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RESEARCH ARTICLE

A system dynamics model of China's electric power structure adjustment with constraints of PM10 emission reduction

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Abstract

Recently, Chinese state environmental protection administration has brought out several PM10 reduction policies to control the coal consumption strictly and promote the adjustment of power structure. Under this new policy environment, a suitable analysis method is required to simulate the upcoming major shift of China's electric power structure. Firstly, a complete system dynamics model is built to simulate China's evolution path of power structure with constraints of PM10 reduction considering both technical and economical factors. Secondly, scenario analyses are conducted under different clean-power capacity growth rates to seek applicable policy guidance for PM10 reduction. The results suggest the following conclusions. (1) The proportion of thermal power installed capacity will decrease to 67% in 2018 with a dropping speed, and there will be an accelerated decline in 2023–2032. (2) The system dynamics model can effectively simulate the implementation of the policy, for example, the proportion of coal consumption in the forecast model is 63.3% (the accuracy rate is 95.2%), below policy target 65% in 2017. (3) China should promote clean power generation such as nuclear power to meet PM10 reduction target.

Keywords The adjustment of electric power structure · PM10 · System dynamics · Air-pollution reduction policy

Introduction

In recent decades, the air quality of China has dropped dramatically owing to coal consumption, motor vehicle exhaust, and scattered coal combustion. As terrible haze days appeared frequently, the air pollutant prevention has become the most notable issue in China. Data from CAS (Chinese Academy of Sciences) indicates that the main sources of PM10 emissions in Beijing are secondary inorganic aerosols and industrial pollution, and they account for 50% of total PM10 emissions, followed by coal consumption (18%) and others (biomass burning and automobile exhaust, etc.) (Guo et al. 2015). Coal combustion, which causes secondary inorganic aerosols and industrial pollution, seems to be the chief culprits of PM10. And thermal power industry is the major consumer of coal resources. According to the statistics published by China's National Bureau of Statistics in 2016, China's electricity industry coal consumption was 1879 million tones, accounting for about 70% of the total coal consumption. In order to realize PM10 emission reduction, adjusting energy structure and controlling coal consumption all be China's first priority during the 13th five-year plan. Under this environment, the proportion of clean energy will keep increasing. But, the approval of newly added thermal power projects will not stop to ensure stable power supply.

Under the restriction of environmental protection policy, the air quality in China has been improved, but there is still a certain distance from the current environmental conditions to ideal one, especially the concentration of PM10 and other particles that is seriously exceeded. China with a characteristic of rich in coal but lack of oil and gas, coal is the major energy source in energy structure and it is mainly consumed by the electric power industry. Therefore, the power system reformation is necessary to improve environmental pollution in China. The Chinese government has introduced some policies to

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control air pollution, but the results of these policies are unknown, so we should use some comprehensive methods to simulate the dynamic process of power structure adjustment driven by emission-reduction policies. The dynamic evolution process of power structure adjustment is complex and closely related to many fields, it has nonlinear characteristics. The system dynamics (SD) has advantages of integrity and dynamics, and it can simulate the real behavior of the market and explain the relationship between variables (Li and Sun 2013). Taking into account these advantages, we should set up a complete SD model by analyzing technical factors, such as PM10 emission from coal combustion, and economical factors, such as denitration subsidies of electricity price and renewable energy generation with constraint of PM10 emission to seek the applicable solution of electric power structure adjustment.

After analyzing the relationship between China's power industry and PM10 emissions, a complete SD model is built to simulate China's evolution path of power structure with constraints of PM10 reduction considering both technical and economic factors. The simulated results enable us to predict the developing trend of China's power industry and air quality. Further scenario analyses using SD method are conducted under different clean-power capacity growth rates to seek applicable policy guidance for PM10 reduction. The SD model we built provides a realistic platform for predicting China's power structure transformation and PM10 emission control.

Literature review

Some scholars are interested in the linkage between energy policies and environmental pollution. In the past years, China's related policies about power industry have led excessive investment in thermal power installed capacity and low efficiency (Peggy and Kenneth, 2014). Awareness of energy saving and emission reduction is continuously strengthening, in order to promote the transformation of energy structure the state council of China that has promulgated some effective policies and controls the excessive development of high energy-consuming industries such as thermal power industry. The implementation of China's sustainable development policies can result in CO_2 (Tan et al. 2014; Wen and Li 2014; Wang et al. 2007) and SO_2 (Zhang et al. 2014) abatement currently. Coal-fired power structure may translate into clean and efficient energy power such as nuclear power (Zheng et al. 2013). Encouraged by the adjustment of energy structure, China's renewable energy development is greatly improved (Cai et al. 2007). The fossil-fuel utilization declines as the increase of renewable energy utilization (Mathews and Tan 2013). It is worth noting that at current stage, the thermal power is the current domestic main form of energy power generation. We should not only study the emission of carbon dioxide (Wang et al., 2007) and some models of carbon emissions (Zhou et al. 2017; An et al. 2016; Duro and Padilla 2014), but other harmful gases and respirable particulate matter is also needed to pay attention to, so this article seeks applicable policy guidance for PM10 reduction.

With the deterioration of air quality, people pay more and more attention to the emission of air pollutants. Airborne particulate matter (PM) now exceeds sulfur dioxide and nitrogen oxides to become principal urban pollutant in most major cities of China (Yao et al. 2010). Some scholars have discussed the sources of inhalable particles in the atmosphere; they find that coal-fired electric power is one of the sources of inhalable particles (Zhao et al. 2010; Sui et al. 2016). Monte Carlo simulation can quantify the uncertainties of atmospheric pollutants in China (Zhao et al. 2011). Some studies have estimated the emission of inhalable particles from the harbor (Song and Shon 2014). However, they do not take the local policy factors into account, and the system dynamics model in this paper solves to do it.

The power industry is also a complex system which is often analyzed by using system dynamics, for example, the renewable energy power generation industry. SD model shows the complex logical relationship between the feed-in tariffs (FIT) and renewable portfolio standards (RPS) and reveals the process of coordination between the two policy tools in the development of the renewable energy power industry (Zhang et al. 2017). The combination of system dynamics and vector autoregressive (VAR) model can be used to study the clean development of power supply structure (Song et al. 2017). Some scholars in electricity and energy sector often used Long-Range Energy Alternatives Planning (LEAP) model to study energy conservation and emission reduction (Betulozer and Selahattin 2013). But, the dynamic behaviors of thermal power system and the complicated feedback of coal system are not included in these studies. Regional energy system is complex and uncertain, so the inexact two-stage dynamic programming model is also useful for regional electricity operation management (Li et al. 2014), but the situation considered in this model is more single when compared to the system dynamics model.

The SD approach has been considered in the sustainable management of power systems, while it has not been addressed in the adjustment of electric power structure. Scholars use SD methodology to simulate the process of energy efficiency improvement (Li and Sun 2013), and the development strategy (Sheikhifini et al. 2014; Zhu and Huang 2013; Salman and Tahar 2013) and behavior of the renewable energy sectors (Grcia et al. 2013; Liu et al. 2014). SD models are also widely used in energy conservation and emission reduction policies in electricity industry (Zhao et al. 2013; Saysel and Hekimogiu 2013), in traditional industry (Li et al. 2012; Nastaran and Abbas 2013), and in a specific city (Feng et al. 2013). Regional Integrated Assessment Tool (RIAT+) has been used to study how to improve air quality and help policy-maker make reasonable decisions. Some results show that the average concentrations of PM10 and NO2 were decreased under the control of reasonable air quality indicators (Relvas et al. 2017a). In order to explore the effect of energy construction adjustment on environment, the nonlinear dynamics theory can be used to analyze the dynamic behavior of the novel system (Fang et al., 2017). Similarly, a study analyzed the impact of coal-consumption control and pollutants emission reduction scenarios on energy system structure adjustment, and the results are valuable for the adjustment of power generation schemes in regional energy systems (Xie et al. 2017).

Evaluating the effectiveness of air pollution policy has vital implications for helping formulate effective emission control policies in China and other countries (Li et al., 2017). The use of modeling tools to support decision-makers to plan air quality policies is widespread in Europe (Relvas et al. 2017b); these methods have important reference for this paper. To improve air quality, China has continuously introduced several air-pollution reduction policies, which selected the specific goals of PM10 emission and coal reduction. Therefore, a SD model is needed to analyze the process of China's current energy structure adjustment under the changing policy environment.

By summing up, we can find that most of the researches use the system dynamics model to analyze the relationship between energy development and related policies, the dynamic change of power system, and the relationship between energy and environment. However, not only our research takes into account the above three aspects, but also the constraints of emissions and technical factors such as desulfurization and denitrification are considered. All of which are not available in the past research, which is the innovation of this paper.

Methods

Causal loop diagram

SD is a systems model and dynamic simulation methodology for analysis of dynamic complexity in socio-economic systems (Betulozer and Selahattin 2013), and the control and feedback effect between system variables (Zheng et al. 2013). Some quantitative models can be used for simulation analysis, but the SD model can better simulate the development process of China's power system (Guo and Wei 2016), due to its systematicness and dynamics. Thus, SD model has obvious advantages in solving dynamic problems, reflecting the process of power structure adjustment, and analyzing the influence of PM10 emission-reduction policies to thermal power and coal consumption. So, this study established a SD model to simulate the dynamic interactions of power industry and coal industry during the structure adjustment.

Previous researches concern too much about national economic factors (Yan et al. 2018) but ignore technical factors (Du et al. 2018). Our work creatively integrated technical factors of desulfurization, denitration, and PM10 emission estimation into common SD model to ensure the accuracy of simulated results.

To accelerate the control of air-pollution and improve the livelihood of people, the Chinese government has introduced many laws managing the power industrial structure since year 2012. The current air pollution is serious in China, we should vigorously develop clean energy, optimize the industrial layout and energy structure, under the guidance of the 12th five-year plan. In June 2013, *the Ten Measures for the Control of Air Pollution has been promulgated, which stressed that it is necessary to* control high energy-consuming enterprises and strengthen the emissions reduction mechanism of incentive and constraint. In September 2013, the Action Plan for the Control of Air Pollution (Action Plan for short) clearly points out the PM10 emission target.

Most of these China's air-pollution reduction policies clearly pointed out the adjustment of energy structure and the promotion of clean energy. The proportion of coal consumption in total energy consumption should be reduced to less than 65% by year 2017. The ever-changing policy environment will surely have far-reaching impact on China's power structure. Facing the ever-shifting constraint which brings by policy environment, it is necessary to establish a dynamic model to analyze China's current power structure. Considering the advantages of integrity and dynamics, this study established a SD model to simulate the process of power structure evolution. According to the above policy analysis, PM10 emission-reduction policies will influence the dynamic system from seven respects:

1. Prohibit inferior coal import.
2. Prohibit new coal-fired power projects.
3. Shut down small thermal power units.
4. Promote clean-power generation.
5. Promote the use of clean coal.
6. Implement unit transformation of energy-saving.
7. Implement desulfurization and denitration renovation.

What we need to explain is that economic growth as an important factor in all walks of life is affected; it will lead to the change of energy demand and power market and then affect the thermal power and the coal industry, so data selected in this paper have been taken into account of economic factors, but there is no single list of economic growth factors.

In the long-term, these PM10 emission reduction measures will help adjust China's power structure. Figure 1 shows the causality loop of electric power structure adjustment under air-pollution. Causality loop diagram is a directed graph applied to analyze the interaction relationship between the different variables of dynamic system. Causal loop consists of reinforce chain. Reinforce chains expressing positive influence are called positive chain with "+" arrows. Reinforce chains expressing negative influence are called balance chain with "−" arrows. Main loops in this SD model are shown in Fig. 1.

1. Coal loop

The coal loop mainly analyses the interaction of coal industry. Air-pollution policies limited PM10 emission and coal consumption, by shutting down small thermal power units and limiting the approval for thermal power project. Further, the decline of coal consumption will lead to the decline of coal demand and its increasing rate. The profit and production investment of coal industry may suffer the impact of coal-demand decline as well. The ban of inferior-coal import will lead to a slight decline in coal supply. The fluctuation of coal supply-demand ratio will affect the coal price and decide fuel costs of thermal power enterprises. To achieve the PM10 emission goal, thermal power enterprises have to burn cleaning coal. It will accelerate the coal cleaning rate and squeeze the profit of coal industry.

2. Installed capacity loop

Under the constraints of PM10 emission reduction, there are many reasons that can reduce the construction of thermal power. These reasons include the retirement of small-capacity thermal power unit, the ban against thermal power projects, the shrinkage of thermal power profits and the policy guidance. On the other hand, these air-pollution reduction policies will promote clean energy. With the rapid growth of clean-energy projects, the proportion of thermal power will be greatly reduced.

3. Energy loop

The pressure of PM10 emission reduction will promote energy-saving reconstructions. The enhancement of energy-saving ability can bring down the coal consumption rate. And, the better result is that coal-consumption will be further reduced and gradually replaced by clean energy.

4. Desulfuration and denitration loop

The main gaseous pollutants which can translate into PM10 are NOx and SO2 (Claudio et al., 2010). Under the

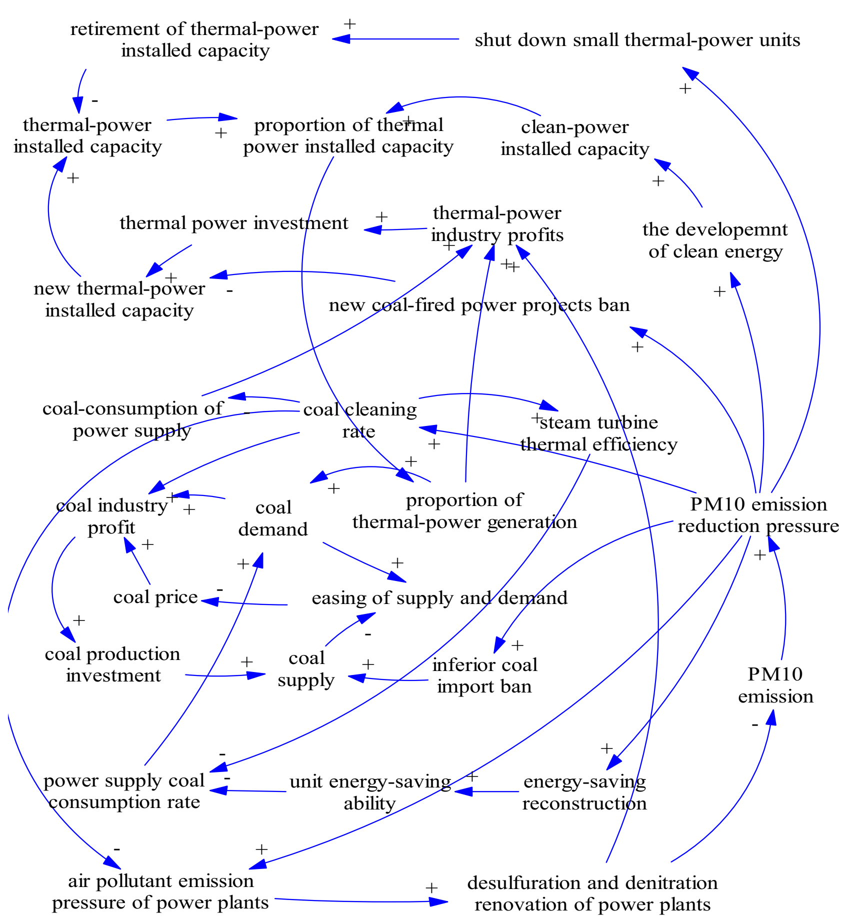


Fig. 1 Causality loop of electric power structure adjustment under PM10 emission reduction

high pressure of PM10 emission reduction, the government intends to push forward the desulfuration and denitration renovation by raising desulfuration and denitration feed-in tariff and subsidies proportion. Desulfuration and denitration renovation can relieve the PM10 emission reduction press and lower the intensity of relevant policies. And, the feed-in tariffs can increase thermal power profits to some extent.

Flow diagram

After drawing the causal loop diagram, we built a diagram of China's power structure adjustment with constraints of PM10 emission reduction, as shown in Fig. 8, using Vensim software. Variables showing cumulative results are set as state variables (shown in boxes). Variables showing changing rate of state variables are set as rate variables (which were shown with double triangles). The rest are set as auxiliary variables. The model parameters and its initial values are listed in Table 1.

Data in this paper were collected from China Energy Statistical Yearbook, China Environmental Aspect Bulletin, China Statistical Yearbook, and China Weather Bureau. In order to simulate the electric power structure adjustment under the constraint of PM10 emission reduction, we used Vensim_PLE software in this study (as shown in Fig. 2).

The direction of arrow indicates the influence interaction between those parameters. The flow graph is suitable for modeling the cause and effect relations between various components. Due to the limited length of the article, we only enumerated the functional relationships with great significance in this paper. The modeling details of subsystems are described in the following sub-sectors.

PM10 emission subsystem

To stimulate the PM10 emission of China, especially the PM10 emission of power industry, we built the PM10 emission subsystem, as shown in Fig. 2. The main gaseous pollutants which can translate into PM10 are NOx and SO2 (Claudio et al., 2010). A receptor model has been developed which enables the PM10 concentration to be divided into three components: primary combustion particles, secondary particles, and other particles (John, 1997; John et al. 2001). NOx measurements and sulfate (transferred from and calculated by SO2) measurements are used as indicator for primary particles and secondary particles, respectively (John, 2002). Other particles which are primarily made up of resuspended dust and sea salt are not research focused in this paper. We focus on how to reduce PM10 emission by controlling its gaseous pollutants source (SO2 and NOx) released from the coal-fired process of power units. From the perspective of source control, SO2 and NOx should be reduced by certain percentage in order to meet the PM10 emission targets set by Action Plan.

Equation (1) is used to represent the function of SO2 emission, and Eq. (2) is used to represent the function of NOx emission.

$$emission_{SO2} = 1.6 \times coal_p \times content_S \times \left(1 - \frac{capacity_{DS}}{capacity_{thermal}} \times efficiency_{DS}\right) \quad (1)$$

$$emission_{NOx} = 1.63 \times coal_p \times (content_N \times conversion_N + 0.00938) \times \left(1 - \frac{capacity_{DN}}{capacity_{thermal}} \times efficiency_{DN}\right) \quad (2)$$

where $emission_{SO2}$ is the SO2 emission of thermal power industry (100 t), $emission_{NOx}$ is the NOx emission of thermal power industry (100 t), $coal_p$ is the coal consumption of power industry (million ton), $content_s$ is the average sulfur content of coal, $content_N$ is the average nitrogen content of coal, $conversion_N$ is the nitrogen oxide conversion rate of nitrogen in coal, $capacity_{DS}$ is the installed capacity of desulfuration capacity (million MW), $capacity_{DN}$ is the installed capacity of denitration capacity(million MW), $capacity_{thermal}$ is the thermal power installed capacity (million MW), $efficiency_{DS}$ is the average coal desulfuration efficiency, and $efficiency_{DN}$ is the average coal denitration efficiency. China's average sulfur content of coal is about 1.5%, and coal desulfurization

Table 1 Description of key parameters

Parameter	Unit	Initial value	Data source
Domestic coal production	Million ton	3573.5	China Statistical Yearbook (2012)
Energy-saving capacity of thermal power unit	Million ton	30,000	Information Distributing Platform of China Electricity Council
Hydropower and other power installed capacity	MW	323,940	Information Distributing Platform of China Electricity Council
Total SO_2 emission	Million ton	21.17	China Environmental Aspect Bulletin (2012)
Total NO_x emission	Million ton	23.38	China Environmental Aspect Bulletin (2012)
Thermal power installed capacity	MW	81,900	Information Distributing Platform of China Electricity Council
Amount of clean coal	Million ton	2050	Information Distributing Platform of China Coal Market Online
Desulfuration capacity	MW	753,480	Information Distributing Platform of China Electricity Council
Denitration capacity	MW	226,044	Information Distributing Platform of China Electricity Council

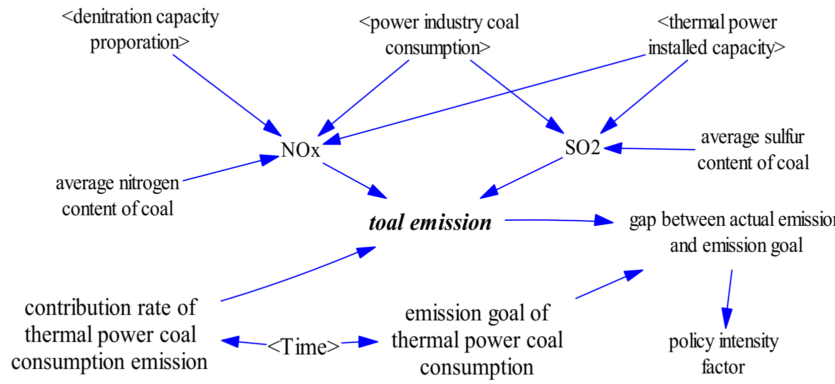


Fig. 2 Flow diagram for PM10 emission subsystem

efficiency is about 90%. China's nitrogen content of coal is in the range of 0.8~1.8%, and the average is about 1.5%. The nitrogen oxide conversion rate of nitrogen in coal is 25%, and China's coal denitration efficiency is about 48% (Zhang and Liu 2008).

Equation (3) is used to represent the function of PM10 emission goal, where $emission_{target}$ is the target of China's annual air-pollution emission (million ton), only being decided by time. The total amount of SO2 and NOx emission in China is 44.55 million t. Action Plan pointed out that the concentration of PM10 should be 10% lower than 2012 until 2017. As the sources of primary combustion particles and secondary particles, SO2 and NOx should be reduced by the same percentage in order to meet the PM10 emission targets. We assume that the combined emission will drop at a constant speed in 5 years and keep this speed that continues to drop in the following decades.

$$emission_{target} = 44.55 \times (1{-}2\% \times (Time{-}2012)) \tag{3}$$

Equation (4) is used to represent the intensity of China's PM10 reduction policy, where $emission_{total}$ is the total emission (100 t) decided by SO2 and NOx emission. We use the gap between realistic emission and emission target to decide the following policy intensity. If the total emission exceeds the goal, then the more difference between the goal and reality, the more severe measures of emission-reduction policies are.

$$intensity = IF\_THEN\_ELSE\left(\left(emission_{total}-emission_{target}\right) < 0, 1, 1 + \left(emission_{total}-emission_{target}\right)/emission_{target}\right) \tag{4}$$

Thermal power subsystem

To stimulate the thermal power industry of China, we built the thermal power subsystem, as shown in Fig. 3. We assume that thermal power generated energy accounts for a time-varying proportion of total generated energy. Thermal power industry will use part of their profits to invest newly added installed capacity.

Equation (5) is used to represent the average thermal power electricity price. Where $purchase_{grid}$ is grid purchase of thermal power containing desulfurizing price, $subsidies_{DS}$ is desulfuration subsidy, and $subsidies_{DN}$ is denitration subsidy. We assume that the average thermal power price is the weighted average of the desulfurization and denitration electricity price, desulfurization electricity price, and non-desulfurization electricity price, and the weight is the relevant installed capacity.

$$\begin{aligned} price_{thermal} &= \left(purchase_{grid} + subsidies_{DN}\right) \times \frac{capacity_{DN}}{capacity_{thermal}} \\ &+ purchase_{grid} \times \left(\frac{capacity_{DS}}{capacity_{thermal}} - \frac{capacity_{DN}}{capacity_{thermal}}\right) \\ &+ \left(purchase_{grid} - subsidies_{DS}\right) \times \left(1 - \frac{capacity_{DS}}{capacity_{thermal}}\right) \end{aligned} \tag{5}$$

Equation (6) is used to represent thermal power installed capacity, where $capacity_{thermal}$ is the installed capacity of thermal power and $capacity_{else}$ is the installed capacity of hydropower and wind power et al.

$$\begin{aligned} capacity_{thermal}(t) &= capacity_{thermal}(t-dt) \\ &+ (capacity\_increasing_{thermal} - capacity\_reduction_{thermal})dt \end{aligned} \tag{6}$$

Equation (7) is used to represent the proportion of thermal power installed capacity. An integral function was used to describe thermal power installed capacity. Thermal power installed capacity at time t ($capacity_{thermal}(t)$) depends on the capacity at time $t-dt$, thermal power installed capacity increasing rate ($capacity\_increa\sin g_{thermal}$) and reduction rate ($capacity\_reduction_{thermal}$).

$$proportion_{thermal} = \frac{capacity_{thermal}}{capacity_{thermal} + capacity_{else}} \tag{7}$$

Coal subsystem

To stimulate the coal supply and demand of China, we built the coal subsystem, as shown in Fig. 4. We assume that China's coal price depends on coal supply and demand ratio. And, the coal consumption of power industry is influenced by

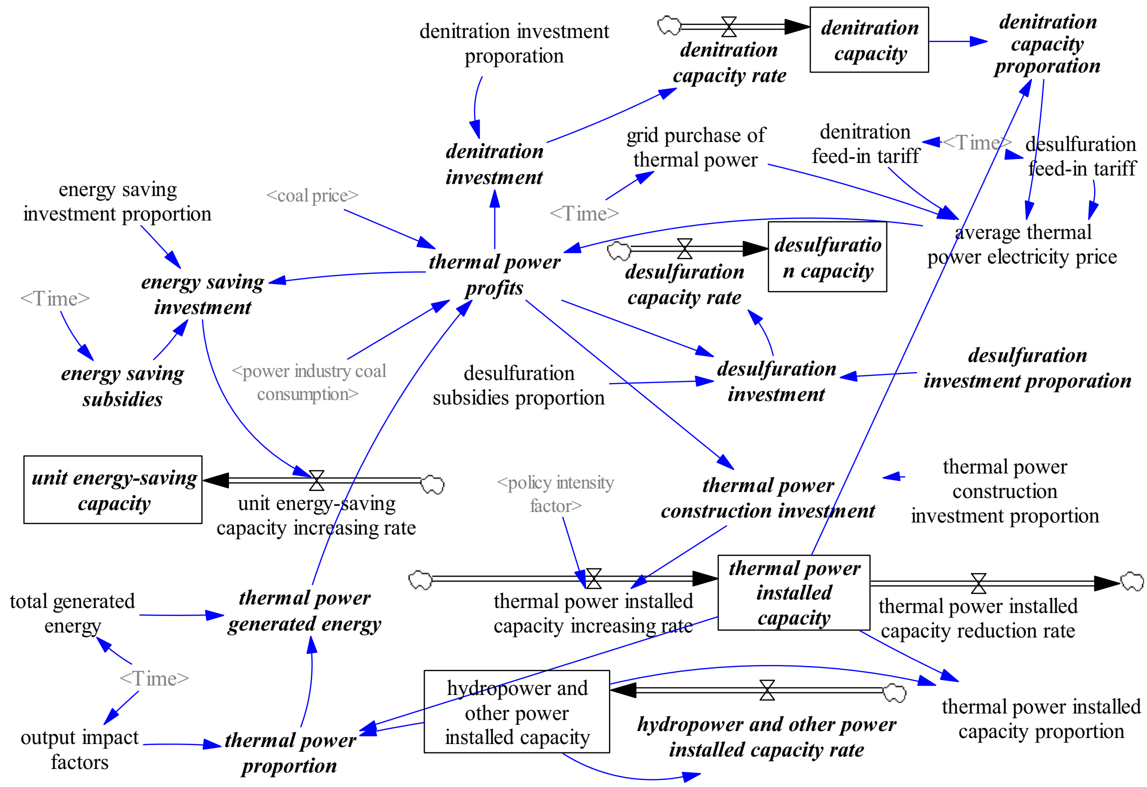


Fig. 3 Flow diagram for thermal power subsystem

coal cleaning rate, which depends on the investment of coal washing equipment.

Equation (8) is used to represent the coal demand of thermal power industry where $generation_{thermal}$ is the generating capacity of thermal power, $rate_{coal}$ is the coal consumption rate of power supply, $rate_{fiducial}$ is the fiducial value of coal consumption rate, $factor_{turbine}$ is the impact factor of turbine heat-efficiency, and $factor_{bolier}$ is the impact factor of boiler heat efficiency. Equation (9) is used to represent the coal consumption rate of power supply, where $efficiency_{boiler}$ is the efficiency factor of boiler and $efficiency_{turbin}$ is the efficiency factor of steam turbine. The fiducial value coal consumption rate equals to 325.

$$coal_{thermal} = generation_{thermal} \times rate_{coal} = generation_{thermal} \times \frac{rate_{fiducial}}{factor_{turbining} \times factor_{bolier}} \tag{8}$$

$$rate_{coal} = 325 / \left(efficiency_{boiler} {}^{*} efficiency_{turbin}\right) \tag{9}$$

Equation (10) is used to represent the amount of washed coal. The amount of washed coal at time t ($coal_{washed}(t)$) depends on the amount at time $t-dt$ ($coal_{washed}(t-dt)$) and the increasing rate of washed coal ($coal\_increa\sin g_{washed}$).

$$coal_{washed}(t) = coal_{washed}(t{-}dt) + (coal\_increasing_{washed})dt \tag{10}$$

Model validation

Authenticity and sensitivity test is necessary after designing the model. This paper analyzes the error rate of eight variables between true value and simulation in 2012–2014 so that we can justify the appropriateness of the proposed model. These variables cover all key variables with overall situation and representativeness. Table 2 lists the authenticity test results. The true value of denitration installed capacity cannot be found yet. The errors of other variables are controlled within − 10~10%, which meet the requirement of authenticity test.

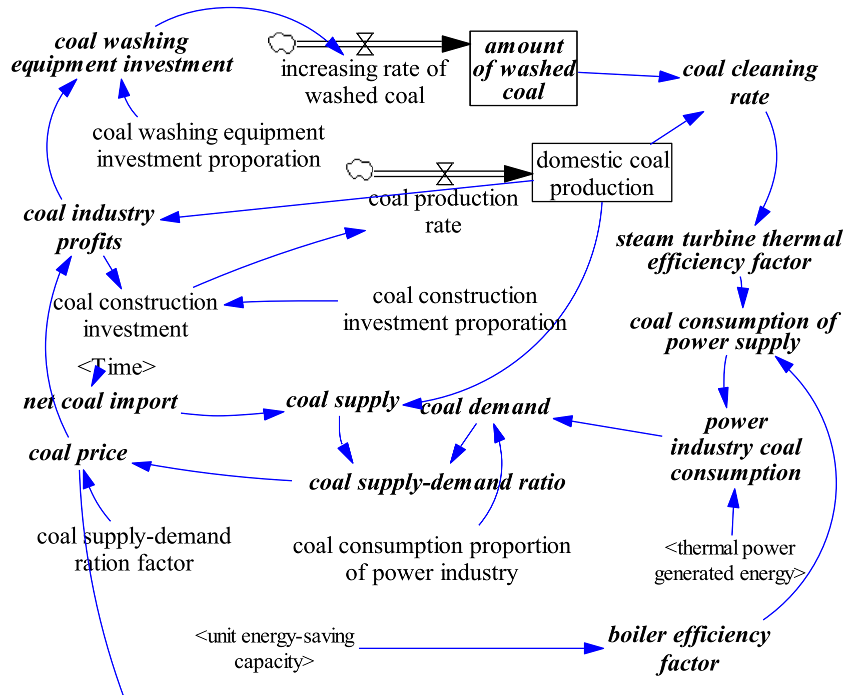
Results and discussion

Adjustment of electric power structure

The application of SD model can realize simulating electric power structure adjustment under PM10 reduction constrains. A yearly time step with numeric computation in continuous-time basis is used. Simulation length is 2013–2032. The simulation result shows the forecasting tendency of each variable.

Figure 5 shows the simulated results of thermal power capacity and its proportion, proportion of thermal power generation, and proportions of desulfurization capacity and denitration capacity. These results indicate the following:

Fig. 4 Flow diagram for coal subsystem



1. Although the absolute installed capacity of thermal power is increasing as the economy growth, the installed capacity proportion is dropping as the development of clean power generation. The proportion will decrease from 70.5% in 2013 to 67% in 2018 with a dropping speed, remain nearly constant in 2017–2022, and experience accelerated decline after 2023.
2. Under the affluence of coal resource, China enjoys a high proportion of thermal power generation (about 80%) for a long time to come. But, the proportion of thermal power generation would remain downward trend in 2013–2032 and would be down to 72.9% by 2032.
3. Desulfurization capacity proportion will exceed 95% in 2024 and continue to increase. China will complete the desulferized renovation generating units within 10 years. In 2013, China's thermal power unit denitration penetration proportion is only 28%. As listed in Table 2, the denitration capacity proportion will show S-curve at a slow-fast-slow increasing rate in 2013–2032. By 2032, the denitration capacity proportion will reach 78.9%. The development degree of China's coal-fired unit denitrification will rise to a certain height in the following decades.

Coal consumption and PM10 emission

Action Plan pointed out that by 2017, the proportion that coal accounts for the total energy consumption should fall below

Table 2 Authenticity test results

Year	Thermal power installed capacity (10^3 MW)			Proportion of thermal power installed capacity		
	True value	Simulation	Error (%)	True value	Simulation	Error (%)
2013	826	862	− 4.18%	0.705	0.696	1.29%
2014	843	915	− 7.87%	0.695	0.673722628	3.16%
2015	869	990	− 12.22%	0.687	0.657370518	4.51%
Year	Proportion of thermal power generation			Desulfurization installed capacity proportion		
	True value	Simulation	Error (%)	True value	Simulation	Error (%)
2013	0.802	0.804	− 0.25%	0.922	0.906	1.77%
2014	0.816	0.749	8.95%	0.925	0.915	1.09%
2015	0.804	0.731	9.99%	0.927	0.923	0.43%
Year	Denitration installed capacity proportion			Coal consumption of thermal power industry (million ton)		
	True value	Simulation	Error (%)	True value	Simulation	Error (%)
2013	0.286	0.31	− 7.74%	2280.05	2178	4.69%
2014	0.303	–	–	2220	2245	− 1.09%
2015	0.327	–	–	2100	2011.00	4.43%
Year	SO_2 emission (10^4 ton)			NOx emission (10^4 ton)		
	True value	Simulation	Error (%)	True value	Simulation	Error (%)
2013	1704.11	1856	− 8.18%	2756.47	2527	9.08%
2014	1640.43	1821	− 9.92%	2658	2478	7.28%
2015	1533.36	1643	− 6.67%	2480	2289.00	8.34%

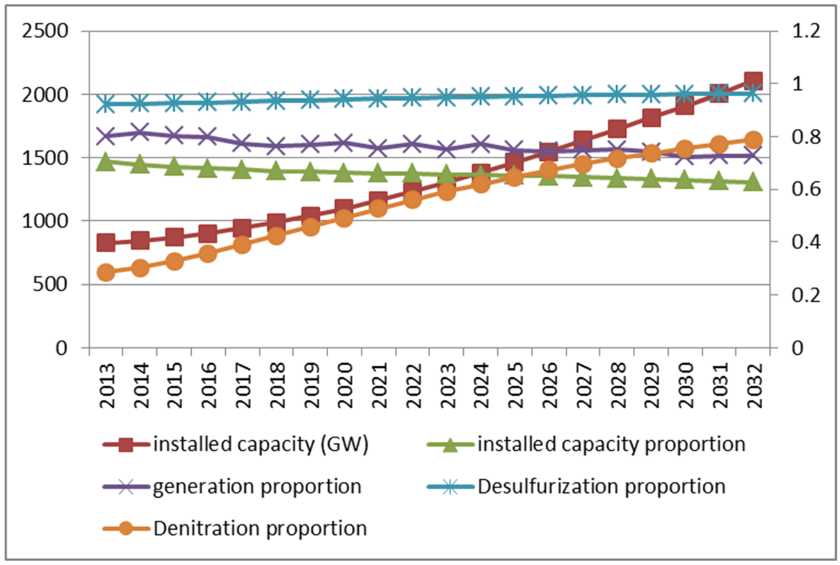


Fig. 5 Simulated results of electric power structure

65%, and the PM10 concentration should be decreased by more than 10% over 2012. The forecasting results of our SD model can be used to estimate the fulfillment of these policy goals with historical data.

Figure 6 shows the simulated results of coal consumption of thermal power industry, SO2 emission, and NOx emission. These results indicate the following:

1. China's total energy consumption in 2017 is estimated to be 4152.90 million t of standard coal based on multiple-regressive model. The simulated coal consumption of thermal power industry (accounting for about 70% of the total coal consumption) in 2017 is 1841 million t. So, the total coal consumption in 2017 is estimated to be 2630 million t accounting for 63.3% of total energy consumption. It indicates that the current energy structure adjustment schemes are helpful to the control of coal consumption.
2. According to the simulation results, SO2 emission will reduce to 15.70 million t in 2017, which is 7.90% lower than 2012. And, NOx emission will reduce to 25.15 million t in 2017, which is 8.78% lower than 2012. The emission declines in nearly uniform speed during the simulated period and has a short-term rebound in 2017. SO2 emission has an obvious rise in 2017, but the coal consumption of thermal power industry keeps decreasing at the same time. The main cause for this phenomenon is the ultra-low emission policy of China's thermal power industry. The implement of this policy will reduce the proportion of thermal power emission in the total emission. But, the total emission will not decrease because of the emission of vehicle and scattered coal combustion.
3. NOx measurements are used as an indicator for primary PM10, and sulfate (transferred from and calculated by SO2) measurements are used as an indicator for secondary PM10 [26]. By 2017, the sum of PM10's two most

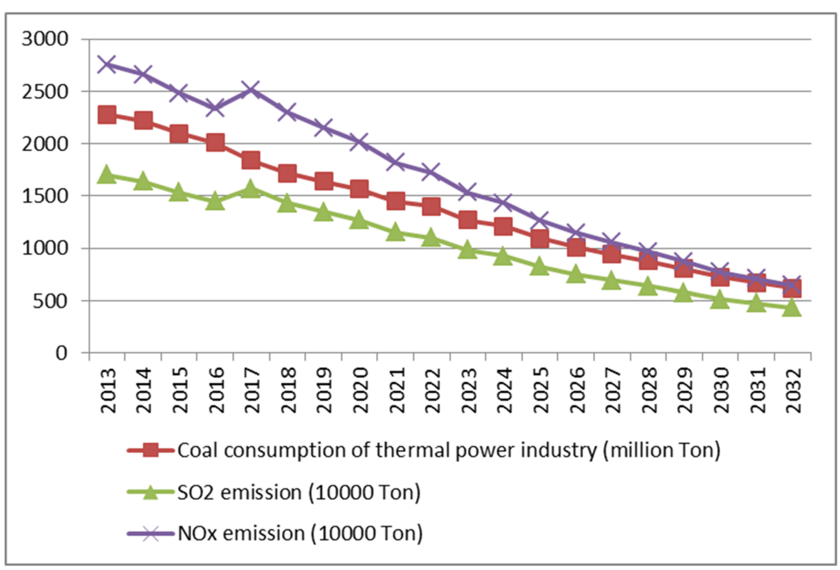


Fig. 6 Simulated results of coal consumption and emissions

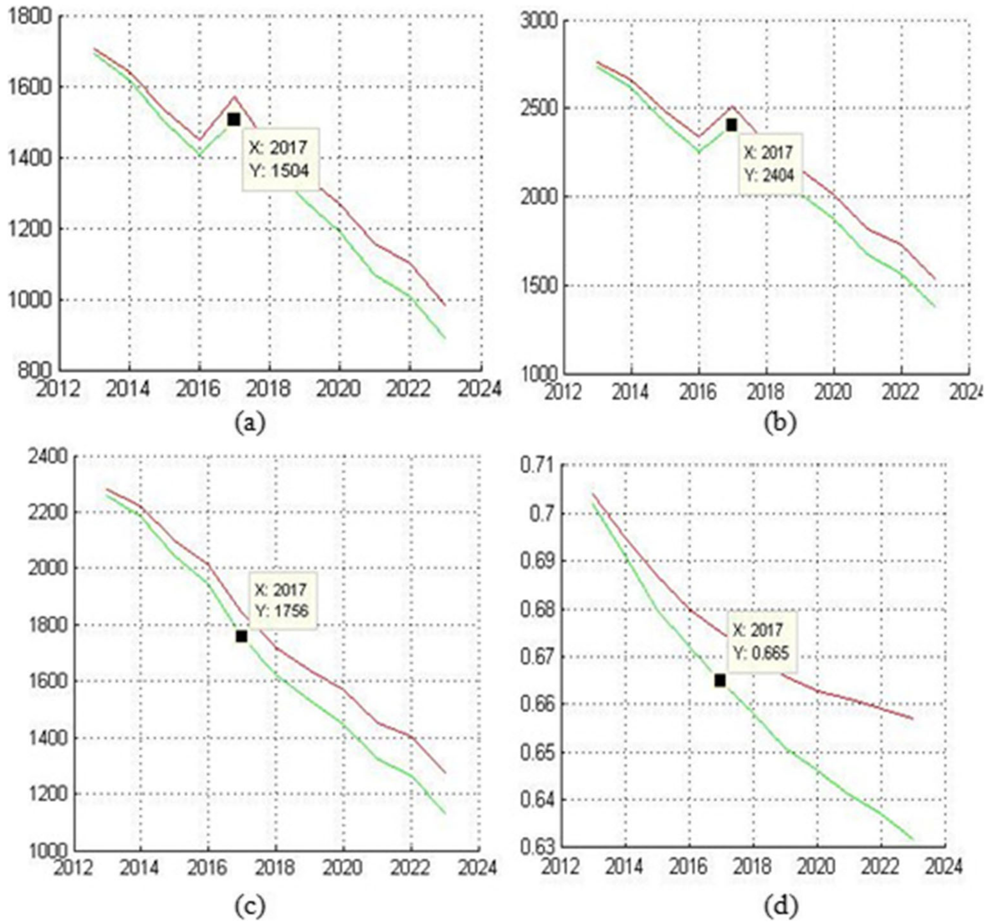


Fig. 7 Compare results at two growth rates. **a** SO_2 emission, **b** NO_x emission, **c** coal consumption of thermal power industry, and **d** proportion of thermal power installed capacity (simulated results of 7% are shown in red, 8% are shown in green)

components (NOx and SO2) will be 8.33% lower than 2012. So, if we continue the current path of electric power structure adjustment, China can hardly meet the PM10 emission reduction target.

Scenario analysis

In order to find out if the development of clean power can help China meet the emission target, scenario analysis was made by increasing the growth rate of clean-power capacity without changing other parameters of existing SD model. The above simulation sets the growth of clean-power capacity as 7%, which is estimated according to the history data. On the basis of current emission-reduction policies, if China can push new measures to assist clean-energy industries, this growth rate may reach 8% as clean-energy technology improves and costs fell. To explain, due to the ever-changing policy environment, it is not appropriate to predict the development of China's clean power in the far future. Thus, we set the stimulation period as 2013–2023. To compare results of emissions, coal consumption and proportion of thermal power installed-capacity at two different growth rates are shown in Fig. 7.

Under the new growth rate, the SO2 emission will reduce to 15.04 million t by 2017, which is 11.01% lower than 2012. The NOx emission will reduce to 25.15 million t by 2017, which is 12.07% lower than 2012. Therefore, China can probably achieve its target of reducing PM10 emission by 10%. Meanwhile, the coal demand and installed capacity of thermal power will be significantly reduced.

In general, the predicted achievements of power-structure transformation are not efficient enough to help China achieve the reduction target of PM10 mentioned in Action Plan. But, if the growth of clean-power generation could speed up, the PM10 emission target can be realized. So, decision-makers should bring out some assistant policies to fill in the gap between current simulation and targeted level of emission reduction.

Conclusions

In this paper, we build a system dynamics model which can simulate China's evolution path of power structure with constraints of PM10 reduction considering both technical and economic factors; the main conclusions are as follows:

1. A solution of simulating the adjustment of electric power structure under the pressure of PM10 reduction is provided. The SD model we built can forecast the trend of

installed capacity as well as generated energy, and obtain a better path of power structure evolution.

2. The simulated results in 2013–2032 proposed in this work show that China's PM10 reduction policies can result in significantly transformed electric power structure. The installed capacity proportion of thermal power will decrease from 70.5% in 2013 to 67.5% in 2017 with a dropping speed, and its generation proportion will slowly decrease from 80.2% in 2013 to 77.4%.
3. But, the simulation results also indicate that, by 2017, the sum of PM10's two most components (NOx and SO2) will be 8.33% lower than 2012. Therefore, if we continue the current path of electric power structure adjustment, China can hardly meet the PM10 emission reduction target (10%).
4. Further, China should promote clean power generation by breaking technical limitations and bringing out some subsidy policies. If the growth rate of clean-power capacity could reach 8%, the sum of PM10's two most components (NOx and SO2) will be 11.67% lower than 2012 in 2017. Meanwhile, the coal demand and installed capacity of thermal power will be significantly reduced. In fact, Chinese develop clean energy actively and control pollution since the 13th five-year plan, so the results of this paper are of some value to policy making.

The system dynamics model of this paper not only takes account of many factors such as economy, energy, and policy but also adds some technical factors (desulfurization and denitrification) and takes the emission of PM10 as the limiting condition to make the model more comprehensive and practical. Secondly, the experimental results have a low error, which can well simulate the evolution of the reform of China's power system. In a word, this paper provides reference for the adjustment of China's power structure and the formulation of energy saving and emission reduction policies.

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Appendix

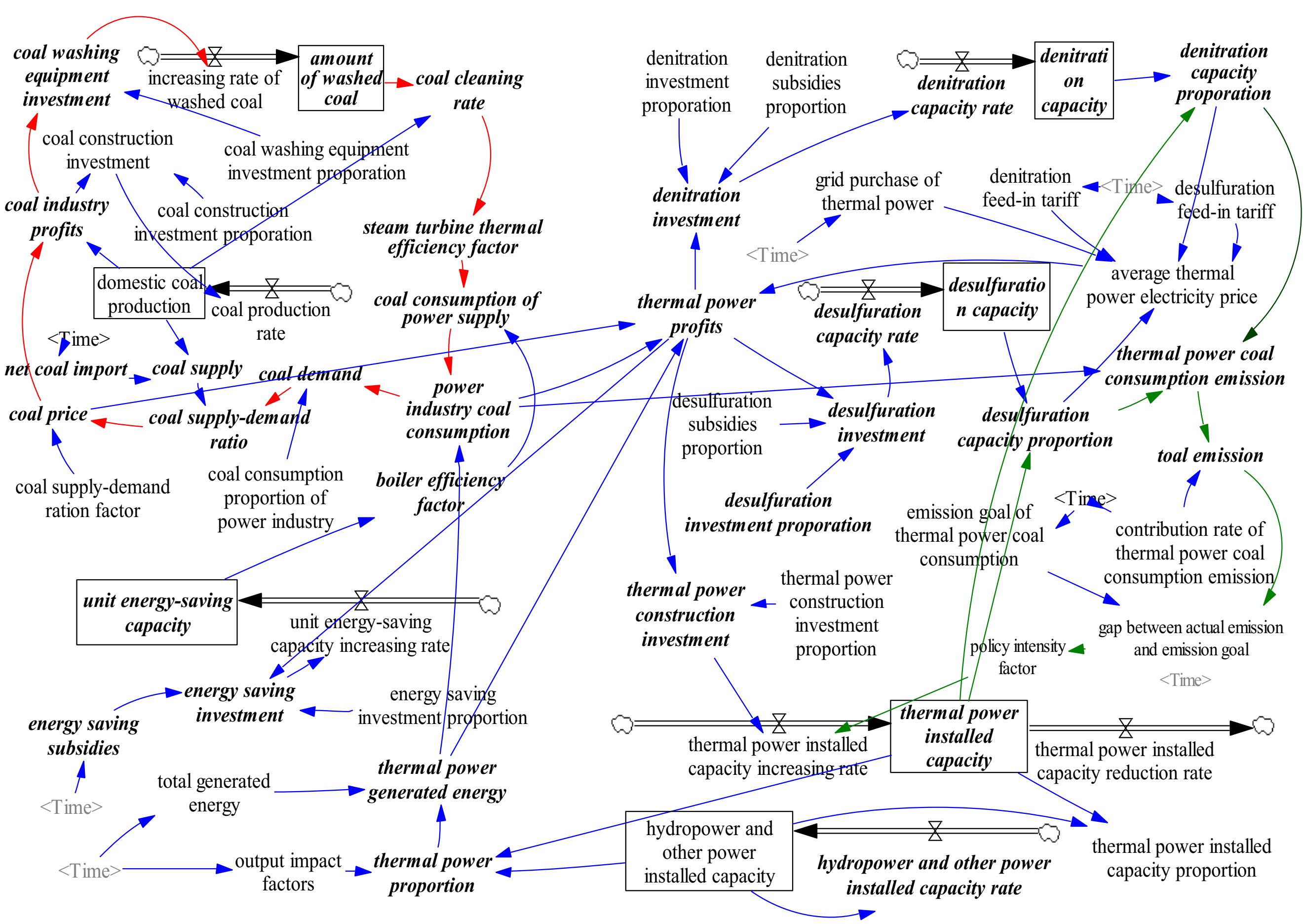

Fig. 8 Flow graph of electric power structure adjustment under air-pollution reduction

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