustment method in Tianjin, is also given in order to realize a reduction in both emissions and abatement costs.

The rest of this paper is structured as follows: Section 2 consists of a literature review, Section 3 introduces a collaborative optimization model, while Section 4 offers empirical analysis of the collaborative optimization model in Tianjin. Section 5 discusses the research results, and Section 6 concludes the paper.

2. Literature Review

The problem of coordinated governance in the context of air pollutants and greenhouse gases has attracted the attention of scholars both at home and abroad. Some researchers have used LEAP, TRACE-P EI, CMAQ, and BenMAP models, as well as empirical research methods, to verify the synergistic effects of air pollutant and greenhouse gas emission reduction [1,10,11]. The following research pays attention to the methods of collaborative reduction from a number of perspectives. For example, a self-management approach determined by a committee was established to facilitate the control of the total quantity of greenhouse gas and air pollutant emissions [12]; structural emission reduction measures are easier to achieve with the coordinated control [13]; factors such as discount rate and weight will affect the emissions reduction supply curve [3]. A few papers have also focused on the correlation between energy consumption, and emissions of air pollutants and greenhouse gases. Meng et al. (2016) used multi-objective means to discuss collaborative emission reductions according to the common constraints of different forms of energy consumption, while also formulating a cleaner energy distribution plan [9]. Yuan (2017), meanwhile, provided a comprehensive analytical framework in order to quantitatively evaluate the effects of energy measures in mitigating climate change and combating air pollution [14]. Other studies have focused on the abatement costs of air pollutants and greenhouse gases. For example, Chae (2010) conducted cost effectiveness and synergy evaluations of air improvement and greenhouse gas control measures in Seoul, South Korea [15], while Yang et al. (2013) estimated the environmental damage costs of air pollutants in various provinces and cities in China [16]. Liu et al. (2019) have also conducted a cost–benefit analysis of measures taken by the transport sector in China's Pearl River delta region to improve air quality and mitigate climate change [4]. The above literature either discusses methods for the collaborative reduction of air pollutants and greenhouse gases from a technical and management level or analyzes abatement costs from an economic perspective. However, both emissions and abatement costs form important components of collaborative governance in China [17]. The singular pursuit of emission reduction or abatement cost reduction is not conducive to supporting both environmental quality and economic development. In addition, due to the homologous nature of air pollutants and greenhouse gases, optimizing the energy structure is the key to achieve collaborative governance in the long-term [7,18]. However, only a few articles have discussed emission reduction schemes from the perspective of energy consumption, and these studies have not also considered the abatement costs.

Some scholars have combined energy structure with air quality and carbon emissions to conduct the research. Bilgen (2014) studied the environmental impacts of fuel types, industry, and global energy consumption, finding that the energy consumption structure and emission conditions of SO_2, NO_x, and CO_2 had a significant impact on acid rain and the greenhouse effect [19]. Zhang et al. (2015) considered energy pollution reduction and other indicators to carry out a critical assessment of China's existing energy model [20], while Xing et al. (2017) examined various social factors that affect the emissions of greenhouse gases and air pollutants and emphasized the importance of energy transformation [7]. Yang et al. (2018) adopted an LMDI model to quantify carbon emissions resulting from energy consumption in Wuhan, indicating that energy structure optimization contributed significantly towards the inhibition of carbon emissions growth [8]. Existing research has investigated the relationship between energy structure, environmental quality, economic development, and the effectiveness of energy structure at a macro level. However, there has not been an in-depth systematic analysis of energy structures that can simultaneously ensure both environmental quality and economic development. In addition, most previous research results demonstrate that the proportion of new renewable energy schemes should be increased in order to optimize the energy structure. However, there are no renewable energy sources to completely replace fossil fuels at this time. Consequently, it is of practical significance for China to optimize its fossil fuel energy structure according to the pollution characteristics of these forms of energy in terms of the abatement costs related to air pollutants and greenhouse gases.

In recent years, multi-objective methods have been increasingly applied to social problems, such as environmental improvement and energy structure adjustment. Meng et al. (2016) used a multi-objective method to establish a collaborative emission reduction model for greenhouse gases and air pollutants, and also designed the optimal-pole algorithm subsequently [20]. Mohamadpour and Hassanzadeh (2018) took reverse logistics as their research object, adopting a multi-objective mixed-integer linear planning model to alleviate environmental problems and solved it using the distance method and the ε-Constraint method [21]. Li et al. (2019) proposed a new air quality index (AQI) analysis and prediction system, which uses a multi-objective multi-verse optimization algorithm to predict the hourly AQI series and to overcome randomness and non-stationarity [22]. As the multi-objective function exists within a certain decision space, a solution that can combine multiple objectives and achieving optimality is urgently needed. As this kind of overall consideration is more suitable for the coordinated governance of air pollutants and greenhouse gases, this paper uses the mathematical method offered by the multi-objective approach to research.

This paper focuses on the collaborative optimization of emissions and abatement costs. The originality lies in the following two points: (1) considering emissions and abatement costs for air pollutants (SO_2 and NO_X) and greenhouse gases (CO_2) simultaneously, a multi-objective optimization method is adopted to explore a clean and economically beneficial collaborative optimization scheme so as to achieve unification between environmental benefits and economic benefits; (2) from the perspective of energy structure, using the complementarity of coal, oil, and natural gas in terms of energy consumption, according to their combustion mechanism and pollution production characteristics, limited energy is reasonably arranged in different social sectors in order to achieve collaborative optimization without disrupting production.

3. Collaborative Optimization Model

We begin this section by determining the functional relationship between energy consumption and the emissions related to air pollutants and greenhouse gases. Following this, the abatement cost function is constructed in order to analyze the relationship between energy consumption and abatement costs. On this basis, the multi-objective method is adopted to establish a collaborative optimization model for emissions and abatement costs. Finally, in order to obtain solutions that are close to ideal values, the distance method is introduced to solve the problems related to a multi-objective approach.

3.1. Functional Relationship between Energy Consumption and Emissions

The energy in this paper refers to fossil fuels that release air pollutants (SO_2 and NO_X) or greenhouse gases (CO_2).

According to the air pollutant and greenhouse gas emission prediction method proposed in "Resources (energy), Environment, Economic Prediction and Research Report of the National 13th Five-Year Plan", society can be divided into multiple energy-consuming sectors. Following this, the quantitative relation between energy consumption and the emissions of air pollutants and greenhouse gases can be determined based on desulphurization efficiency, the denitration efficiency of different sectors, the carbon emission factors of different forms of energy, combustion loss rate, and the NO_X emission factors of different energy in different sectors.

The SO_2 emission function is shown in Equation (1), where x_{ij} is the amount of the jth energy consumed by the ith sector, α_j is the sulfur content per unit of the jth energy, β_j is the sulfur conversion rate of the jth energy, and γ_{1i} refers to the desulphurization efficiency of the ith sector.

$$E_1 = \sum_i \sum_j 2\alpha_j \beta_j (1 - \gamma_{1i}) x_{ij} \tag{1}$$

The NO_X emission function is shown in Equation (2), where η_{ij} is the NO_X emission factor of the ith sector of the jth energy consumption, and γ_{2i} refers to the denitration efficiency.

$$E_2 = \sum_i \sum_j \eta_{ij} (1 - \gamma_{2i}) x_{ij} \tag{2}$$

The CO_2 emission function is shown in Equation (3), where c_j refers to the carbon emission factor of the jth energy, and w_j refers to the combustion loss rate of the jth energy.

$$E_3 = \sum_i \sum_j 0.98 c_j \left(1 - w_j\right) x_{ij} \tag{3}$$

According to the above analysis, although the production mechanisms of SO_2, NO_X, and CO_2 are different, they all depend on the energy consumed by the society and are all positively linearly correlated with energy consumption. In addition, due to differences in the technological means, the methods of use, and the amount of energy used by various sectors of society, the emissions of air pollutants and greenhouse gases also vary considerably. Even different sectors that use the same form of fuel will produce different emission amounts. For example, for NO_x, this gas can be formed not only during combustion of the fuel, but also at the high temperature to oxidize nitrogen molecules in the air.

3.2. Functional Relationship between Energy Consumption and Abatement Costs

It can be seen from Equations (1) and (2) that exhaust gas with SO_2 and NO_X must be de-sulfurized and de-nitrated before it can be discharged into the air. Furthermore, the cost of performing these operations is classified as abatement costs; the CO_2 emissions cannot be disposed of freely under constraints relating to known viable technologies. Carbon emission reduction, in the short term, can therefore only be achieved by reducing the production amount at the source of the emissions, thereby slowing economic growth. The potential loss of output is classified as the abatement costs.

3.2.1. Functional Relationship between Energy Consumption and Abatement Costs for Air Pollutants

It is generally believed that the abatement costs are related to the amount of air pollutants emissions and removals (Zhou et al., 2018) [23]. Some studies suggest that abatement costs are also correlated with regional economic conditions (Tang & Chen, 2017) [24]. The abatement cost function of air pollutants is usually obtained through regression analysis.

This paper comprehensively considers the amount of air pollutants emissions and removals, while also describing economic indicators in the target area in order to conduct the regression calculation of the cost of air pollutant governance in each region. The SO_2 abatement cost function is shown in Equation (4), and Equation (5) is obtained by logarithmic processing of Equation (4). Following this, linear regression will be performed by software in order to obtain the various parameter values.

$$Y_1 = \theta_1 E_1^{\phi_1} R_1^{\mu_1} P^{\beta_1} \tag{4}$$

$$\ln Y_1 = \ln \theta_1 + \phi_1 \ln E_1 + \mu_1 \ln R_1 + \beta_1 \ln P \tag{5}$$

where Y_1 is the abatement cost function of SO_2, R_1 represents the amount of SO_2 removed, and $\theta_1, \phi_1, \mu_1, \beta_1$ are the constants. θ_1 is a combined impact factor, including regional industrial structure, enterprise ownership structure, etc., which can generally be considered unchanged in the short term; and ϕ_1, μ_1, β_1 are the elastic coefficients of emissions, removals and economic indicators respectively.

The parameter P is normalized by a series of indicators that characterize the regional economic development level. $P = \alpha_1 A_1 + \alpha_2 A_2 \cdots \alpha_q A_q$ is obtained through principal component analysis, where α_k is the coefficient, A_k represents the normalized value of the economic indicator, and $k = 1, 2, \cdots, q$.

Similarly, the abatement cost function of NO_X can be obtained by Equation (6), where Y_2 is the abatement cost function of NO_X, R_2 is the amount of NO_X removed, and $\theta_2, \phi_2, \mu_2, \beta_2$ are the constants.

$$Y_2 = \theta_2 E_2^{\phi_2} R_2^{\mu_2} P^{\beta_2} \quad (6)$$

The amount of air pollutants removed is defined as the difference between those produced and those emitted. That is, the product of the amount of air pollutants produced, and the rate of air pollutants removed. The quantitative relationship between energy consumption and the abatement costs of SO_2 and NO_X is obtained by substituting Equations (1) and (2) into Equations (4) and (6), as shown in Equations (7) and (8) respectively.

$$Y_1 = \theta_1 \left(\sum_i \sum_j 2\alpha_j \beta_j (1 - \gamma_{1i}) x_{ij} \right)^{\phi_1} \left(\sum_i \sum_j 2\alpha_j \beta_j \gamma_{1i} x_{ij} \right)^{\mu_1} P^{\beta_1} \quad (7)$$

$$Y_2 = \theta_2 \left(\sum_i \sum_j \eta_{ij} (1 - \gamma_{2i}) x_{ij} \right)^{\phi_2} \left(\sum_i \sum_j \eta_{ij} \gamma_{2i} x_{ij} \right)^{\mu_2} P^{\beta_2} \quad (8)$$

3.2.2. Functional Relationship between Energy Consumption and Abatement Costs for Greenhouse Gases

Some researchers have conducted a comprehensive analysis of the cost of greenhouse gas governance, concluding that the CO_2 marginal abatement costs of different regions, different energy structures, and industrial structures are quite different. In terms of the technical and structural constraints, carbon emissions cannot be disposed of freely. To achieve the short-term goal, it can only be accomplished by compressing the production scale of the carbon emission sector and slowing economic growth. Therefore, the governance of CO_2 comes at the cost of potential GDP losses [25].

Wu et al. (2019) proposed an improved DDF-DEA method to effectively avoid the occurrence of marginal emission reduction of non-positive CO_2 and calculate the provincial CO_2 marginal abatement cost [2]. Our analytical framework is based on this model. The greenhouse gas abatement cost function is shown in Equation (9), where Y_3 is the abatement costs of CO_2, $MC(r)$ is the marginal abatement costs of reducing CO_2 by r units, and R is the amount of CO_2 removed.

$$Y_3 = \int_0^{R_3} MC(r) d_r \quad (9)$$

Taking each year as a time scale, the marginal abatement cost of the year n can be used as the unit cost of CO_2 for the year. Since there is no centralized emission reduction measure for CO_2, that is, where the amount of CO_2 production is equal to its emissions, the amount R_3 of CO_2 removed is regarded as the difference between the actual amount E'_3 of CO_2 emissions and that E_3 of target emissions in the nth year. As this paper aims to reduce the amount of CO_2 emissions, set $R_3 = \begin{cases} E'_3 - E_3 & E'_3 \geq E_3 \\ 0 & E'_3 < E_3 \end{cases}$.

The equation for the greenhouse gas abatement cost function of the nth year is as follows:

$$Y_3 = \begin{cases} MC(r)_n\left(E_3' - E_3\right) & E_3' \geq E_3 \\ 0 & E_3' < E_3 \end{cases} \tag{10}$$

Both E_3 and E_3' are functions of x_{ij}, as shown in Equation (3).

3.3. Multi-Objective Model for Collaborative Optimization

Society can be divided into M sectors with N optional energy sources. The decision variable $x = \left(x_{ij}\right), i = 1, 2, \cdots, M, j = 1, 2, \cdots, N$ is the jth energy consumption of the ith sector; and E_1, E_2, E_3 are the emissions of SO_2, NO_X, and CO_2, respectively; while Y denotes total abatement costs; and $Y = Y_1 + Y_2 + Y_3$, Y_1, Y_2, Y_3 denotes the abatement costs of SO_2, NO_X, and CO_2. The minimum value is adopted by the objective function, as shown below.

$$\min E_1 = \sum_i \sum_j 2\alpha_j \beta_j (1 - \gamma_{1i}) x_{ij}$$
$$\min E_2 = \sum_i \sum_j \eta_{ij} (1 - \gamma_{2i}) x_{ij}$$
$$\min E_3 = \sum_i \sum_j 0.98 c_j \left(1 - w_j\right) x_{ij}$$
$$\min Y = \theta_1 \left(\sum_i \sum_j 2\alpha_j \beta_j (1 - \gamma_{1i}) x_{ij}\right)^{\phi_1} \left(\sum_i \sum_j 2\alpha_j \beta_j \gamma_{1i} x_{ij}\right)^{\mu_1} P^{\beta_1} +$$
$$\theta_2 \left(\sum_i \sum_j \eta_{ij} (1 - \gamma_{2i}) x_{ij}\right)^{\phi_2} \left(\sum_i \sum_j \eta_{ij} \gamma_{2i} x_{ij}\right)^{\mu_2} P^{\beta_2} + MC(r)_n \left(E_3' - \sum_i \sum_j 0.98 c_j \left(1 - w_j\right) x_{ij}\right)$$

The energy supply must meet the social development needs, but it is also subject to some conditions, such as reserves and exploitation capacity. Therefore, energy demand constraints and supply constraints can be expressed as in Equations (11) and (12), where $\rho_j, j = 1, 2, \cdots, N$ refers to the coefficient of the jth energy converted into standard energy; $D_i, i = 1, 2, \cdots, M$ refers to the total energy demanded to develop the ith sector; and $S_j, j = 1, 2, \cdots, N$ refers to the upper limit of the jth energy supply.

$$\sum_j \rho_j x_{ij} \geq D_i, i = 1, 2, \cdots, M \tag{11}$$

$$\sum_i x_{ij} \leq S_j, j = 1, 2, \cdots, N \tag{12}$$

In addition, energy consumption must be positive, i.e., $x_{ij} \geq 0, i = 1, 2, \cdots, M, j = 1, 2, \cdots, N$. In summary, the obtained collaborative optimization model is shown in Equation (13).

$$\begin{aligned} &\min(E_1, E_2, E_3, Y) \\ &s.t. \begin{cases} \sum_j \rho_j x_{ij} \geq D_i, i = 1, 2, \cdots, M \\ \sum_i x_{ij} \leq S_j, j = 1, 2, \cdots, N \\ x_{ij} \geq 0, Y_l \geq 0, l = 1, 2, 3 \end{cases} \end{aligned} \tag{13}$$

3.4. Distance Method and Solving Process

Using the distance method to solve the multi-objective problem is more conducive towards obtaining a solution that is close to the ideal value (Branke et al., 2008) [26]. First, each objective function is solved independently under given constraints (Mirzapour Al-E-Hashem et al., 2011) [27] where the minimum value of SO_2, NO_X, and CO_2 emissions are E_1^*, E_2^*, and E_3^* respectively, while the minimum cost of governance is Y^*. The second stage involves taking the ideal values E_1^*, E_2^*, E_3^*, and Y^*

of the four objective functions of the target space and minimizing the Euclidean distance d between the four targets and their ideal values under the established constraints set by the model. The solution of the original multi-objective function can be obtained by solving the nonlinear programming problem in Equation (14).

Where $\omega_1 = \frac{W_1}{W_1+W_2+W_3+W_4}$, $\omega_2 = \frac{W_2}{W_1+W_2+W_3+W_4}$, $\omega_3 = \frac{W_3}{W_1+W_2+W_3+W_4}$, $\omega_4 = \frac{W_4}{W_1+W_2+W_3+W_4}$ represents the relative weight of the four goals regarding SO_2 emissions, NO_x emissions, CO_2 emissions, and abatement costs respectively, while $\omega_1 + \omega_2 + \omega_3 + \omega_4 = 1$.

$$\min d = \left(W_1\left(E_1 - E_1^*\right)^2 + W_2\left(E_2 - E_2^*\right)^2 + W_3\left(E_3 - E_3^*\right)^2 + W_4(Y - Y^*)^2\right)^{\frac{1}{2}} \tag{14}$$

4. Empirical Analysis of Collaborative Optimization Model in Tianjin

There are two reasons for choosing Tianjin as the sample of this empirical study. First, Tianjin is an important economic center and a major city in northern China. However, it is also one of the country's most polluted areas where economic development and pollution control have become severe issues. Second, the energy consumption pattern of Tianjin is dominated by fossil fuels, which is typically representative of most industrial cities across China and, therefore, representative as an example for empirical analysis. This paper employs data from Tianjin from 2006 to 2016 to verify the model. Due to the lag in the publication of statistical yearbooks, the data for 2016 is the latest available data for this study.

4.1. Determination of Parameters in Emissions Function

Drawing on the work of Meng et al. (2016) [7], in order to reduce the number of calculations according to the amount of energy consumption, Tianjin can be divided into five social sectors: large-scale agriculture (farming, forestry, herding, fishery, and water conservation), industry (including power generation and heating), transportation, retail and accommodation, and consumption of living. At the same time, based on the similarity of the pollutant discharge coefficient in energy consumption, the various forms of fossil fuel energy included in the energy yearbook are classified as coal, oil, and natural gas. Therefore, a collaborative optimization model with 15 variables is established.

As the SO_2 and NO_X generated in daily life are difficult to process centrally, the desulfurization and denitrification procedures considered in this paper mainly involve the industrial field. The desulfurization rates of coal, oil and, gas in Tianjin industrial departments are 0.3, 0.3, and 0 respectively, while the denitrification rates are 0.196, 0.08, and 0, respectively. According to both "Resources (energy), Environment, Economic Prediction and Research Report of The National 13th Five-Year Plan" and "China energy yearbook", the parameters in the emission function, namely the discharge coefficients of various energies, are shown in Table 1.

Table 1. Discharge Coefficients.

Product No.	Sectors	Energies	SO_2 Emission Factor	NO_X Emission Factor	CO_2 Emission Factor
			10^{-3} kg/kg (m^3)	10^{-3} kg/kg (m^3)	10^{-3} kg/kg (m^3)
1	Large-scale agriculture	Coal	12	3.75	1977.90
		Oil	18	8.26	2984.75
		Natural gas	0	1.462	2184.03
2	Industry	Coal	8.4	8	1977.90
		Oil	12.6	8.86	2984.75
		Natural gas	0	2.085	2184.03
3	Transportation	Coal	12	7.5	1977.90
		Oil	9	36.25	2984.75
		Natural gas	0	2.085	2184.03
4	Retail and accommodation	Coal	12	3.75	1977.90
		Oil	9	5.77	2984.75
		Natural gas	0	1.462	2184.03
5	Consumption of living	Coal	12	1.88	1977.90
		Oil	9	16.7	2984.75
		Natural gas	0	0.736	2184.03

Source: "Resources (energy), Environment, Economic Prediction and Research Report of The National 13th Five-Year Plan" and "China energy statistical yearbook 2017".

4.2. Determination of Parameters in Abatement Cost Function

4.2.1. Determination of Parameters in Air Pollutants Abatement Cost Function

In determining the abatement cost function of air pollutant in Tianjin, this paper makes the following assumptions and simplifications:

(i) The data of air pollutant emissions and removals in Table A1 refers to those of the industrial sector. As the SO_2 and NO_X generated by other sectors are difficult to be processed centrally, only the industrial SO_2 and NO_X governance data are included in the statistical yearbook.

(ii) The data of air pollutant abatement costs in Table A1 refers to the "Operating Cost of Air Pollutants Governance Facilities" in the "China Environmental Yearbook", including energy consumption, equipment depreciation, equipment maintenance, personnel salaries, management expenses, process chemical costs, and other expenses related to the operation of the facility.

The "China Environment Yearbook" was used so as to obtain data about air pollutant governance in Tianjin on the basis of the above assumptions and simplifications. The indicators of the on-the-job worker's average wage, per capita GDP, fixed assets investment, and industrial added value of employees were used to characterize Tianjin's macroeconomic and industrial development level, while the "Tianjin Statistical Yearbook" was adopted to obtain Tianjin macroeconomic data (as listed in Table A1).

The economic parameter P' of each year was generated using principal component analysis. Due to the negative number relating to this, in order to facilitate the next dynamic measurement analysis, according to the principle 3σ of statistics, the formula $P = H + P'$ was used to coordinate the translation to eliminate the negative influence, while the final economic parameters P of each year were also obtained (as listed in Table A2).

Following this, the abnormal data was interpolated, while SPSS software was used to execute regression analysis on the variables involved in the SO_2 abatement cost function. The results show that the linear relationship between the dependent variable and all independent variables is not significant (as is described in Table A3). It was also found that there were multiple collinearity problems, in which the tolerance of P was small and the VIF value was large. Especially when the data of 2006–2010 was processed separately, the tolerance was 0.067 and the VIF value reached 13.08, which means that multiple collinearity is more severe. Furthermore, through the Sobel test, it was found that the economic parameters play a mediating role between the amount of SO_2 removals and abatement costs (Sig < 0.05), while also playing a mediating role between that of SO_2 emissions and abatement costs (Sig < 0.05). Due to the existence of multiple collinearity and mediating effects, the economic parameter was removed from the abatement cost function.

The function of the SO_2 abatement costs for Tianjin was regressively determined (as outlined in Table A4). For the F-test, with sig. 0.016, the linear relationship between the dependent variable and all independent variables was significant, producing a tolerance of 0.962 and a VIF of only 1.039. There was no collinearity problem in this instance. After removing the logarithm, according to Equation (3), the abatement cost function of SO_2 in Tianjin can be obtained in the following:

$$Y_1 = 9 \cdot 10^9 \left(\sum_i \sum_j 2\alpha_j \beta_j (1 - \gamma_{1i}) x_{ij} \right)^{-1.726} \left(\sum_i \sum_j 2\alpha_j \beta_j \gamma_{1i} x_{ij} \right)^{0.746}$$

Similarly, after the abnormal data was interpolated, SPSS software was used to analyze the variables involved in the NO_X abatement cost function. It was also found that the regression coefficient of P to Y_2 was not significant and that there is also a collinearity problem. The economic parameter was removed from the abatement cost function.

The function of the NO_2 abatement costs for Tianjin was regressively determined (as listed in Table A5). For the F-test, with sig. 0.015, the linear relationship between the dependent variable and all independent variables was found to be significant, with a tolerance of 0.777, while for the VIF it was only 1.287. There is no collinearity problem. After removing the logarithm, according to Equation (3), the abatement cost function of NO_X in Tianjin can be obtained in the following:

$$Y_2 = 7.75 \cdot 10^8 \left(\sum_i \sum_j \eta_{ij} (1 - \gamma_{2i}) x_{ij} \right)^{-1.362} \left(\sum_i \sum_j \eta_{ij} \gamma_{2i} x_{ij} \right)^{0.579}$$

4.2.2. Determination of Parameters in Greenhouse Gas Abatement Cost Function

This paper draws on Wu et al. (2019) to improve the DDF-DEA method so as to calculate the provincial marginal abatement cost of CO_2 [2], where the marginal abatement cost of CO_2 in Tianjin in 2016 was 2208.83 yuan/t. After substituting into Equation (10), the abatement cost function of CO_2 in Tianjin in 2016 is as follows:

$$Y_3 = \begin{cases} 0.220883\left(E_3' - E_3\right) & E_3' \geq E_3 \\ 0 & E_3' < E_3 \end{cases}$$

E_3' can be calculated by Equation (3) using the data in Tables 1 and 2, E_3 is function of x_{ij}, as shown in Equation (3).

4.3. Determination of Constraint Parameters in a Collaborative Optimization Model

Corresponding to model 3.13, in terms of the demand constraint, ρ_j is the coefficient of energy converted into standard coal, while the corresponding coefficients of coal, oil, and natural gas were 0.71, 1.4, and 14.3 respectively. D_i constitutes the sector's energy demand, which is expressed in this paper using the standard coal value of the ith sector.

In the supply constraint, S_j is the supply of energy. Coal, oil, and natural gas cannot be supplied indefinitely. However, if the energy supply is set too low, this will result in less space available for energy structure adjustment. Conversely, if the setting is too high, coal, and oil will be substituted by natural gas, which is inconsistent with the realities of natural gas supply. Therefore, this paper set the energy supply at 150% of the total energy consumption in Tianjin in the jth year.

According to the terminal consumption of coal, oil, and natural gas by social sectors of Tianjin in 2016, as well as the coefficients of various forms of energy converted into standard coal, the final consumption amounts of Tianjin in 2016 are shown in Table 2.

Table 2. Final Consumptions of Energies in Tianjin.

Product No.	Sectors	Standard Coal D_i (10^7kg)	Final Consumptions		
			Coal (10^7 kg)	Oil (10^7 kg)	Natural Gas (10^8 m^3)
1	Large-scale agriculture	60.219	20.1	32.82	0
2	Industry	2361.973	707.57	1066.39	25.64
3	Transportation	391.2698	21.48	255	1.33
4	Retail and accommodation	160.496	11.6	27.86	7.92
5	Consumption of living	425.9593	73.83	209.41	5.62
Total		3399.9171	834.58	1591.48	40.51

Source: "China energy statistical yearbook 2017".

5. Results and Discussion

With the model parameters and distance method above, MATLAB can be used to solve the final optimization problem (including 8 constraints and 15 decision variables). Referring to the practice in Reference [28], this section outlines the final results and discusses the importance of different objectives in collaborative optimization, how to adjust energy consumption in different sectors of society to achieve clean and economic collaborative optimization, and the impact of the addition of abatement cost objectives on the optimization scheme.

5.1. Optimization Scheme and Analysis

According to the above method, the emissions of SO_2, NO_X, and CO_2 were 233,000 tons, 261,000 tons, and 700,000 tons, respectively, while the aggregate abatement costs were 15.48 billion yuan (the specific optimization scheme is listed in Table 3). In 2016, the actual emission amounts of SO_2, NO_X, and CO_2 in Tianjin were 260,000 tons, 294,000 tons, and 729,000 tons, respectively, while the abatement costs was found to be 16.10 billion yuan, indicating that the projected environmental and economic benefits obtained by the optimization scheme were much better than those of the current situation (as listed in Table 3).

In terms of the importance of each target, the weight values ω_1, ω_2, ω_3, ω_4 of the four targets in the optimization scheme were 0.21, 0.11, 0.33, and 0.35, respectively. In order to achieve collaborative governance, as well as to improve environmental and economic benefits, it is necessary to focus on abatement costs (especially CO_2 abatement costs) and CO_2 emissions. On the one hand, Tianjin is not only the largest open coastal city in China, but also one of the country's most important industrial cities. The large amount of energy consumption within the city means that its greenhouse gas emissions are high. Tianjin is the only municipality to have participated in low-carbon provinces and cities, greenhouse gas emission lists, and regional carbon emissions pilot, which all involve the challenge of reducing CO_2 emissions. On the other hand, through upgrading industrial infrastructure and promoting the development of high-tech industries, Tianjin has made great contributions to reducing carbon emissions. This region has its reduced emission range and has a relatively high MAC compared to undeveloped regions. According to the calculations of Wu et al., in 2019, the Beijing–Tianjin–Hebei region had the highest shadow price of CO_2 in China, making CO_2 emissions and its abatement costs a priority.

In terms of the governance of air pollutants, the weight of SO_2 (0.21) was higher than that of NO_X (0.11), while SO_2 should constitute the main control object of air pollutants. Tianjin is one of the SO_2 pollution control areas regulated by the state, while the reduction emission of SO_2 began at the start of this century and has since been rolled out fully. The government has taken active measures to promote the use of clean energy and eliminate backward enterprises, while also developing and promoting desulfurization technologies and other specific measures as well. However, due to the development and positioning of Tianjin as an industrial city, it is also necessary to continue to rely largely on fossil fuel-derived energy in order to maintain its economic development level. The energy characteristics of China—abundant coal, limited oil, and scarce gas—make coal an important commodity in Tianjin's energy structure. The SO_2 released by coal combustion accounts for over 90% of the region's total SO_2 emissions. Therefore, Tianjin SO_2 has not yet been fundamentally governed.

Using the corresponding energy allocation scheme (as listed in Table 4), the consumption ratio of coal, oil, and gas (converted to standard coal) was adjusted from the original 17.5%: 65.5%: 17.0% respectively, to 15.8%: 58.4%: 25.8%. In other words, the law that gas should be used instead of oil and coal should be followed in order to cope with the contradiction between the strong growth of energy consumption and the need to reduce environmental damage. Comparing the actual energy consumption data and optimization schemes of various social sectors, we can say that the optimized amount of natural gas used is equal to that of its supply. At this time, the energy allocation scheme is concentrated on increasing the proportion of natural gas in the industrial sector, while the amount of natural gas assigned to the industrial sector is dominant in the overall supply of natural gas. The consumption ratio of coal, oil, and natural gas (converted to standard coal) was also adjusted from the original 21.3%: 63.2%: 15.5% to 13.5%: 49.6%: 37.0%. In the energy structure, the proportion of natural gas used has been greatly increased, meaning that the main source of air pollutants in the industrial sector-SO_2 and NO_X, have been greatly reduced.

5.2. Impact of Abatement Costs Goals

On the basis of previous studies which have focused on collaborative reduction of air pollutants and greenhouse gases from a technical and management level, or unilaterally analyzing abatement costs from an economic perspective, this paper analyzes both emissions and abatement costs to ensure successful outcomes to collaborative governance. In order to analyze the impact of the addition of abatement costs goals on emission reduction effects and energy structure optimization with sufficient depth, the following comparisons are made to analyze the optimization schemes considering both emissions and governance costs and the schemes that only considering emissions.

If only environmental benefits are involved, the emissions of SO_2, NO_X, and CO_2 will be the main control targets, while the weight of abatement costs will be $\omega_4 = 0$. Using the same method, the emissions of SO_2, NO_X, and CO_2 are 220,000 tons, 175,000 tons, and 672,000 tons, respectively, compared with the actual emissions of Tianjin in 2016 (260,000 tons, 294,000 tons, 729,000 tons). At the same time, considering the environmental and economic benefits, gas emissions (233,000 tons, 261,000 tons, 700,000 tons, respectively) are lower, indicating that the emissions of SO_2, NO_X, and CO_2 in the environmental benefit optimization scheme are lower. Furthermore, the addition of economic benefits also limits the improvement level of environmental benefits. In other words, some environmental benefits must be sacrificed in order to improve economic efficiency (as described in Table 3).

In terms of the importance of each target, the weights $\omega_1,\ \omega_2,\ \omega_3$ of the three objectives in the environmental benefit optimization scheme are 0.32, 0.17, and 0.51, respectively. In order to improve environmental benefits, the reduction of greenhouse gas emissions should be prioritized, while SO_2 should be the main control object of air pollutants. Its weight should also be higher than that of NO_X. This observation is similar to the conclusion when considering both environmental and economic benefits, which is also based on the unique circumstances of Tianjin's urban development foundation and positioning.

Table 3. Comparison of optimization scheme and existing scheme.

Product No.	Sectors	Coal (10^7 kg)			Oil (10^7 kg)			Natural Gas (10^8 m^3)		
		Scheme 1	Scheme 2	Before Optimization	Scheme 1	Scheme 2	Before Optimization	Scheme 1	Scheme 2	Before Optimization
1	Large-scale agriculture	17.9	1.4	20.1	33.4	5.6	32.8	0	3.6	0
2	Industry	444.2	1.3	707.6	829.2	1580	1066.4	60.7	10.4	25.7
3	Transportation	116.4	3.1	21.5	217.2	0	255.0	0	27.2	1.3
4	Retail and accommodation	47.7	0.1	11.6	89.1	115.1	27.9	0	0	7.9
5	Consumption of living	126.3	1.8	73.8	235.8	103.2	209.4	0.1	19.6	5.6
Total		752.5	7.7	834.6	1404.7	1803.9	1591.5	60.8	60.8	40.5

Note: Scheme 1 is the optimization scheme considering emissions and abatement costs; Scheme 2 is the optimized scheme considering emissions.

Table 4. Comparison of optimized and existing energy structure.

Product No.	Sectors	Coal%			Oil%			Natural Gas%		
		Scheme 1	Scheme 2	Before Optimization	Scheme 1	Scheme 2	Before Optimization	Scheme 1	Scheme 2	Before Optimization
1	Large-scale agriculture	21.4%	1.7%	23.7%	78.6%	13.0%	76.3%	0.0%	85.3%	0.0%
2	Industry	13.5%	0.0%	21.3%	49.5%	93.7%	63.2%	37.0%	6.3%	15.5%
3	Transportation	21.4%	0.6%	3.9%	78.6%	0.0%	91.2%	0.0%	99.4%	4.9%
4	Retail and accommodation	21.4%	0.0%	5.1%	78.6%	100%	24.3%	0.0%	0.0%	70.6%
5	Consumption of living	21.3%	0.3%	12.3%	78.4%	33.9%	68.8%	0.3%	65.8%	18.9%
Total		15.8%	0.1%	17.5%	58.4%	74.3%	65.5%	25.8%	25.6%	17.0%

Note: Scheme 1 is the optimization scheme considering emissions and abatement costs; Scheme 2 is the optimized scheme considering emissions.

In terms of energy allocation (as outlined in Table 4), compared with the actual consumption data and environmental benefit optimization scheme, the consumption ratio of coal, oil, and gas (converted to standard coal) was adjusted from the original 17.5%: 65.5%: 17.0% to 0.1%: 74.3%: 25.6%. Put simply, natural gas is still the most desired form of fossil fuel-based energy, while coal should be almost completely replaced by oil and natural gas. When considering the environmental and economic benefits simultaneously, the consumption ratio of the three is 15.8%: 58.4%: 25.8%. In other words, in terms of balancing the economic benefits, it is necessary to retain part of the consumption ratio of coal. In view of the current situation in Tianjin, in order to reduce abatement costs, the status of coal within the overall energy structure cannot be completely replaced, which is more consistent with the reality.

At the same time, the environmental benefit optimization program still needs to meet the development needs. However, compared to the optimization scheme that involves both environmental and economic benefits, the energy allocation optimization scheme focuses on the use ratio of natural gas in the transportation sector, in which the natural gas use ratio accounts for 99.4% of its total energy consumption and the fuel consumption ratio is decreased from 91.2% to 0; at the same time, the proportion of consumption of living of coal dropped to almost zero, while the proportion of natural gas increased from 18.9% to 65.8%. This is in line with the fact that natural gas consumption has witnessed explosive growth in recent years, while it is again stated that the emission reduction targets concerning air pollutants are constrained by the supply of natural gas. Higher environmental benefits will be accomplished if the transportation sector's project, "oil to gas" is promoted and the proportion of coal used in daily life is reduced. However, under the premise of limited costs concerning atmospheric control, it is better to satisfy the environmental and economic benefits of the industrial sector by prioritizing meeting the growing demand for natural gas.

6. Conclusions

Previous studies have typically discussed the collaborative emission or abatement costs for air pollutants and greenhouse gases unilaterally, or have instead explored the relationship between energy structure, environmental quality and economic development from the macro level and calculated the effectiveness of energy structure optimization. Considering the differences in the combustion mechanism and pollution production characteristics of fossil energy, such as coal, oil and natural gas, this research used a multi-objective method to construct a collaborative optimization model of the emissions and abatement costs for air pollutants and greenhouse gases. By rationally arranging the energy consumption of different sectors and adjusting the energy structure, the optimization of multiple objects, such as air pollutant emissions, greenhouse gas emissions, and abatement costs can be achieved. In order to verify the effectiveness of the proposed optimization method, this paper took Tianjin as an example, using yearbook data to determine the parameters in the emissions function, the abatement cost function, and the constraints. Finally, the Tianjin collaborative optimization model was found to be effective and the collaborative optimization scheme was also proposed.

Although the validity of the aforementioned model has been verified, there are still some factors that may affect its application in environmental management. Energy costs are often a key affecting factor. The energy characteristics of China—abundant coal, limited oil, and scarce gas—make oil and natural gas supply insufficient and costly relative to coal, which will affect the use of the model. Frequent energy price volatility exacerbates this effect. Energy conversion costs are another influencing factor. For example, in many cases, the switch from coal and oil to natural gas implies additional installation costs and requires the expansion of the pipeline network.

The proposal concerning "Collaborative Governance" in terms of air pollutants and greenhouse gases in developed countries is mainly used to evaluate the welfare effect of greenhouse gas emission reduction policies more comprehensively. China, as a developing country, was chosen due to the characteristics of its economic development and the economic structure of its energy sector. Collaborative governance, in order to realize air pollutants and greenhouse gas reduction emission, plays an essential role in preserving healthy living conditions and managing energy scarcity, while also continuing to succeed in the industrialization process. Atmospheric concerns, such as frequent extreme weather events and the destruction of our ecological balance, are in conflict with the process of industrialization unless processes such as collaborative governance evolve to counter their adverse effects. Collaborative governance based on China's national interests is particularly important, while establishing a unified model framework and data specifications for initiating atmospheric collaborative governance in major regions of China is a topic worthy of further research.

A limitation of this research is only focusing on energy consumption, energy structure and abatement technology, but seldom involves state policy and strategy, and social and cultural factors due to the indirect effects of them on pollutant emissions. Therefore, further research could quantify these aspects in the described model. Another limitation is the algorithm. Although the distance method can effectively solve the multi-objective optimization problem, it also, to a certain extent, reduces the solution space. Furthermore, it also results in a strong dependence on the initial solution. Multi-objective intelligent algorithms (multi-objective genetics, multi-target particle swarms, etc.) and a number of other related methods can be applied to the future research of multi-objective collaborative optimization problems.

Author Contributions: X.Z. conceived and designed the model; X.Z. and X.R. wrote the paper; M.C. and Q.M. critiqued the defects of draft. All of the authors read and improved the final manuscript.

Funding: This research is funded by the National Nature Science Foundation of China (Grant No. 71572096), Shandong University Foundation of Special Research Topics for the 40th Anniversary of Reform and Opening-up, and the 70th Anniversary of the Founding of New China (Grant No. HSS1807).

Acknowledgments: We would like to thank all the students in the research group for giving us many valuable suggestions in the process of our writing.

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

Appendix A. Collection and Organization of Air Pollutants Governance and Macroeconomic Data in Tianjin

The operating costs of complete de-sulfurization facilities were not given before 2006; the emissions of NO_X have not received sufficient attention before 2011; the removal and emission amount of NO_X were only given in the environmental yearbooks of some years and not others; the operating costs of separate de-nitration facilities were also not given, which implies that, since 2011, the construction of de-nitration facilities has been included in the regulations, while the operating costs of de-nitration facilities have been counted separately. In 2016, the abatement costs of SO_2, NO_X, soot, dust, and other waste materials was combined again; the operating costs of separate de-sulfurization and de-nitration facilities were also not given. Therefore, based on the China Environment Yearbook 2007-2016, this paper selects environmental data, such as SO_2 emissions, SO_2 removal amounts, and SO_2 removal costs, for each year from 2006 to 2015, while the NO_X emissions, NO_X removal amounts, and NO_X removal costs for each year from 2011 to 2015 are also selected. Among them, the removal amount represents the difference between the generated amount and the emission amount.

The economic indicators are mainly based on the "Tianjin Statistical Yearbook 2007–2016", using the average wages of on-the-job workers, per capita GDP, fixed assets investment, industrial value-added, and other indicators used to characterize regional macroeconomic and industrial development. The industrial air pollutant emissions, as well as the governance and macroeconomic data of Tianjin, are shown in Table A1.

Table A1. 2006–2015 Tianjin industrial air pollutants governance and macroeconomic data.

	Environmental Indicators						Economic Indicators			
Year	SO_2 Emissions/t	SO_2 Removal/t	SO_2 Removal cost/10,000 Yuan	NO_x Emissions/t	NO_x Removal/t	NO_x Removal cost/10,000 Yuan	Average Wages of on-the-Job Workers/Yuan	Per Capita GDP/Yuan	Fixed Assets Investment/100 million Yuan	Industrial Value—Added/100 million Yuan
2006	232,282	176,665	13,905.3				28,682.00	42,672.00	1849.80	313.47
2007	224,775	164,662	37,077.7				34,938.00	48,591.00	2388.63	408.55
2008	209,844	220,907	82,570				41,748.00	59,463.00	3404.10	774.47
2009	172,980	256,518	92,213.9				44,992.00	63,453.00	5006.32	211.74
2010	217,620	374,014	92,891.8				52,963.00	74,048.00	6511.42	809.21
2011	222,000	357,000	232,651.6	300,404	9174	11,050.5	55,636.00	86,518.00	7510.67	1052.33
2012	215,481	408,428	90,104	275,553	21,847	10,023	62,225.00	94,741.00	8871.31	724.56
2013	207,793	1,218,063	124,620.2	250,646	99,285	23,760.2	68,864.00	101,824.00	10,121.21	582.09
2014	195,395	654,737	140,848.4	216,947	150,843	45,009.9	73,839.00	107,078.00	11,654.09	407.03
2015	154,605	367,668	121,456.3	150,210	93,367	50,476.7	81,486.00	109,916.00	13,065.18	−75.14

Source: China environmental yearbook 2007–2016; Tianjin statistical yearbook 2007–2016.

Table A2. Major economic parameters of Tianjin.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Economic Parameters	1.5625	1.8105	2.1772	2.4318	2.8594	3.1661	3.5223	3.8545	4.1539	4.4619

Table A3. Tianjin SO_2 abatement cost function regression results considering economic parameters.

Model	Meaning	Coefficient	S.D.	t	Sig.
lnθ	Constant	28.916	20.207	1.431	0.202
lnE1	SO_2 emissions	−2.025	1.839	−1.101	0.313
lnR1	SO_2 removal	0.514	0.505	1.018	0.348
lnP	Constant	0.162	0.374	0.432	0.681

Table A4. Tianjin SO_2 abatement cost function regression results.

Model	Meaning	Coefficient	S.D.	t	Sig.
lnθ	Constant	22.921	15.292	2.230	0.061
$\ln E_1$	SO_2 emissions	−1.726	1.179	−2.211	0.063
$\ln R_1$	SO_2 removal	0.746	0.240	2.924	0.022

Table A5. Tianjin NO_X abatement cost function regression results.

Model	Meaning	Coefficient	S.D.	t	Sig.
lnθ	Constant	20.468	3.871	3.871	0.034
$\ln E_2$	NO_X emissions	−1.362	0.271	0.271	0.037
$\ln R_2$	NO_X removal	0.579	0.084	0.084	0.021

References

1. Fu, J.Y.; Yuan, Z.L. Evaluation of Effect and Analysis of Expansion Mechanism of Synergic Emission Abatement in China's Power Industry. *China Ind. Econ.* **2017**, 43–59.
2. Wu, L.P.; Chen, Y.; Feylizadeh, M.R. Study on the estimation, decomposition and application of China's provincial carbon marginal abatement costs. *J. Clean. Prod.* **2019**, *207*, 1007–1022. [CrossRef]
3. Wu, X.C.; Zhao, L.; Zhang, Y.X.; Zheng, C.H.; Gao, X.; Cen, K.F. Cost and potential of energy conservation and collaborative pollutant reduction in the iron and steel industry in China. *J. Appl. Energy* **2016**, *184*, 171–183. [CrossRef]
4. Liu, Y.H.; Liao, W.Y.; Li, L.; Huang, Y.T.; Xu, W.J.; Zeng, X.L. Reduction measures for air pollutants and greenhouse gas in the transportation sector: A cost-benefit analysis. *J. Clean. Prod.* **2019**, *207*, 1023–1032. [CrossRef]
5. Subramanyam, V.; Kumar, A.; Talaei, A. Energy efficiency improvement opportunities and associated greenhouse gas abatement costs for the residential sector. *J. Energy* **2017**, *118*, 795–807. [CrossRef]
6. Wang, Z.; Zhu, Y.S.; Zhu, Y.B.; Shi, Y. Energy structure change and carbon emission trends in China. *J. Energy* **2016**, *115*, 369–377. [CrossRef]
7. Xing, R.; Hanaok, T.; Kanamori, Y.K.; Masui, T.K. Greenhouse Gas and Air Pollutant Emission of China's Residential Sector: The Importance of Considering Energy Transition. *Sustainability* **2017**, *9*, 614. [CrossRef]
8. Yang, W.; Wang, B.; Xiang, D.X.; Lu, T.F.; Yu, J.; Sun, L.S. Study on decomposition and low-carbon development of energy consumption in Wuhan. *China. Ind. Econ.* **2018**, *28*, 13–16.
9. Meng, Q.C.; Rong, X.X.; Zhang, Y.M.; Wan, X.L.; Liu, Y.Y.; Wang, Y.Z. Collaborative Emission Reduction Model Based on Multi-Objective Optimization for Greenhouse Gases and Air Pollutants. *PLoS ONE* **2016**, *11*, e0152057. [CrossRef]
10. Zhou, J.; Mao, X.Q.; Hu, T.; Zeng, A.; Xing, Y.K.; Corsetti, G. Implications of the 11th and 12th Five-Year Plans for energy conservation and CO_2 and air pollutants reduction: a case study from the city of Urumqi, China. *J. Clean. Prod.* **2015**, *112*, 1767–1777. [CrossRef]

11. De Oliveira, J.A.P.; Doll, C.N.H.; Kurniawan, T.A.; Geng, Y.; Kapshe, M.; Huisingh, D. Promoting win–win situations in climate change mitigation, local environmental quality and development in Asian cities through co-benefits. *J. Clean. Prod.* **2013**, *58*, 1–6. [CrossRef]
12. Tsai, Y.T.; Liang, C.J.; Huang, K.H.; Hung, K.H.; Jheng, C.W.; Liang, J.J. Self-management of greenhouse gas and air pollutant emissionsin Taichung Port, Taiwan. *J. Transp. Res. Part D Transp. Environ.* **2018**, *63*, 576–587. [CrossRef]
13. Gu, A.L.; T, F.; Feng, X.Z. Assessment and analysis on co-benefits of pollution control and greenhouse gases emission reduction in key sectors. *J. China Popul. Resour. Environ.* **2016**, *26*, 10–17.
14. Yuan, J.H.; Qu, X.M.; Wang, G.H. Establishing a Framework to Evaluate the Effect of Energy Countermeasures Tackling Climate Change and Air Pollution: The Example of China. *Sustainability* **2017**, *9*, 1555. [CrossRef]
15. Chae, Y. Co-benefit analysis of an air quality management plan and greenhouse gas reduction strategies in the Seoul metropolitan area. *J. Environ. Sci. Policy.* **2010**, *13*, 205–216. [CrossRef]
16. Yang, X.; Teng, F.; Wang, G.H. Incorporating environmental co-benefits into climate policies: A regional study of the cement industry in China. *J. Appl. Energy* **2013**, *112*, 1446–1453. [CrossRef]
17. Islam, M.; Kanemoto, K.; Managi, S. Impact of Trade Openness and Sector Trade on Embodied Greenhouse Gases Emissions and Air Pollutants. *J. Ind. Ecol.* **2016**, *20*, 494–505. [CrossRef]
18. Ma, L.M.; Zhang, X. The spatial effect of China's haze pollution and the impact from economic change and energy structure. *China Ind. Econ.* **2014**, *4*, 19–31.
19. Bilgen, S. Structure and environmental impact of global energy consumption. *J. Renew. Sust. Energ. Rev.* **2014**, *38*, 890–902. [CrossRef]
20. Zhang, S.H.; Worrell, E.; Crijns-Graus, W. Synergy of air pollutants and greenhouse gas emissions of Chinese industries:A critical assessment of energy models. *J. Energy* **2015**, *93*, 2436–2450. [CrossRef]
21. Mohamadpour, T.B.; Hassanzadeh, A.S. A multi-objective model to configure an lectronic reverse logistics network and third party selection. *J. Clean. Prod.* **2018**, *198*, 662–682.
22. Li, H.M.; Wang, J.Z.; Li, R.; Lu, H.Y. Novel analysis–forecast system based on multi-objective optimization for air quality index. *J. Clean. Prod.* **2019**, *208*, 1365–1383. [CrossRef]
23. Zhou, Z.; Xing, Y.Y.; Sun, H.H.; Yu, X.H.; Tan, Z.; Shao, Q. Study on the mechanism setting of $PM_{2.5}$ emission reduction index-A case study on haze control of Beijing-Tianjin-Hebei. *J. Syst. Eng. Theory Practi.* **2018**, *38*, 710–718.
24. Tang, X.B.; Chen, X.H. Mechanism of regional atmospheric pollution collaborative reduction compensation. *China Ind. Econ.* **2017**, *27*, 76–82.
25. Zhou, P.; Zhou, X.; Fan, L.W. On estimating shadow prices of undesirable outputs with efficiency models: A literature review. *J. Appl. Energy* **2014**, *130*, 799–806. [CrossRef]
26. Deb, K.; Miettinen, K. *Multiobjective Optimization: Interactive and Evolutionary Approaches*; Springer: Berlin/Heidelberg, Germany, 2008.
27. Al-E-Hashem, M.S.M.J.; Malekly, H.; Aryanezhad, M.B. Multi-objective robust optimization model for multi-productmulti-site aggregate production planning in a supply chain underuncertainty. *Int. J. Prod. Econ.* **2011**, *134*, 28–42. [CrossRef]
28. Mondal, B. Biodiesel production and fuel properties of three minor tree-borne seed oils. *Banat J. Biotechnol.* **2016**, *7*, 5–16. [CrossRef]