The evaluation of the development mode of electric energy and air pollution control in Beijing based on the IPAC-SGM model

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Abstract. In recent years, China broke out a large-scale of fog and haze, particularly Beijing. Energy production and consumption of fossil fuel combustion emissions is the main source of environmental pollution and haze, and it is most prominent in the power industry. In this paper, we evaluate the relationship between Beijing power structure and the prevention and control of atmospheric pollution by Integrated Policy Assessment Model for China – Second Generation Model (IPAC-SGM). This paper explores the propulsion effect of the new energy industry on Beijing's air pollution prevention and control by simulating the change of development of electric energy in Beijing under three scenarios which are benchmark scenario, general policy scenario and reinforced policy scenario.

1. Introduction
With the rapid development of China's economy and society, environmental security issues have become increasingly prominent. The air pollution problem has been widely concerned. Beijing air pollution situation is grim, especially the haze problem. In 2015, there were 186 days that air quality reached the standards, accounting for 51% of the year. Heavy pollution had appeared for 46 days, accounting for 13%. The annual average of PM 2.5 of Beijing was concentration of 80.6 micrograms / cubic meter, which was 1.3 times more than the value of national standard, 10 times more than the maximum annual average of the number which World Health Organization recommended. Air pollution brought a significant negative impact on climate, environment, human health and economic development. It is imperative to further strengthen the haze control and improve the air pollution situation.

For a long time, Beijing local power support and heat supply depend on four coal-fired thermal power plants. These plants only have small units with low energy efficiency and serious pollution problems. In recent years, the government has introduced policies to regulate the production of power industry and reduce pollution emissions from electricity production. Beijing will fully shut down coal-fired units and reduce 9.2 million tons’ coal burning and put southeast, southwest, northeast, northwest four gas thermoelectric centers into operation in 2017. When coal-fired power plants complete gas transformation, there will no longer be a new built power plant. At the same time, Beijing also significantly improves clean energy consumption. It is of great theoretical and practical significance to carry out the evaluation of economic model and policy research of air pollution to prevent and control the air pollution and adjust energy structure.
2. Construction and implementation of IPAC-SGM model

IPAC-SGM model is a sub-model of IPAC model (Integrated Policy Assessment Model for China). It is based on computable generality model (CGE) Theory, and joins various economic activities of the association and impact of the medium or long-term energy and environment analysis and various types of energy and environmental policies for economic evaluation and analysis.

2.1. The objective function of IPAC-SGM

In IPAC-SGM model, economic goal is taken as the main objective function, and environmental target as the constraint condition policies as the scenarios. The minimum input cost of power sources is set as the objective function. The objective function is shown in Equation (1):

$$f(X) = C_1 + C_2 + C_3 + C_4 + C_5$$

(1)

$c_1$ represents electricity energy supply costs which mainly refer to the fuel cost of thermal power generation and nuclear power generation:

$$C_1 = \sum_{j=1}^{n} (x_{j,t} \times b_{j,t} \times p_{j,t}) \times \frac{1}{(1+i)^t}$$

(2)

In equation (2), $x$ — the power generation of the $j$th generating unit in the year $t$; $i$ — Discount rate; $b$ — The fuel consumption rate per unit of the $j$th generating unit in the year $t$; $p$ — The first $t$ year $j$ class power unit fuel unit price.

$c_2$ represents new energy input costs which mainly refer to the new energy power generation of fixed capital investment and operation & maintenance costs. For the easy calculation, we take a certain percentage of fixed investment as operation & maintenance costs:

$$C_2 = \sum_{j=1}^{n} (x_{j,t} - x_{j,t-1}) \times M_{j,t} \times \frac{1}{(1+i)^t}$$

(3)

In equation (3), $H$ — annual utilization hours of $j$ type of generating units in $t$ year; $M$ — specific investments of $j$ type of generating units in $t$ year.

$c_3$ represents the marginal cost of traditional energy technology innovation.

$$C_3 = \int_{0}^{G} MC(T_c) dG$$

(4)

In equation (4), $MC$ — the marginal cost of $T_c$ technology for traditional energy, the values of $k$ take 1, 2, 3, 4; $i_1$ — the reform of traditional coal combustion methods to reduce carbon dioxide emissions; $i_2$ — CO$_2$ capture and storage technology; $i_3$ — CO$_2$ capture and utilization technology; $i_4$ — CO$_2$ Capture, Utilization and Storage technology.

$c_4$ represents environmental management costs calculated by the loss of environmental damage:

$$C_4 = \sum_{k=1}^{n_k} \sum_{j=1}^{n} (s_{j,k,t} \times x_{j,t} \times v_{j,k,t} \times \frac{1}{(1+i)^t})$$

(5)

In equation (5), $n_w$ — species number of environmental pollutants; $k$ — the type of pollutants, including SO$_2$, NO$_x$, and soot; $s_{j,k,t}$ — the emission rate of $k$ type pollutants from $j$ type of generating units in $t$ year; $v_{j,k,t}$ — the environmental value of $k$ type pollutants from $j$ type of generating units in $t$ year. $c_5$ represents purchased electricity cost which is the product of the incoming input and the electricity price:

$$C_5 = \sum_{j=1}^{n} e_{j,t} \times p_{j,t}$$

(6)

In equation (6), $e_{j,t}$ — purchased power of $j$ class of electricity in $t$ year; $p_{j,t}$ — purchased power price of $j$ class of electricity in $t$ year.
2.2. Restrictions

(1) Power supply and demand balance constraints. The yearly sum of all types of energy power generation and purchased power is not less than the total amount of electricity demand in Beijing:

\[ \sum_{j=1}^{n} (x_{j,t} \times (1 - \epsilon_{j,t}) \times (1 - \delta_{j,t})) + \sum_{j=1}^{n} e_{j,t} \geq E_t \]  

In equation (7), \( E_t \) — electricity demand of year \( t \); \( \epsilon_{j,t} \) — the electricity consumption rate of \( j \) type of generators in year \( t \); \( \delta_{j,t} \) — line loss rate for \( j \) type of generators in year \( t \).

(2) Technology evolution constraints. Annual activity amount of energy technology is not greater than the product of allowable maximum installed capacity and available factor:

\[ C_{j,t} \leq C_{j,t,\text{max}} \times \pi_{j,t} \]  

In equation (8), \( C_{j,t} \) — annual activity amount of energy technology for the \( j \)th class of energy technology in year \( t \); \( C_{j,t,\text{max}} \) — the maximum installed capacity of the \( j \)th class of generator sets in year \( t \); \( \pi_{j,t} \) — annual utilization coefficient of the \( j \)th class of generator sets in year \( t \).

(3) Environmental Constraints. Carbon emissions and pollutant emissions from all kinds of generating units must be allowed within the maximum emissions:

\[ \sum_{i=1}^{m} x_{j,t} \times b_{j,t} \times E_{j,t} \leq E_{\text{max},t} \]  

In equation (9), \( E \) — carbon emissions and pollutant emissions (respectively carbon emissions, \( SO_2 \), \( NO_x \), and soot emissions) coefficient of the \( j \)th generator in year \( t \); \( E_{\text{max},t} \) — the maximum carbon emissions allowed by all generating units in year \( t \).

2.3. Evaluation index

(1) Low carbon power structure indicators

Low-carbon power structure refers to the installed proportion of non-fossil energy power generation.

\[ \eta_1 = \frac{G_1}{G_2} \times 100\% \]  

In equation (10), \( \eta_1 \) — low carbon power structure indicators; \( G_1 \) — installed capacity of non-fossil energy generating units; \( G_2 \) — total installed capacity of all generating units.

(2) Electricity industry carbon productivity indicators.

Electricity industry carbon productivity refers to the power output generated by carbon emissions of electricity industry. It can directly reflect the efficiency of carbon resources.

\[ \eta_2 = \frac{P}{T} \]  

In equation (11), \( \eta_2 \) — electricity industry carbon productivity index; \( P \) — total power generation; \( T \) — carbon emissions from power industry.

(3) Energy efficiency technical indicators

Energy efficiency technical indicators refer to the average energy consumption value of unit production (expressed by standard coal amount).

\[ \dot{\eta}_i = \frac{L}{G} \]  

In equation (12), \( \dot{\eta}_i \) — energy efficiency technical indicators; \( L \) — total coal consumption of power industry; \( G \) — total power generation of power industry.

(4) Emission indicators

Emission indicators measure carbon emissions and pollutant emissions.
\[ \mu_i = \frac{\gamma_i}{G} \tag{13} \]

In equation (13), \( \mu_i \) — emission indicators; \( \gamma_i \) — total emissions from power industry; \( G \) — total power generation.

3. Scenario setting and model calculation

3.1. Scenario setting

This article sets three scenarios to evaluate the relationship between Beijing power structure and the prevention and control of atmospheric pollution:

**Scenario 1: Baseline scenario.** The Beijing municipal government continues to follow existing policies and adjusts only to certain circumstances.

**Scenario 2: General policy scenario.** The Beijing government seeks energy improvement policies and measures to gradually improve the status of energy use. In 2020, total coal consumption in Beijing will be controlled below 10 million tons and the proportion of clean energy will be more than 7%. By 2030, total coal consumption in Beijing will be controlled below 6 million tons, and the proportion of renewable energy will be more than 10%.

**Scenario 3: reinforced policy-driven scenario.** The Beijing Municipal Government in energy development policy system focuses on the concept of low-carbon environmental protection. Beijing will effort to reduce coal. By 2020, total coal consumption will be controlled below 7 million tons, proportion of clean energy will be more than 10%; by 2030, total coal consumption will be below 3.5 million tons, proportion of renewable energy will be 18% or more.

3.2. Model calculation results and analysis

3.2.1. Power and energy production in different situations. In general policy scenario and reinforced policy scenario, proportions of thermal power structure decrease rapidly, accounting for only 90.9% and 89.6%. In reinforced policy scenario, solar power is encouraged by policies, it grows rapidly from 0.8% in 2016 to 3.69%. Proportion of other clean energy power generation increases gradually. Total proportion exceeds 10% of total power generation. In general policy scenario, new energy power generation also has a certain degree of development, mainly by limiting thermal power development and promoting new energy power generation technology.

3.2.2. Comprehensive evaluation of low-carbon economy development of electric energy

(1) Low carbon power structure indicators

| Table 1. | Structural indicators of low-carbon power supply in Beijing from 2016 to 2020. |
|-----------|--------------------------------------------------------------------------------|
|           | 2016 | 2020 | 2025 | 2030 |
| Benchmark scenario | 0.032 | 0.044 | 0.0522 | 0.0615 |
| General policy scenario | 0.032 | 0.0641 | 0.0740 | 0.0905 |
| Reinforced policy scenario | 0.032 | 0.0712 | 0.0836 | 0.1039 |
It can be seen that proportions of non-fossil energy power generation in general policy scenario and reinforced policy scenario are increasing to around 10% by 2030, while proportion of non-fossil energy power generation structures in benchmark scenario increases only 6.15%. Therefore, some constraints and incentive policies can optimize power structure, reduce pollutant emissions and achieve low-carbon development.

(2) Electricity industry carbon productivity indicators

| Table 2. Carbon productivity indicators of the Beijing electric power industry from 2016 to 2020. |
|--------------------------------------------------|
| 2016 | 2020 | 2025 | 2030 |
| Benchmark scenario | 10.52 | 10.66 | 10.75 | 10.86 |
| General policy scenario | 10.52 | 10.89 | 11.01 | 11.2 |
| Reinforced policy scenario | 10.52 | 10.97 | 11.11 | 11.37 |

From the data in table 2, carbon productivity indicators grow fast in general policy scenario and reinforced policy scenario, which indicates that level of low-carbon development of power industry is high. In particular, in reinforced policy scenario, carbon productivity index in 2020 is close to 11kwh / kg, reaching 11.37kwh / kg in 2030, nearly more 1kwh / kg than level in 2016. It indicates that policies of promoting low-carbon development in power industry bring good effects.

(3) Energy efficiency technical indicators

| Table 3. Technical indicators of energy efficiency in Beijing's power industry from 2016 to 2020. |
|--------------------------------------------------|
| 2016 | 2020 | 2025 | 2030 |
| Benchmark scenario | 370.26 | 364.03 | 360.71 | 357.05 |
| General policy scenario | 370.26 | 356.31 | 352.91 | 345.92 |
| Reinforced policy scenario | 370.26 | 353.77 | 348.81 | 341.13 |

In reinforced policy scenario, energy efficiency technical indicator drops rapidly, from 370.26g / kWh in 2016 down to 341g / kWh in 2030. In this scenario, the Beijing government takes a series of measures, such as shutting down small power generation enterprises, restricting large-scale thermal power plant to reduce energy consumption and emissions, and investing in research and development of new energy power generation technology, promote the development of energy technology effectively.

(4) Emission indicators

Emission indicators response to the effect of power industry's energy-saving emission reduction and low-carbon development. In general policy scenario, the Beijing government requires power generation enterprises to realize low-carbon development, and introduce market mechanism such as carbon emissions trading to promote energy-saving and emission reduction. By 2030, carbon dioxide emissions will reduce to 739.88g/kwh. In reinforced policy scenario, the data will be less 37 g/kwh than that of 2016. At the same time, in general policy scenario and reinforced policy scenario, proportions of pollutant emissions are showing downward trends. It mainly due to the strong constraints on thermal power and the the development of carbon emissions trading. The results show that emission reduction technology and the promotion of new energy power generation technology can reduce carbon emissions to a great extent.
Table 4. Beijing’s power industry emissions of three scenarios from 2016 to 2020.

| Scenario            | 2016  | 2020  | 2025  | 2030  |
|---------------------|-------|-------|-------|-------|
| Benchmark scenario  | $\mu_1$ | 773.21 | 760.16 | 756.28 | 749.62 |
|                     | $\mu_2$ | 3.01   | 2.98   | 2.95   | 2.93   |
|                     | $\mu_3$ | 2.7    | 2.65   | 2.63   | 2.6    |
| General policy      | $\mu_1$ | 773.21 | 748.09 | 742.85 | 739.88 |
| scenario            | $\mu_2$ | 3.01   | 2.94   | 2.93   | 2.91   |
|                     | $\mu_3$ | 2.7    | 2.6    | 2.57   | 2.52   |
| Reinforced policy   | $\mu_1$ | 773.21 | 745.21 | 740.69 | 736.11 |
| scenario            | $\mu_2$ | 3.01   | 2.94   | 2.92   | 2.9    |
|                     | $\mu_3$ | 2.7    | 2.57   | 2.54   | 2.48   |

4. Conclusion

According to the calculation results of the model substitution data, the demand for electric energy in Beijing is increasing under three scenarios, but the change of consumption of standard coal is different. In reinforced policy scenario, coal consumption in power industry will reach peak around 2018, then decline after a period of moderate. Solar power will grow rapidly by encourage policies, from 0.8% in 2016 to 3.69%. The proportion of other new energy power generation has gradually increased. The economic evaluation indicators in three scenarios are in the best position, which indicates Beijing Municipal Government’s efficient impact on varieties of electric power policies. For instance, it forces to abate coal-fired dramatically, takes financial subsidies to encourage construction of clean energy facilities, develops carbon trading, emissions trading and other market mechanisms to improve structure of electric power, sets up a series of low-carbon energy laboratories to develop more efficient using techniques of new energy etc.. All of the policies mentioned above have positive functions and great impacts on the development of electric power and prevention of air pollution in Beijing.

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