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Environmental and Health Co-Benefits of Coal Regulation under the Carbon Neutral Target: A Case Study in Anhui Province, China

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Abstract: Coal regulation has been implemented throughout China. However, the potential benefits of pollution abatement and the co-benefits of residents' health were rarely assessed. In this study, based on the analysis of historical coal consumption and multiple coal regulation measures in Anhui Province, China, four scenarios (Business as Usual (BU), Structure Optimization (SO), Gross Consumption Control (GC), and Comprehensive Measures (CM)) were constructed to indicate four different paths from 2020 to 2060, which is a vital period for realizing carbon neutrality. The results show that reductions of SO_2, PM_{10}, and $PM_{2.5}$ emissions in the SO scenario are higher than those in the GC scenario, while the reduction of NO_x emission is higher in the GC scenario. Compared with the BU scenario, residents' health benefits from 2020 to 2060 are 8.3, 4.8, and 4.5 billion USD in the CM, GC, and SO scenarios, respectively, indicating that the achievements of coal regulation are significant for health promotion. Therefore, the optimization and implementation of coal regulation in the future is not only essential for the carbon neutrality target, but also a significant method to yield environmental and health co-benefits.

Keywords: energy system; coal regulation; pollution abatement; environmental benefits; health benefits

Citation: Xie, W.; Guo, W.; Shao, W.; Li, F.; Tang, Z. Environmental and Health Co-Benefits of Coal Regulation under the Carbon Neutral Target: A Case Study in Anhui Province, China. *Sustainability* **2021**, *13*, 6498. https://doi.org/10.3390/su13116498

Academic Editors: Wei-Hsin Chen, Alvin B. Culaba, Aristotle T. Ubando and Steven Lim

Received: 3 May 2021
Accepted: 4 June 2021
Published: 7 June 2021

1. Introduction

Coal production and consumption provide strong support for a rapid and stable economic development and resident living in China. In 2019, China consumed 2809.99 Mt of standard coal, accounting for 51.7% of global coal consumption [1]. Coal consumption accounted for approximately 57.7% of the total primary energy consumption in China, a much higher percentage than in developed countries [2]. Compared with renewable energies and natural gas, the rough way uses of coal caused serious environmental pollution [3]. In addition, a large number of epidemiological studies have confirmed that the increase in the concentration of SO_2, NO_x, and particulate matter (PM) in the air will greatly increase the probability of people suffering from various respiratory diseases, and even cause death [4–7]. Faced with this situation, the China State Council issued the "Air Pollution Prevention and Control Action Plan (APPCAP)" in 2013, which focuses on the prevention and control of air pollutants with a focus on fine PM. In 2018, after the completion of the APPCAP, the State Council released the "Three-Year Action Plan for Winning the Battle of Blue Sky", a project that is in line with the APPCAP to further improve the atmospheric environment in China. In addition, the Chinese government has also issued a series of pollution prevention policies, such as the "Guiding Opinions on Promoting Electricity Substitution". In terms of coal regulation, it can be generally summarized as the following two points: first, promote the optimization of the coal consumption structure, accelerate the construction of "coal to electricity" and other related projects, reduce the use of scattered coal, and increase the proportion of thermal coal in coal consumption; second, control the gross of coal consumption, actively develop wind power, hydropower, photovoltaic power generation, and other new types of primary energy, and increase the proportion of non-fossil energy consumption. In 2020, China pledged to reach a carbon peak by 2030 and become carbon neutral by 2060, indicating that the country has to increase its solar and wind capacity massively to substitute coal consumption [8].

In future, the structure optimization and total quantity control of coal consumption will be promoted with more efforts to realize the carbon peak and carbon neutrality. It is significant to assess the potential and effects of coal-related measures in the future, especially the benefits on residents' health in different scenarios, so as to identify the optimized path to achieve an ecological civilization.

Previous studies on coal consumption focus mainly on the following three aspects: (1) greenhouse gases (GHGs) emissions caused by coal consumption [9–11]; (2) the impacts of coal consumption on the atmospheric environment [12–14]; (3) the effects of the coal consumption control policies [15,16]. In terms of GHGs emissions from coal consumption, certain studies only focus on the current estimate of GHG emissions and analyze the influence factors of carbon emissions [17]. Most studies focused on predicting GHG emissions have used the bottom-up method [18], the co-integration method [19], or the system dynamics approach [20]. Other studies attempted to explore ways to limit greenhouse gas emissions in the future through the trade of carbon emission permits and environmental taxes [21–23]. In terms of pollutant emission from coal consumption, most studies focused on analyzing the impacts of coal consumption on the environment from a single sector, due to the difference of emissions from coal utilization in various industries, especially energy-intensive industries, such as thermal power generation [24], building materials [25], and the steel and chemical industry [26,27]. Some studies assessed the potential of industry to reduce pollutants by technological improvements [28]. With the introduction of coal regulation in China, the research on coal regulation has gradually attracted the attention of scholars. Certain studies have explored how the current coal regulation policy has improved the air environment since the release of the APPCAP in China [29,30]. Other studies use game models, a system simulation approach, and other methods to estimate the emission reduction effect of future coal regulation on GHGs and air pollutants based on the simulation of future coal control policies [31–33]. In addition, a few studies have explored the effects of coal regulation policies from the perspective of the health risks to residents [34].

In summary, most of the researches on coal regulation focused on the abatement of pollutant emission, and only a few evaluated the effects of coal regulation on residents' health. In the future, residents' demand for a better living environment is also an important factor to be considered in coal regulation, which deserves more attention.

Anhui Province of China, a typical region to implement coal regulation policies currently and in the future, is selected as the research area. As an inland province in the Yangtze River Delta Region, it has great potential for future development. In addition, Anhui is one of the 14 key coal bases in China due to its huge coal production. The economic development of Anhui is highly dependent on coal. Therefore, assessing the effects of coal regulation is not only essential for Anhui, but also a significant reference for energy transition in other provinces in China. The rest of this paper is organized as follows. Section 2 introduces the research methods and materials, Section 3 gives the research results, Section 4 is the discussion, and Section 5 presents the conclusions of this paper.

2. Methods and Materials

Based on the coal consumption and the structure, economic development, and related coal regulation policies in Anhui in the past 20 years, four coal consumption scenarios were established against the background of carbon neutrality in the future, and the air pollutant emissions caused by coal consumption during 2020–2060 were assessed. Then, we further analyzed the health benefits of coal regulation to residents.

2.1. Methods

2.1.1. Air Pollutant Emissions

There are three methods to calculate the emission of air pollutants: the actual measurement method, the material conservation method, and the empirical calculation method (emission factor method) [35,36]. Considering that the actual measurement method is not easy to undertake and the material conservation method cannot reflect the differences of pollutant emissions from coal consumption in various industries, this study uses the emission factor method to estimate the emissions of various types of air pollutants caused by coal consumption. It mainly considers the emission of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ air pollutants. The air pollutant emissions can be calculated as follows [36,37]:

$$APE_j = \sum_i CC_i \times EF_{ij} \tag{1}$$

where APE_j is the emission of air pollutant j (t); CC_i is the coal consumption in sector/industry i (t); EF_{ij} is the emission factor of air pollutant j in sector/industry i (t/t).

2.1.2. Health Benefits Estimation

The air pollutant concentration model is used to assess health risks caused by air quality. However, this type of model usually needs to consider a series of factors, such as time, climate, temperature, humidity, population density, etc., which cannot be determined based on long-term forecasts. On this basis, some scholars adopted a simplified modeling method by assuming the uniform diffusion of air pollutants in the study area and combining the population intake fraction (IF) to assess the health risks of residents [38,39]. Bennett et al., defined the IF as the proportion of the intake of a certain type of pollutant by the population [40], which is expressed by following equation:

$$Dose_j = APE_j \times IF_j \tag{2}$$

where $Dose_j$ represents the amount of inhaled pollutant j by an individual (t); IF_j represents the population intake fraction of air pollutant j.

This study considered four health outcomes due to SO_2, NO_x, PM_{10}, and $PM_{2.5}$: death, respiratory disease, cardiovascular disease, and asthma, respectively. The health outcomes are assessed by the human inhalation dose and concentration-response relations, which can be determined from Equation (3). The health benefits are estimated by the unit economic valuation of health outcomes h and health benefits as shown in Equation (4).

$$HO_{hj} = Dose_n \times \frac{CR_{hj} \times f_{hj} \times 10^{12}}{365 \times BR} \tag{3}$$

$$HB_{hj} = HO_{hj} \times UV_h \tag{4}$$

where HO_{hj} represents the number of cases with health outcome h caused by air pollutants j (case); CR_{hj} represents the concentration-response coefficient of the health outcome h caused by air pollutants j (case × m^3/ug); f_{hj} represents the baseline of mortality or morbidity incidence rate for the health outcome h caused by air pollutants j; BR is the respiratory rate, and the standard value is 20 m^3/d. HB_{hj} represents the total health benefit lost by the health outcome h caused by the pollutant j (USD), and UV_h is the unit value for the health outcome h (USD/case).

2.2. Materials

2.2.1. Sector Classification of Coal Consumption

Sectors using coal resource in Anhui Province can be divided into two major branches and several specific sectors, as shown in Figure 1. The first branch is transformation sectors. The further processing of coal resources can transform them into secondary energy that can be used clean and efficiently. The second branch includes sectors using coal directly as the terminal energy. In terms of transformation, according to the different processing methods, coal consumption is divided into three industries: the thermal power and heating supply, coal washing, coking and briquettes. In terms of terminal consumption, coal consumption is subdivided into three industrial sectors and residential sector. The primary industry is agriculture. The secondary industry includes building materials, steel, chemical industry, and other manufacturing industries according to the characteristics of products. The tertiary industry consists mainly of transport and storage, hotel and restaurant, and other service industries. The residential sector consists of urban and rural residents.

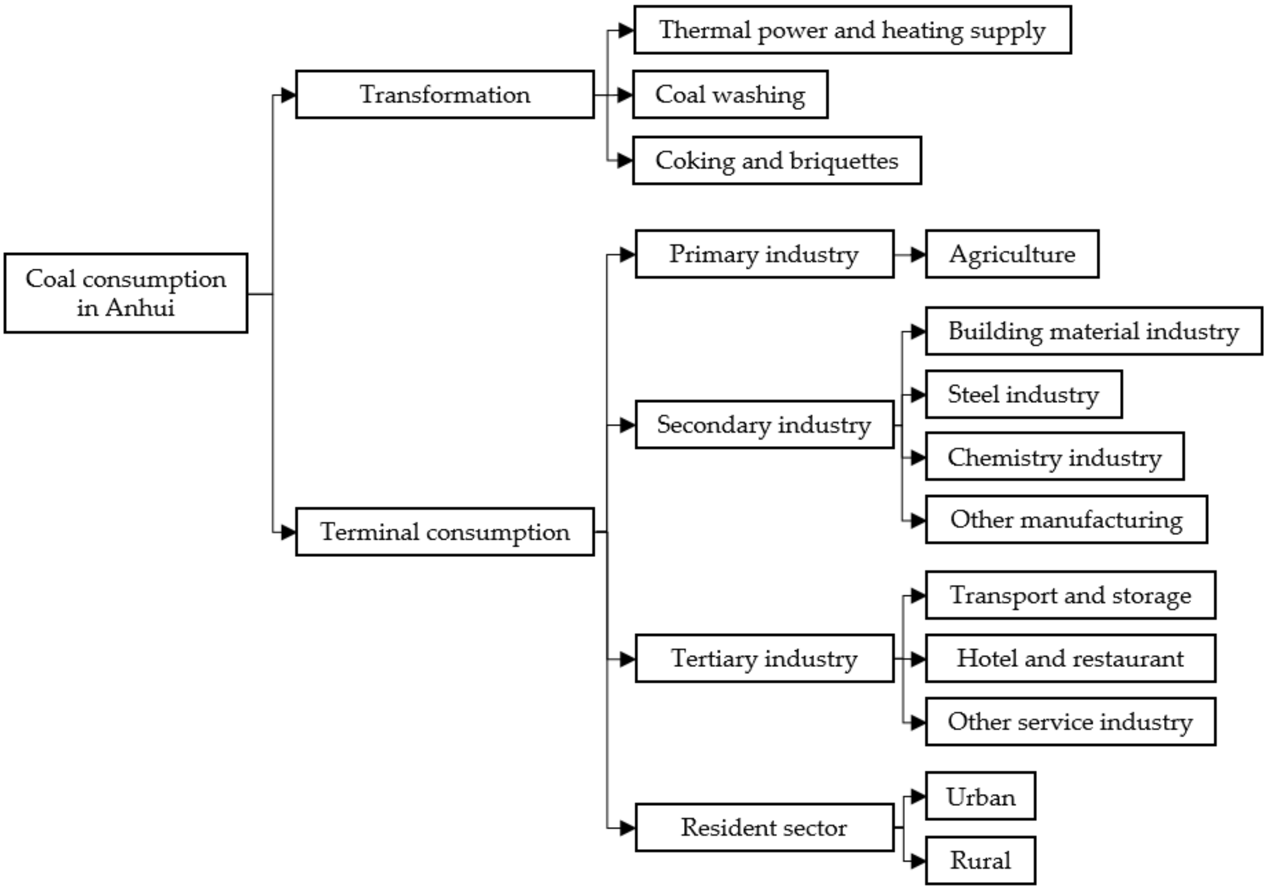

Figure 1. Coal consumption structure in Anhui.

2.2.2. Data Sources

The historical data of coal consumption in various industries (physical quantity) in Anhui are taken from the China Energy Statistical Yearbook and the Anhui Statistical Yearbook [41,42]. The emission factors of coal consumption in different industries are mainly derived from literatures and shown in Table 1. We assume that the emission factors will decrease by 5% every five years due to technological advance and pollution treatment in the future.

Table 1. Emission factors of coal consumption in different industries (Unit: kg/t).

<table>
<tr><th colspan="3">Sector/Industry</th><th>SO_2</th><th>NO_x</th><th>PM_{10}</th><th>$PM_{2.5}$</th></tr>
<tr><td rowspan="3">Transformation</td><td colspan="2">Thermal power and heating supply</td><td>0.65</td><td>0.62</td><td>0.13</td><td>0.11</td></tr>
<tr><td colspan="2">Coal washing</td><td>0.71</td><td>0.92</td><td>2.26</td><td>1.61</td></tr>
<tr><td colspan="2">Coking and briquettes</td><td>0.91</td><td>1.23</td><td>1.45</td><td>1.20</td></tr>
<tr><td rowspan="10">Terminal consumption</td><td>Primary industry</td><td>Agriculture</td><td>8.04</td><td>1.20</td><td>7.16</td><td>5.13</td></tr>
<tr><td rowspan="4">Secondary industry</td><td>Building material industry</td><td>8.40</td><td>2.70</td><td>1.59</td><td>0.76</td></tr>
<tr><td>Steel industry</td><td>6.72</td><td>2.16</td><td>1.27</td><td>0.61</td></tr>
<tr><td>Chemistry industry</td><td>5.38</td><td>2.06</td><td>1.02</td><td>0.49</td></tr>
<tr><td>Other manufacturing</td><td>7.56</td><td>2.43</td><td>1.43</td><td>0.68</td></tr>
<tr><td rowspan="3">Tertiary industry</td><td>Transport and storage</td><td>6.75</td><td>2.30</td><td>2.96</td><td>2.43</td></tr>
<tr><td>Hotel and restaurant</td><td>8.04</td><td>1.20</td><td>7.16</td><td>5.13</td></tr>
<tr><td>Other service industry</td><td>8.04</td><td>1.20</td><td>7.16</td><td>5.13</td></tr>
<tr><td rowspan="2">Residential sector</td><td>Urban</td><td>8.04</td><td>1.20</td><td>13.13</td><td>9.41</td></tr>
<tr><td>Rural</td><td>8.04</td><td>1.20</td><td>13.13</td><td>9.41</td></tr>
</table>

Note: The emission factors of thermal power and heating supply industry come from the "China Power Industry Annual Development Report 2020" [43], while other sectors/industries mainly refer to Gao and Guo's researches [44,45]. Missing data in some industries are adjusted according to the "Practical Manual for Discharge Declaration and Registration" and the "The Second National Pollution Source Census Production and Discharge Accounting Coefficient Manual" [35,46].

In terms of health benefits, the original IF_j were collected from Liu et al. [47]. and adjusted based on Anhui's population density. The IF_j of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ are 3.6×10^{-6}, 25.3×10^{-6}, 29.2×10^{-6}, and 28.9×10^{-6}, respectively, and will continue to be adjusted with the change of population density in the future. The concentration-response coefficient (CR_{hj}) and morbidity/mortality incidence rates (f_{hj}) used in this study were taken from different studies [48,49]. The unit loss of various health risk in the Yangtze River Delta of China was obtained [50] and adjusted according to GDP per capita in 2020, as shown in Table 2.

Table 2. Unit value of different health risks (USD/case).

Health Risk	Unit Loss (Mean and 95% CI)
Mortality	127,591 (119,937, 135,354)
Respiratory hospital admission	835 (765, 896)
Cardiovascular hospital admission	1225 (1052, 1322)
Asthma attack	6 (2, 9)

Note: Adjusted according to GDP per capita in 2020.

2.2.3. Scenario Design

If there is no technological revolution, China's total carbon sink is expected to be about 1.5 billion tons. In 2019, China's carbon dioxide emissions were around 10 billion tons. If the target is to achieve carbon neutrality by 2060, China's fossil energy must be cut to at least one-sixth of the present amount. During 2015–2020, the Anhui government has formulated a series of measures to control coal consumption, including the structural optimization of coal consumption and gross coal consumption control. The coal regulation measures will be implemented sequentially in the future, and are also the main sources to design future coal consumption scenarios.

Based on the government's targets and analysis, we constructed the following four scenarios to evaluate coal consumption in Anhui from 2020 to 2050. The scenarios are (1) Business as Usual (BU), (2) Structure Optimization (SO), (3) Gross Consumption Control (GC), and (4) Comprehensive Measures (CM). The division into four scenarios is shown in Figure 2, and the parameter settings in these four scenarios are shown in Table 3.

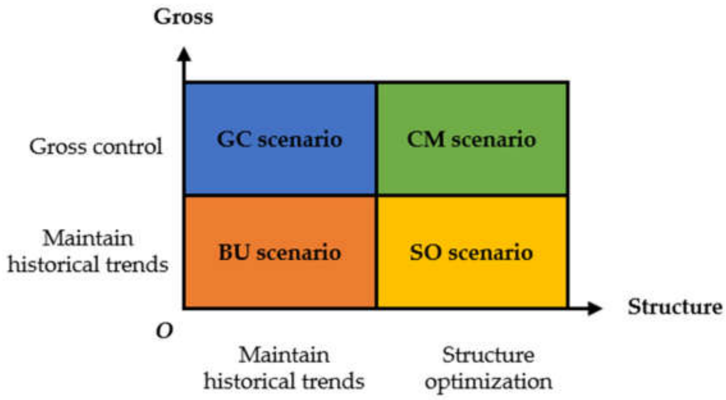

Figure 2. Scenario setting of future coal consumption in Anhui.

Table 3. Parameter setting in the four scenarios.

Gross Coal Consumption	BU Scenario	SO Scenario	GC Scenario	CM Scenario
2020	170 Mt	170 Mt	170 Mt	170 Mt
2025	180 Mt	175 Mt	180 Mt	175 Mt
2030	185 Mt	170 Mt	185 Mt	170 Mt
2040	160 Mt	120 Mt	160 Mt	120 Mt
2050	100 Mt	60 Mt	100 Mt	60 Mt
2060	30 Mt	1 Mt	30 Mt	1 Mt

(1) BU scenario: Anhui will be bound by the commitments made by China in Association of Paris. By developing new primary energy sources, such as hydropower and photovoltaic power generation, and expanding the linkage scale of the "Project of Natural Gas Transmission from West to East China", it will reduce the dependence on coal resources. Coal consumption will reach a peak in 2030 and drop to one-sixth of the current level in 2060. The coal consumption structure will maintain the historical trend.

(2) SO scenario: The trend of total coal consumption in Anhui was consistent with the BU scenario. In the future, the newly introduced coal regulation policy will focus on the control of the consumption of scattered coal. In the terminal coal consumption industry, it will further increase the promotion of the technology for replacing coal with electricity, such as electric boilers, electric kilns, and electric heating, to reduce the proportion of scattered coal consumption [3]. The decline rate of the coal consumption ratio in each terminal industry will be twice that of the BU scenario, and the optimization of the coal consumption structure will be accelerated.

(3) GC scenario: In the future, the coal consumption structure will continue to maintain the historical trend. The newly introduced coal regulation policy will focus on controlling the gross coal consumption. In addition to developing hydropower, photovoltaic power generation, and expanding natural gas consumption, new energy technologies such as hydrogen energy utilization and the co-firing of coal and biomass will be promoted in the future [51]. The province will strive to reach the peak of carbon moderately ahead, leaving a little room to avoid the passive peak situation in 2030. Coal consumption will reach the peak in 2025 and decrease to one-sixth of the current total coal consumption in 2055, realizing carbon neutrality in advance.

(4) CM scenario: It is the combination of the SO scenario and the GC scenario. In the future, the newly introduced coal regulation policies will focus not only on the optimization of the coal consumption structure, but also on the control of gross coal consumption. The decline rate of coal consumption in each terminal industry is over that of BU scenario. In addition, the total coal consumption will peak in 2025 and drop to one-sixth of the current level in 2055, which will guarantee that the national carbon neutrality target can be realized before 2060.

3. Results

3.1. Coal Consumption in Different Scenarios

Based on the simulation of the implementation intensity of the coal regulation policy in Anhui in the future, the coal consumption in the four scenarios established in this study is shown in Figure 3. In the scenarios of BU and SO, the annual coal consumption in Anhui will continue to increase to the peak in 2030 and decrease to 30 Mt in 2060, achieving carbon neutrality and basically realizing the emission reduction commitment made by China. In the GC and CM scenarios, gross coal consumption control will be further strengthened in the future, and China's target of carbon peak and carbon neutrality will be achieved 5 years ahead of schedule, respectively to avoid "passive peak" and "passive neutralization".

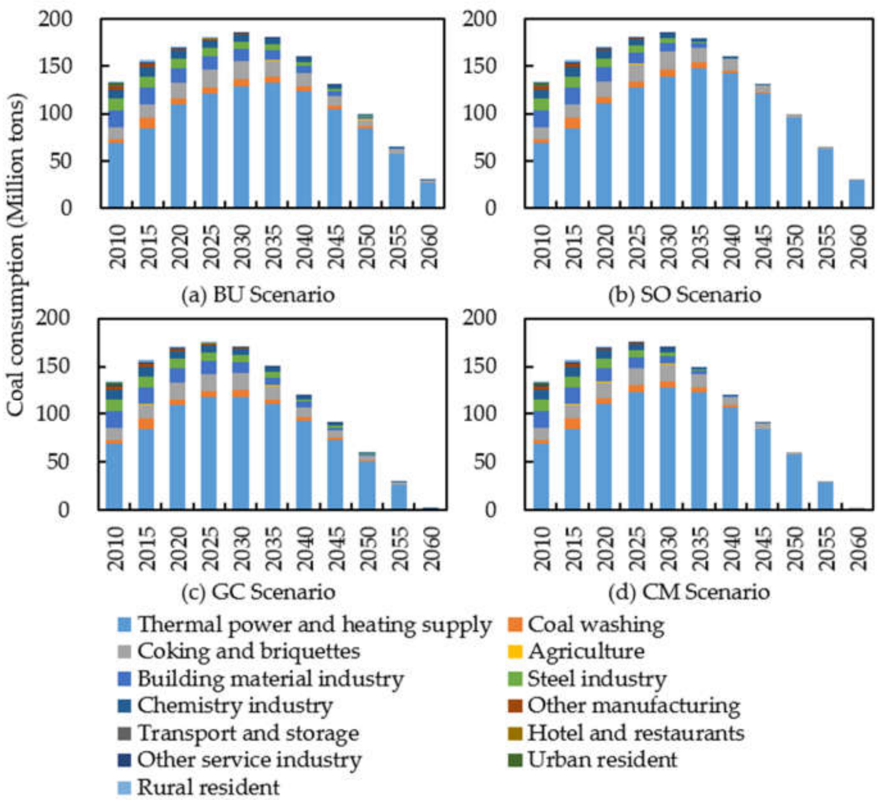

Figure 3. Coal consumption in Anhui in the four scenarios in the future. (**a**) BU Scenario; (**b**) SO Scenario; (**c**) GC Scenario; (**d**) CM Scenario.

The coal consumption in different industries in different scenarios was further analyzed. In the scenarios of BU and TC, the proportion of coal in each industry will maintain the historical change trend. The residential sector will achieve "zero coal consumption" by 2024 and 2028, respectively. Transport and storage and other manufacturing will achieve "zero coal consumption" by 2038. Hotel and restaurant and other service industries are expected to achieve "zero coal consumption" by 2045 and 2046, respectively. The steel industry will achieve "zero coal consumption" by 2059. Building materials and chemical industries with high energy consumption will not achieve "zero coal consumption" by 2060, which indicates that coal regulation policies such as electricity substitution still have great potential for implementation in the secondary industry. In the thermal power and heating supply and coking and briquettes industry, the future annual coal consumption will further increase, indicating that the use of coal will be cleaner and more efficient.

In the SO and CM scenarios, the coal consumption ratio of each terminal industry declines twice as fast as the historical trend. The residential sector will achieve "zero coal consumption" by 2021 and 2023, respectively. The sectors of transport and storage and other manufacturing will achieve "zero coal consumption" by 2028. The hotels and restaurants and other service industries will achieve "zero coal consumption" by 2032. Agriculture will achieve "zero coal consumption" by 2045. The steel, building materials and chemical industries will achieve "zero coal consumption" by 2038, 2041, and 2045, respectively. After 2045, all coal consumption will be used in the transformation sector, and the scattered coal consumption will be effectively eliminated.

3.2. Environmental Benefit Assessment

As can be seen from Figure 4, in all scenarios, the emissions of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ caused by coal consumption will continue to decline from 2020 to 2060. In the BU scenario, even if coal consumption continues to grow during 2020–2030, coal consumption structure can completely offset the increase in pollutant emission caused by the growth of coal consumption.

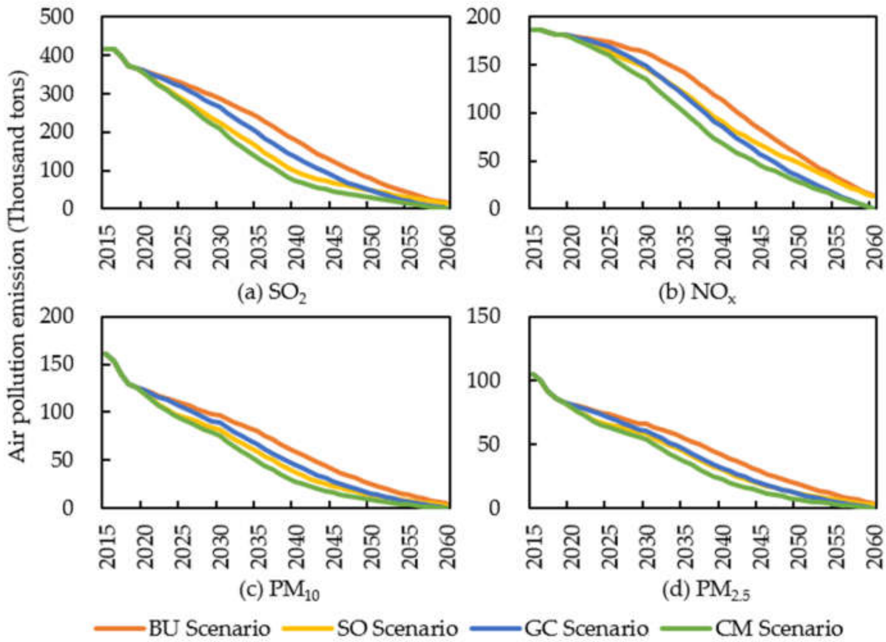

Figure 4. Air pollutants emission in the future four scenarios. (**a**) SO_2; (**b**) NO_X; (**c**) PM_{10}; (**d**) $PM_{2.5}$.

3.2.1. SO_2 Emission Abatement

The variation of SO_2 emissions in the four scenarios are shown in Figure 4a. From the change trend of annual SO_2 emission, the CM scenario has the lowest emission in 2060. During 2020–2050, the annual emission in the SO scenario was lower than that in the GC scenario, and during 2050–2060, the annual emission in GC scenario was lower than that in the SO scenario. The annual emission of SO_2 in the BU scenario is the highest in future. From the perspective of cumulative emissions during 2020–2060, SO_2 emissions in the BU, SO, GC, and CM scenarios are 7.48 Mt, 5.66 Mt, 6.38 Mt, and 4.94 Mt, respectively. The differences indicate that coal regulation can contribute to SO_2 emission reduction. Compared with BU scenario, the cumulative emission reduction of SO_2 in SO scenario is 66.19%. It can be seen that the main factor affecting SO_2 emissions is the coal consumption structure rather than the gross coal consumption. Accelerating optimization of coal consumption structure is one of the effective measures to reduce SO2 emissions in the future.

The SO_2 emissions were further segmented by industry. In 2020, the SO_2 emissions of the building material industry are the highest, adding up to 124.19 kt and accounting for 34.58% of the total annual emission. The thermal power and heating supply industry, which consumes the largest proportion of coal (64.63%), emitted only 71.41 kt. This is because of the implementation of an ultra-low emission reform of thermal power units, resulting in a low SO_2 emission coefficient. The building material, steel, and chemical industries are the key industries to reduce SO_2 emissions in the future.

3.2.2. NO_x Emission Abatement

In the next 40 years, the change trend of NO_x emission caused by coal consumption in the four scenarios is shown in Figure 4b. Similarly to SO_2 emissions, annual NO_x emissions are the highest in the BU scenario and the lowest in the CM scenario. Before 2032, the annual NO_x emissions in the GC scenario are higher than that in the SO scenario, and the emissions in the GC scenario after 2032 are lower than that in the SO scenario. From the perspective of cumulative emissions, NO_x emissions in the BU, SO, GC, and CM scenarios are 4.40 Mt, 3.89 Mt, 3.68 Mt, and 3.28 Mt, respectively. It can be found that gross coal consumption control has a better effect on NO_x emission reduction than coal consumption structure optimization, different from SO_2 emission. To reduce NO_x emission, we must start from the source and control the gross amount of coal consumption. The NO_x emission were segmented by industry. In 2020, NO_x emission are mainly concentrated in the thermal power and heating supply industry, which consume a large amount of coal, accounting for 37.80% of the total annual NO_x emission.

3.2.3. Abatement of PM_{10} and $PM_{2.5}$ Emissions

The emission trends of PM_{10} and $PM_{2.5}$ in the four scenarios in the future are shown in Figure 4c,d. During 2020–2060, the cumulative emissions of PM_{10} in the BU, SO, GC, and CM scenarios are 2.50 Mt, 1.95 Mt, 2.14 Mt, and 1.71 Mt, respectively. The cumulative emissions of $PM_{2.5}$ were 1.72 Mt, 1.41 Mt, 1.46 Mt, and 1.22 Mt, respectively. It can be seen that the emission trend of PM in the four scenarios is similar to that of SO_2, and the emission of PM in the CM scenario is the lowest. NO_x emissions are the highest in the BU scenario. Compared with the BU scenario, the cumulative emission reduction of PM_{10} and $PM_{2.5}$ in the SO scenario was 51.71% and 20.40% higher than that in the GC scenario, respectively. The optimization of the coal consumption structure is also an effective measure to reduce particulate emissions. PM emissions are further divided into industries. In 2020, PM emissions are mainly concentrated in coking and briquettes and the building materials industry. Although the consumption of coal in the residential sector is relatively low, accounting for only 0.62%, the emissions of PM_{10} and $PM_{2.5}$ are 11.18% and 12.09% of the total, respectively. This indicates that the control of PM emissions in the future needs to further strengthen the supervision of the consumption of scattered coal.

3.3. Health Benefit Assessment

From 2020 to 2060, the cumulative number of cases with various diseases caused by coal consumption pollutant emission in the four scenarios is shown in Figure 5. The emission of pollutants from coal consumption leads to the largest number of asthma patients. In the BU scenario, the cumulative number of asthma patients in the next 40 years is up to 6.70 million cases, while in the CM scenario it is 4.75 million cases, with a reduction of 29.03%. The second is respiratory hospital admission. In the BU scenario, the cumulative number of patients will be 0.88 million cases by 2060, which will be reduced by 18.97%, 15.21%, and 29.93% in the SO, GC, and CM scenarios, respectively. The third is cardiovascular hospital admission. The cumulative number of patients in the BU scenario will be 0.40 million cases in the next 40 years, while that in the SO, GC, and CM scenarios will decrease by 16.48%, 15.71%, and 28.54%, respectively. Finally, in terms of mortality, in the BU scenario, the total number of deaths will be 0.23 million cases by 2060, which will be reduced by 14.80%, 16.01%, and 27.52%, respectively, in the SO, GC, and CM scenarios.

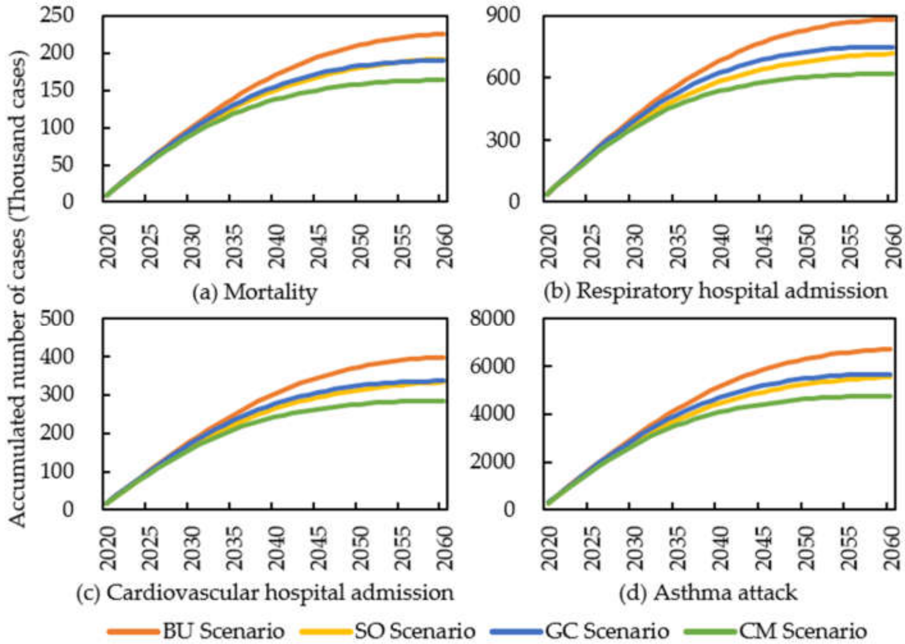

Figure 5. Cumulative number of various diseases in the four scenarios. (**a**) Mortality; (**b**) Respiratory hospital admission; (**c**) Cardiovascular hospital admission; (**d**) Asthma attack.

From the economic perspective of health benefits, compared with the BU scenario, the residents' health benefits of pollutant emission reduction during 2020–2060 in the three coal regulation scenarios are shown in Figure 6. By 2060, the cumulative health benefits of residents in the CM scenario will be the highest, with 8.296 billion USD, followed by the GC scenario, with 4.802 billion USD, and finally the SO scenario, with 4.486 billion USD. It can be further seen that, before 2056, the optimization of the coal consumption structure in the SO scenario has a significant effect on pollutant emission reduction, and the cumulative health benefits of residents are always higher than in the GC scenario. After 2056, the optimization of the coal consumption structure in the SO scenario is basically completed, and the effect of gross coal consumption control on the pollutant emission reduction in the GC scenario begins to be prominent, as the cumulative health benefits of residents exceed those of the SO scenario. In general, coal regulation can achieve significant health benefits for residents.

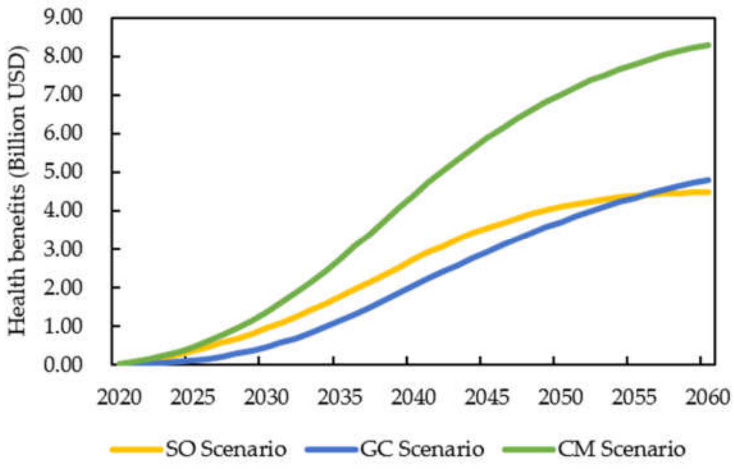

Figure 6. Health benefits of residents in different scenarios of coal regulation.

4. Discussion

4.1. Uncertainty and Sensitivity Analysis

In this study, the uncertainty of parameters will affect the results of the health benefit assessment. The overall uncertainty mainly comes from the following two aspects: (1) estimation of air pollutant emissions; (2) assessment of residents' health benefits.

In the process of pollutant emission calculation, the uncertainty of parameters mainly comes from the selection of the emission coefficients of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ of coal consumption in various industries. However, the different sulfur, nitrogen, and ash contents in coal from different regions, as well as the different installation efficiency of sulfur, nitrogen, and dust removal equipment in the coal utilization equipment of different industries, all have a certain influence on the emission coefficient. At present, there is no authoritative, unified emission factor standard covering all fields needed for this study in the data published in China. We compared and referred to a large number of relevant studies to minimize the error. In addition, in order to be more consistent with the future development of Anhui, we assume that the emission factors of SO_2, NO_x, and PM will decrease by five percentage points every five years.

As for the assessment of the residents' health benefits, the uncertainty of the calculation results mainly involves the selection of the following four parameters: air pollutants in the population intake fraction IF_j; concentration-response coefficient CR_{hj}; mortality/morbidity of related health outcomes f_{hj}; unit economic value of related health outcomes UV_h. The selection of CR_{hj} and f_{hj} is mainly based on the relevant literature research data, and IF_j and UV_h are adjusted according to the number of permanent residents and the level of economic development in Anhui on the basis of relevant studies. As for the assessment of the residents' health benefits, the pollutant concentration (mg/m^3) (non-pollutant emissions (kt)) is usually used to calculate health risks. There is a mismatch between pollutant concentration and pollutant emission, which will be affected by climate, atmospheric environmental factors such as temperature, humidity, and wind direction, therefore the residents' health risk assessment will also have a certain deviation.

To further analyze the uncertainty, the sensitivity analysis of eight parameters involved in the two uncertain aspects of the calculation process is carried out. During each calculation, only one input parameter is changed, and then the residents' health benefits calculated from this parameter are compared with the results calculated without changing the parameters. The sensitivity analysis results of each input parameter are shown in Table 4.

Table 4. Sensitivity analysis of variable parameters on the health benefit.

Parameter	Change Range	Health Benefit Change		
		SO	GC	CM
	Estimation of air pollutant emissions			
SO_2 emission factors	−10%	−1.55%	−0.87%	−1.17%
	10%	1.55%	0.87%	1.17%
NO_x emission factors	−10%	−5.29%	−7.01%	−6.29%
	10%	5.29%	7.01%	6.29%
PM_{10} emission factors	−10%	−2.09%	−1.29%	−1.62%
	10%	2.09%	1.29%	1.62%
$PM_{2.5}$ emission factors	−10%	−1.07%	−0.83%	−0.93%
	10%	1.07%	0.83%	0.93%
	Assessment of residents' health benefits			
Intake fraction IF_j	−10%	−10.00%	−10.00%	−10.00%
	10%	10.00%	10.00%	10.00%
Concentration-response coefficient CR_{hj}	Lower values of 95% confidence	−75.00%	−77.03%	−76.13%
	Higher values of 95% confidence	68.55%	72.45%	70.79%
Mortality/Morbidity f_{hj}	−10%	−10.00%	−10.00%	−10.00%
	10%	10.00%	10.00%	10.00%
Unit economic value UV_h	Lower values of 95% confidence	−6.24%	−6.21%	−6.23%
	Higher values of 95% confidence	6.31%	6.26%	6.28%

When estimating air pollutant emissions, the emission factors of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ of coal consumption in each industry are set to be 10% higher or lower than the original value. The variation of cumulative health benefits of residents in next 40 years in the three coal regulation scenarios are shown in Table 4. It can be seen that when the value of various emission factors is 10% higher than the original value, the residents' health benefits in all coal regulation scenarios will increase. Compared with various emission factors of air pollutants, it is obvious that the NO_x emission factor has the greatest impact on the residents' health benefits. A further analysis of the impact of the uncertainty of pollutant emission factors on the health benefits of residents in various scenarios shows that the uncertainty of the emission factors of SO_2, PM_{10}, and $PM_{2.5}$ are more sensitive to the health benefits of residents in the SO scenario, while the uncertainty of the emission factors of NO_x is more sensitive to the health benefits of residents in the GC scenario.

In terms of the assessment of the residents' health benefits, the concentration-response coefficient CR_{hj} and the unit economic value of related health outcomes UV_h adopted the data with a 95% confidence interval, indicating that the CR_{hj} coefficient had the greatest impact on the residents' health benefits. In addition, the value of the population intake fraction IF_j and the mortality/morbidity f_{hj} of related health results will directly affect the result of residents' health benefits.

4.2. Policy Implications

Although Anhui formulated strict coal consumption control targets, the gross coal consumption is still growing, indicating that it is a tough task. The main reason is that the supporting policies and measures are insufficient. Based on the consideration of environmental and health benefits, the following suggestions are provided for the coal consumption control strategy in the future. Firstly, the government should continue to promote the development of cleaner energies, such as wind energy and solar energy, to reduce the dependence on coal resources. Secondly, it will be useful to allocate annual coal consumption quotas to key enterprises, give priority to enterprises with high energy efficiency and low emissions, and shut down enterprises that do not meet the energy efficiency and emission standards. Thirdly, it is necessary to accelerate the coal consumption structure optimization so as to reduce emissions of SO_2, NO_x, and PM. For enterprises that need energy substitution, fiscal subsidies for equipment replacement are necessary. At present, the building materials, steel, and chemical industries still have a great potential to implement "coal to electricity or gas". Therefore, it is necessary to promote the implementation of "coal to electricity or gas" projects by enterprises. Finally, the government needs to continuously strengthen the monitoring of air pollutant emissions from enterprises and further improve the installation of pollution treatment equipment.

5. Conclusions

Based on historical data analysis and related research on coal regulation policies, this study constructs four scenarios of coal consumption in Anhui from 2020 to 2060. Furthermore, the coal consumption, air pollutant emissions, and effects on residents' health in each scenario are estimated. The main conclusions are summarized as follows.

In the scenarios of BU and SO, coal consumption will continue to increase to the peak in 2030 and decrease to 30 Mt in 2060 to achieve carbon neutrality. In the GC and CM scenarios, the carbon peak and carbon neutrality will be achieved five years in advance, respectively. In the CM scenario, after 2045, all terminal coal consumption industries will completely achieve "zero coal consumption", and coal resources will only be used for transformation.

Air pollutants emissions due to coal consumption are estimated in different scenarios, which will change in different paths. The cumulative emissions of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ during 2020–2060 in the BU scenario are 7.48 Mt, 4.40 Mt, 2.50 Mt, and 1.72 Mt, respectively. Compared with the BU scenario, four types of air pollutants in the SO scenario are reduced by 24.33%, 11.62%, 22.02%, and 18.11%, respectively; and in the GC scenario, they are reduced by 14.64%, 16.50%, 14.51%, and 15.04%, respectively. In the CM scenario, the cumulative emissions of various air pollutants are the lowest in all scenarios, which are 33.92%, 25.54%, 31.56%, and 28.91% lower than those in the BU scenario, respectively. Structure optimization of coal consumption has an obvious effect on the emission reduction of SO_2 and PM, and gross coal consumption control has a better effect on the emission reduction of NO_x.

Residents' health will benefit from reduction of air pollutants emissions due to coal regulation as the number of patients and deaths will be decreased. In the BU scenario, the cumulative number of asthma patients will reach 6.70 million from 2020 to 2060; in the SO, GC, and CM scenarios, it can be effectively reduced by 17.39%, 15.52%, and 29.03%, respectively. From the economic perspective of the residents' health benefits, in the next 40 years, the CM scenario has the highest cumulative health benefits, with 8.30 billion USD, followed by the GC scenario, with 4.80 billion USD, and finally the SO scenario, with 4.49 billion USD. The estimation indicates that coal regulation can achieve significant health benefits for residents.

In summary, reducing coal consumption in China and some key provinces is not only essential for realizing carbon emission peak before 2030 and carbon neutrality before 2060, but also conducive to air quality and health improvement. Technological advance and energy transition in coal-related sectors should be encouraged by government with a strong effort. There are some limitations in this study. We considered the effects of SO_2, NO_x, and PM emissions, but overlooked the impact of other pollutants on residents' health. The intake fraction method was used to evaluate the health benefits of residents, and the results were uncertain to some extent. In addition, the carbon emission permit trading policy that will be promoted in the future will also have a certain impact on coal consumption in Anhui, which should be further explored in future research.

Author Contributions: Conceptualization, W.G. and F.L.; methodology, W.X. and W.G.; software, W.G.; validation, W.G. and W.S.; formal analysis, W.G. and W.S.; investigation, W.G. and F.L.; resources, W.G. and F.L.; data curation, W.G. and W.S.; writing—original draft preparation, W.X. and W.G.; writing—review and editing, W.S. and Z.T.; visualization, W.G.; supervision, W.X. and Z.T.; project administration, F.L.; funding acquisition, F.L. and Z.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (Grant no. 2016YFA0602804) and the Fundamental Research Funds for the Central Universities of China (Grant no. JZ2021HGTB0069).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

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