System Dynamics Project: The case of Electricity in Shanghai

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Abstract

The increasing energy demand in China due to urbanization has made the study of different energy policies in big cities a crucial topic of discussion. This is a complex problem since the electricity market is a multi-actor system where various actors may have a great influence on the main issue we are focusing on. In order to reduce the energy shortage and CO_2 *emissions problems existed in electricity market, a case study on Shanghai was conducted. The model built in this paper was used to forecast the electricity demand and supply under different energy policy scenarios and also to analyze the associated reductions in emissions of* CO_2*. Three different policies were implemented in the model: regulating the electricity price, changing the structure of primary energy consumption of the electricity generating system, building up an inter-regional integrated electricity market. Simulation results show that the problems can be mitigated to some extent under these policies.*

Keywords: Electricity market, Energy shortage, CO_2 emission, Shanghai,

1. Introduction

China is one of the largest countries in the world in terms of its energy demand and environmental problems. By the end of 2000 its electricity production has reached 1368 TWh, ranking second in the world (Gnansounou and Dong, 2004). However, the electricity supply adequacy situation still remains a big problem for multiple regions in East China, which is the most developed area in China, including Shanghai municipality and six other provinces.

Shanghai is a city with high level of urbanization and a fast increasing population which results in a dramatic increase in demand for electricity (Huang and Wang, 2011). When the electricity demand exceeds supply, shortages occur, which hamper the city’s whole economic growth (Shiu and Lam, 2004). Shanghai’s rapid economic developments, its reliance on coal and low efficiency in generating electricity have resulted in severe CO_2 emission problems. In order to solve these problems, natural gas-fired power plants are encouraged due to their advantages in terms of construction time, operation flexibility and environmentally friendly feature (Li, 2003) as well as inter-regional integrated electricity market.

This paper is divided into three main sections. The first section gives an overview of the situation facing megacities around the world with regard to electricity demand. This section summarizes the innovative solutions that have been implemented and the experiences gained from different cases. The second section introduces model development and focuses on its boundary setting, causal loop development, model specification and model testing, (Pruyt, 2013). The last section describes the policies-scenarios that have been tested, and reveals the sensitivity of the policies to some of the key parameters. Finally, the paper discusses the insights from the model analysis and makes suggestions for the problems.

The model gives a clear overview of how the electrical supply and demand system work. Simulation results clearly illustrate the significant effects of policy measures aiming to control electricity shortage and annual CO_2 emissions respectively. Additionally, the relationship between electricity demand and GDP growth is also discussed.

2. Model development

2.1 Boundary

Time horizon: According to historical energy statistics, coal is dominant in primary energy consumption in China and changing the structure of primary energy consumption in the long-term will be of great significance when it comes to gaining a sustainable development in the electricity market. A long time horizon might be appropriate, starting from 2001, which marked the beginning of the China Energy 10th Five Year Plan, ending in the year of 2030. The system is strongly aggregated, thus average effects will be used in the time step of one year.

Shanghai specifically: There are a variety of economic development, energy resource distribution and electricity demand levels in different Chinese provinces. We shall only take Shanghai, one of the largest industrial and commercial centers in China, into account. We think it is meaningful to do research on this specific city because it is highly developed in China, and other cities can follow the example set by Shanghai.

The population of Shanghai was 13.22 million at the end of 2000. In 2000, its GDP was US$55 billion and GDP per capita was US$4162. Both of its high GDP growth and improvement of people’s living standard increase the electricity consumption. Shanghai power system had an installed capacity of 10.6GW in 2000. In 2000, electricity purchased from other regions amounted to 8% of the total power supply and most of the power plants in Shanghai are coal-fired (Gnansounou and Dong, 2004). Effects are made to decrease coal use and increase clean energy use in order to protect the environment (Gielen and Chen, 2001). According to Shanghai’s 10th five-year (2000 – 2005) energy plan, the purchasing of electricity from other regions will increase to around 20% of the total power supply (SMDPC, 2001).

We analyzed the data of historical evolution and present situation of electricity consumption in Shanghai as well as the relations between electricity consumption and its influencing factors, and forecasted electricity demand in the next 30 years. The forecasting is made with scenarios which take into account different development trends in GDP, energy efficiency and population growth.

Population growth is one of the dynamic forces that have great effect on the energy demand. Many papers have stated that there is a causal relationship between electricity demand and economic growth in China (Yuan, Zhao and Yu 2007). Starting in 1992, GDP growth rate of Shanghai has been constant at 10% for 10 years (Changhong, 2006). The annual GDP growth rate varied from 10.5% to 14.2% from 2000 to 2005, and is forecast to be 6.5%-8.5% from 2010 to 2020. As a result, the GDP growth greatly improved the purchasing power of the people, leading to a higher electricity demand. What's more, the government has implement many policies in order to improve the air quality, total coal consumption in Shanghai is likely to be kept between 45 and 50 million tons, and the capacity of coal-combustion power plants will be controlled at about 12GW by 2005 (Shanghai Municipal Government, 2001). The share of natural gas boilers will increase from 4% in 2000 to 40%.

Only the main economic factors, such as income and electricity price, which affect electricity demand, are taken into account. Natural influences such as changes in temperature are not included in this report. The conceptual model used in this paper can be seen as figure 1.

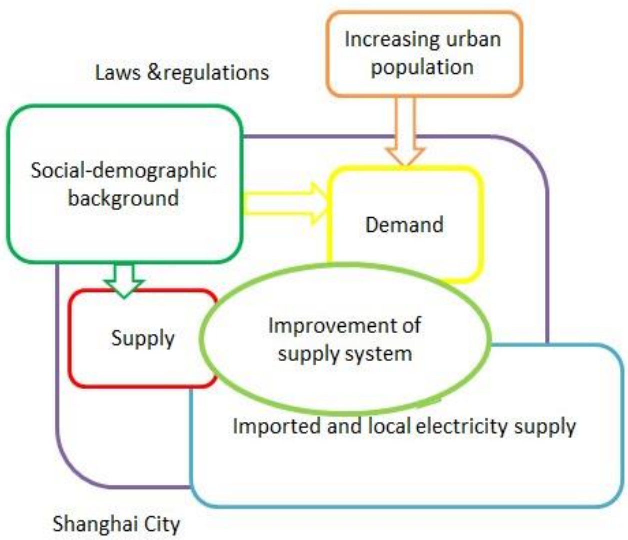


Figure 1, Conceptual model

2.2 Causal loop Development

The driving forces of the Shanghai electricity market are: the development of the social economy and the growth of the population. The key variables involved in this model can be seen in figure 2, more explanations are in Appendix.

Residential demand-supply difference: This variable equals residential demand divided by residential supply, so demonstrating the degree of electricity shortage.

Total CO2 emissions every year: It is the sum of CO_2 emission intensity multiplied by the installed capacity of different kinds of generators.

Residential electricity demand: This variable take both urban and rural aspects of electricity demand into consideration. And the fraction of these two parts is determined by the urbanization level of the city.

Electricity price: This consists of two parts: the historical electricity price before the year 2013 and the projected electricity price from then on.

Total electricity supply: This variable is equal to the sum of electricity supply generated by Shanghai itself and that imported from other provinces.

Urbanization level: This is the proportion of population in cities or towns, relative to the overall population.

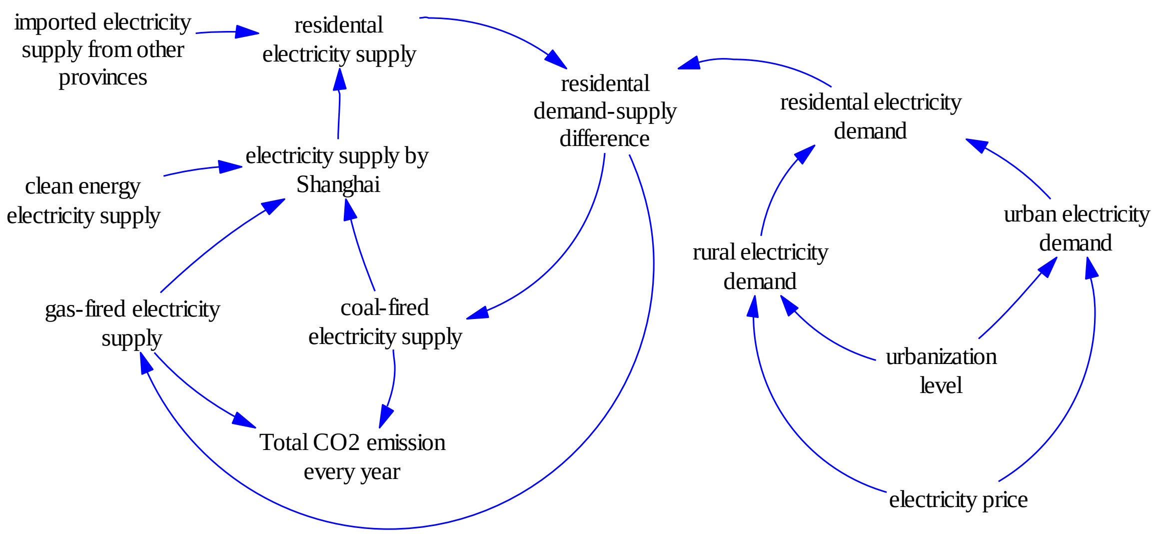


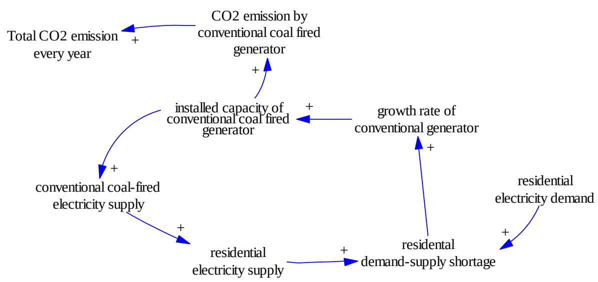
Figure 2, Key variables

2.2.1 Conventional coal fired generator supply loop

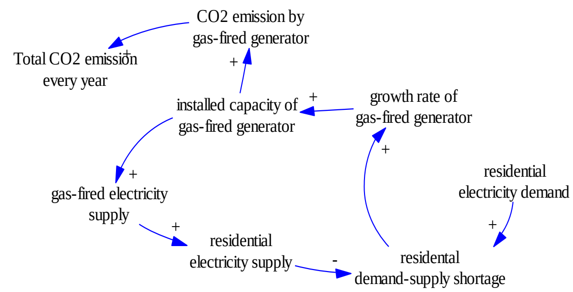
If residential electricity demand increases then a supply shortage will occur which leads to a higher growth rate of conventional generators. The more conventional generators there are the more installed capacity power plants will be in plants. More installed capacity means more CO_2 emissions. As residential supply grows, shortage will reduce, so the shortage problem will be solved or become less serious than before.

2.2.2 Efficient coal-fired generator supply loop & gas-fired generator supply loop

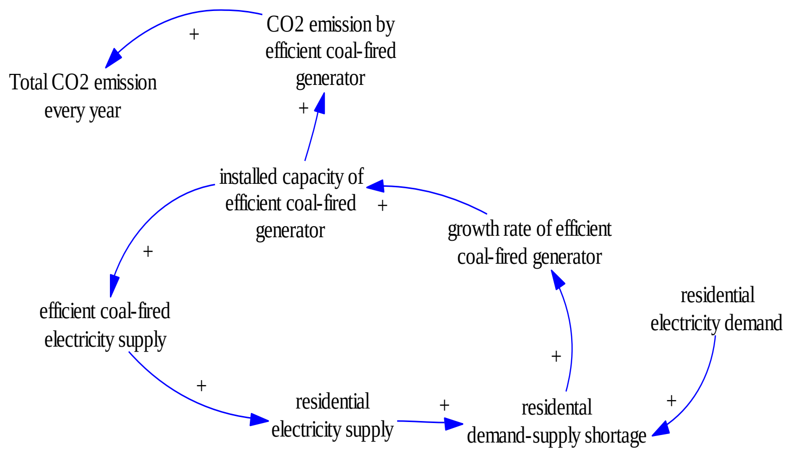
The mechanisms of these two causal loops are almost the same as the conventional coal fired generator supply loop. If a shortage occurs, it will cause the increasing of the growth rate of generators, then the whole capacity of plant will increase which means that supply will increase. Finally the shortage problem will improve.



a) Conventional coal fired generator supply



b) Efficient coal-fired generator supply



c) Gas-fired generator supply loop

Figure 3, Causal loop Development

2.3 Model specification

There are two inflows to the permanent residential population: one is the newly born population per year and the other one is the "net immigrants" which is measured by immigrants minus emigrants annually. The outflow of permanent residential is death population annually.

Regulation of electricity price is considered as one of the main policies. To simplify varieties in the electricity price, RAMP function is used to make the range linear.

The variable clean energy electricity supply is constant and consists of hydro-power, thermal power, wind power and other clean energies.

As the same kind of generators is in homogeneous conditions, carbon dioxide intensity can be averaged.

In addition, the variables like population, GDP growth and electricity price are all exogenously generated, and we use with lookup function to define these variables. Take electricity price for example. We define it as follows:

Electricity price =IF THEN ELSE (Time<2014, historical electricity price, projected electricity price)

The full list of equations can be seen in the Appendix.

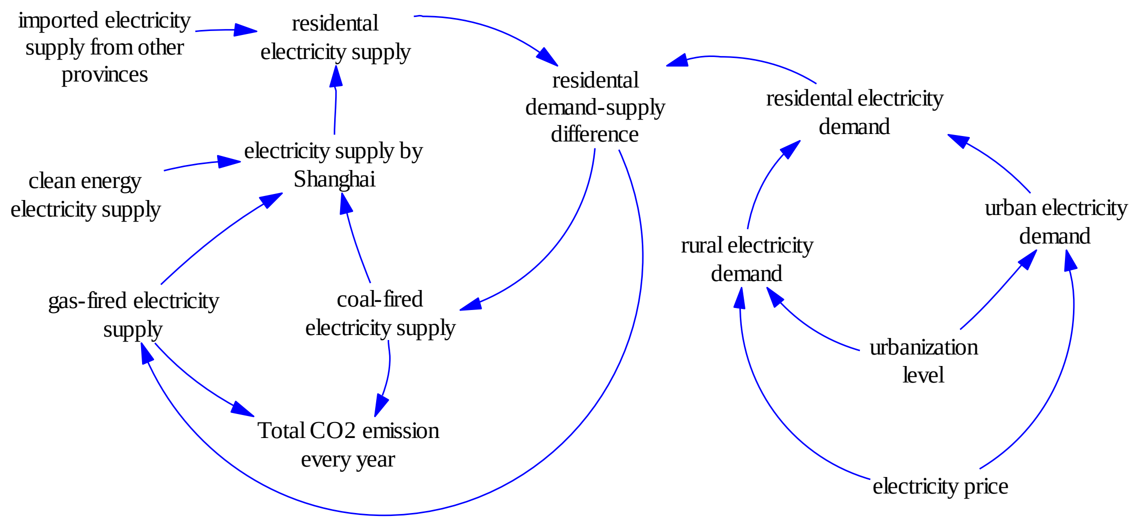


Figure 4 Model specification

2.4 Model testing

(1)Dynamic hypothesis

The reinforcing loop of the coal-fired supply loop will be dominant. Comparable cases show that in recent years, the electricity system in China relied more on coal-fired generators than gas-fired generators. When the electricity shortage represented by the residential demand-supply difference is higher, the supply level will also be higher in reality. The Parameters in the loop might be numerical and/or behaviorally sensitive.

The reinforce loop influenced by the gas-fired supply loop will be weak; the number of gas-fired generators is small compared to the total number.

The loop, 'income effect on population' will lead to goal seeking behavior. Over time, the number of Shanghai's immigrants and emigrants will change and be affected by the income level. When the average income becomes higher, more people tend to come to the city in reality. Overtime, the GDP may stop increasing rapidly, resulting to an equilibrium income, so the number of people coming to the city each year will become a constant in the long-term run.

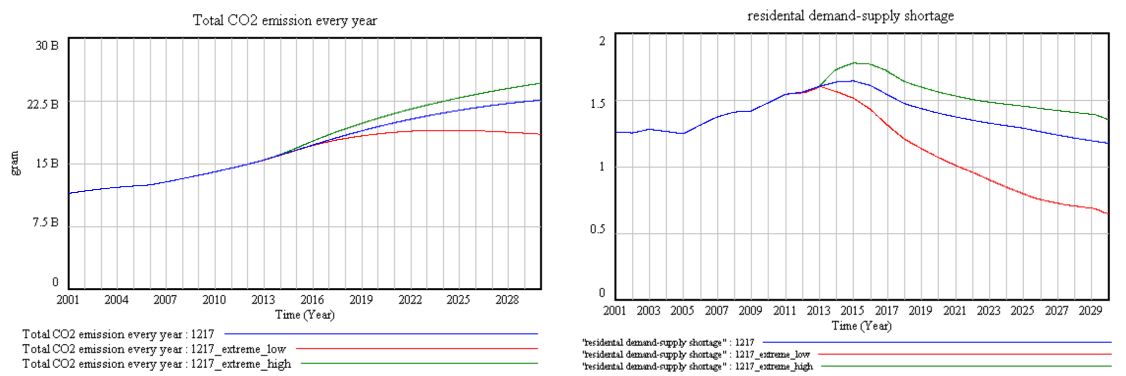
(2)Extreme conditions behavior test

The model output follows the historical data until 2013. This is because the curves of the lookup functions that are used as input for the GDP, electricity price, growth rate of different generators, the ratio between imported and local generated electricity are estimated according to historical data.

GDP growth rate:

If the GDP growth rate is negative in Shanghai, then the curve of CO2 emission will turn from ascending to declining (see the red line in figure 5a). If the GDP growth rate is extremely high the behavior will not change much (see the green line in figure 5a).

If GDP growth rate is negative in Shanghai, the curve of residential demand-supply shortage will go below 1 after year 2021(the red line in figure 5b), which means electricity supply will exceed demand after 2021.If GDP growth rate is extremely high the behavior will not change much(the green line in figure 5b).

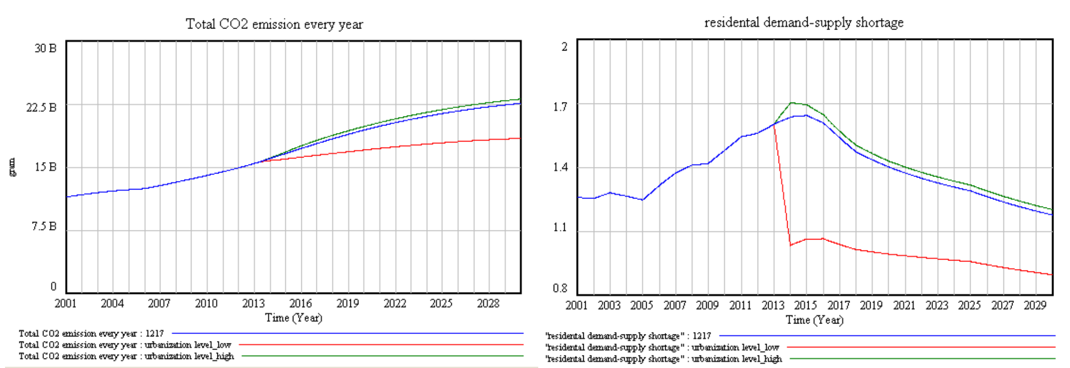


a) Total CO2emission b) Electricity shortage

Figure 5 Test of growth rate

Urbanization level

If the urbanization level in Shanghai is zero after 2013, the CO_2 emission curve will be gentle (see the red line in figure 6a). If urbanization level equals 1 the behavior of CO2 emission will not change much (see the green line in figure 6a).

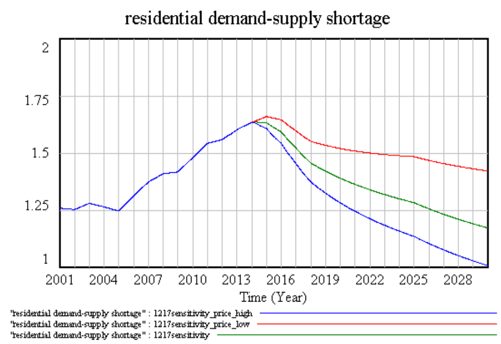


a) Total CO_2 emission b) Electricity shortage

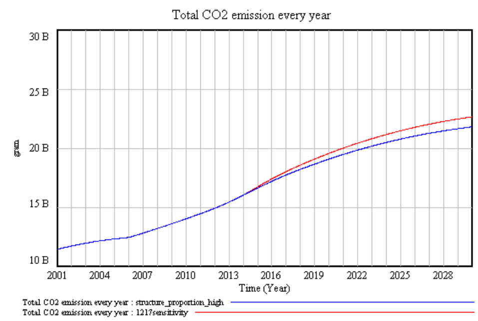
Figure 6 Test of urbanization level

If urbanization level is zero after 2013 in Shanghai, the curve of residential demand-supply shortage will go sharply below 1 after year 2013 (the red line in figure 6b), which means electricity supply will exceed demand. If urbanization level equals 1 the behavior of residential demand-supply shortage will not change much (the green line in figure 6b).

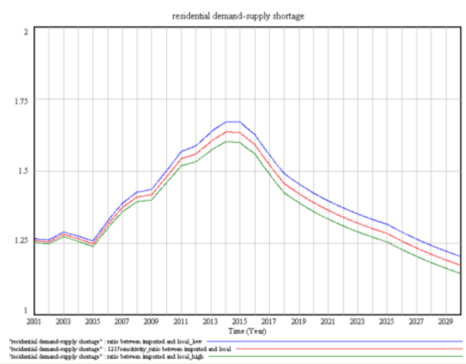
(3)Sensitivity Analysis



a) Electricity price



b) Proportion of gas-fired generator



c) Ratio between import and local ones

Figure 7, Results of Sensitivity analysis

Electricity price

If the growth rate of the electricity price rises by 10%, the behaviour will be shown as the blue line, which means that the supply will be finally equal to the demand. If electricity price stays at a relatively low level, the behaviour will be shown as the red line, which means electricity shortage remains high. In conclusion, the model is sensitive to the electricity price which can be chosen as a policy.

Proportion of gas-fired generators

Raising or decreasing the growth rate of gas-fired generators and coal-fired generators could change the proportion of electricity produced by gas-fired generators for the whole city electricity supply. As the blue curve shows, increasing proportion of gas-fired generators could improve CO_2 emission problem. So the model is sensitive to increases in the proportion of gas-fired generators which could be chosen as a policy.

Ratio between imported electricity and locally generated electricity

If the ratio between imported electricity and local generated electricity becomes 10% higher every year, the shortage behaviour will be like green line shows. It means higher ratio of imported electricity will improve supply problem. In contrast, if the ratio is 10% lower, as the blue line shows, shortage problem will get worse. So the with lookup function “ratio between imported electricity and local generated electricity” can be chosen as a policy but its influence on the model is not as strong as electricity price.

3. Results and discussion

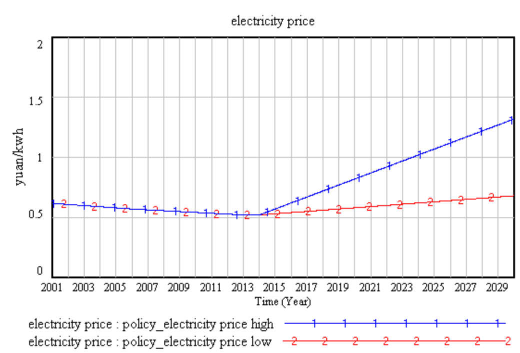
In this chapter, we are trying to implement three different policies to solve the problems mentioned above. We are focusing on the behavior changes of total CO2 emission and electricity shortage (residential demand-supply difference).

3.1 Three policies

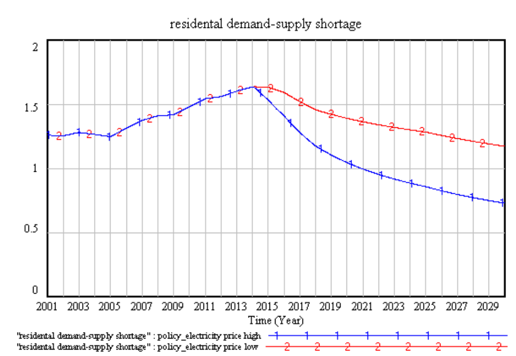
(1)The electricity price

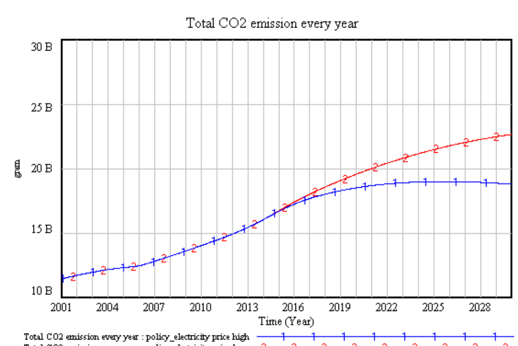
We raise the slope of electricity price function after 2013 from 0.01 (curve 2) to 0.05 (curve 1), and got the following results:

Results:



a) Change of electricity price





c) CO_2 emissions

Figure 8, policy of regulating the electricity price.

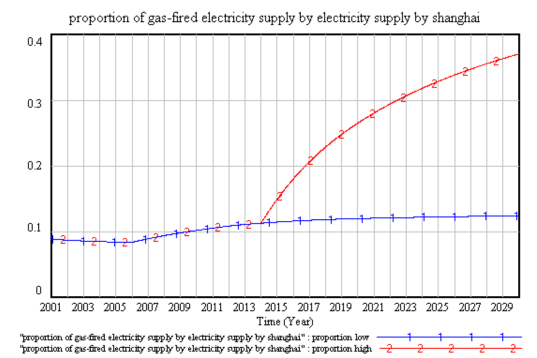
When the electricity price rises, demand will drop and thus lead to a lower shortage. On the other hand, from our model, lower shortage will result in a slower growth rate of generators and CO_2 emission. If higher prices reduce electricity demand, then supply shortage in curve 2 becomes curve 1.

(2) The structure of primary energy consumption of the electricity system

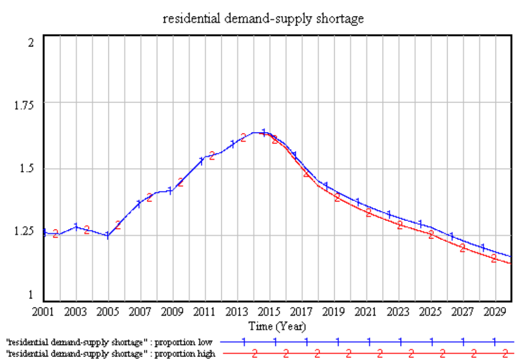
Since the electricity system is mainly dominated by coal-fired and gas-fired generators, we change the mix of primary energy consumption by raising the fraction of gas-fired generators.

Since the GDP trend is growing slower and the budget for building new generators given by government is limited, we make the growth rate of coal-fired generators capacity lower (from 950000 Kwh/year to 550000 Kwh/year) and gas-fired generator higher (from 140000 Kwh/year to 600000 Kwh/year).

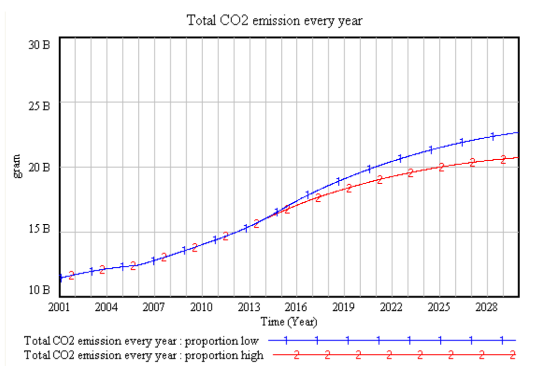
Results: After implementing this policy, electricity system is no longer relied so much on coal as before. In contrast, gas-fired generators are more environmentally friendly than coal-fired ones.



a) Change of the structure



b) Electricity shortage



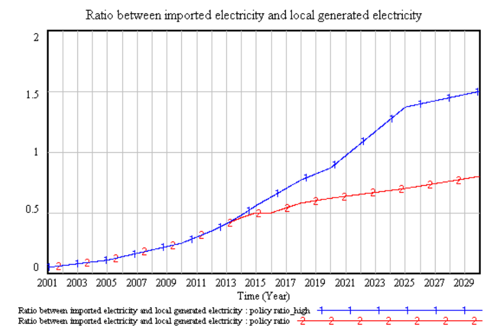
c) CO_2 emissions

Figure 9, change the structure of primary energy consumption of the electricity system.

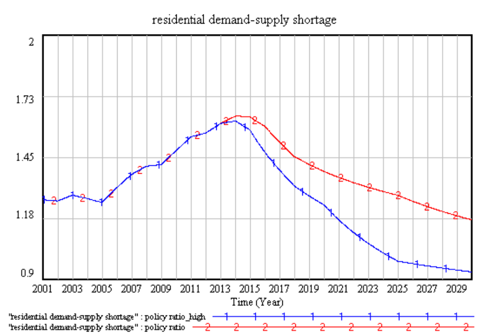
(3) Change the ratio between electricity supplies imported and generated by Shanghai

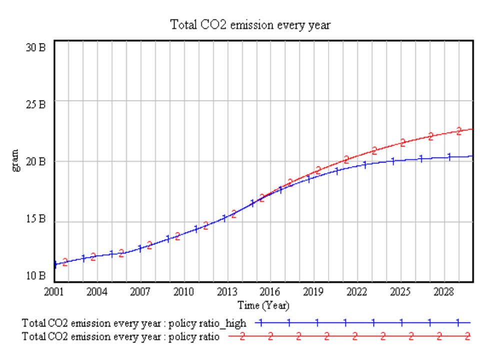
Importing electricity from other cities or regions is also an important policy to solve problems as we have mentioned above. In this case, we raise the ratio between electricity imported and generated by Shanghai itself after 2013.

Results: the shortage problem (residential) will become less severe than the previous one, and the behavior of total CO2 emission turns from an upward tendency to an approximate gentle one.



a) Change of the ratio between local and imported electricity





b) Electricity shortage c) CO_2 emissions

Figure 10, Change the ratio between electricity supplies imported and generated by Shanghai.

3.2 Explanation of behavior

Residential demand-supply shortage: This variable remains nearly stable at a level of 1.25 from the year 2001 to 2005, because in this period the GDP is no so high resulting in a relatively low demand. Then the shortage keeps increasing after 2006, and reached is peak in year of 2014, from which the shortage started to decline.

Total CO_2 emission every year: This variable keeps on increasing all the time, but it makes sense that in the first few years, it increases in a relatively low speed, and then from some point of the curve it starts to slow its pace to increase.

Residential electricity demand: The demand increases rapidly before the year of 2013. And after that, it begins to increase slowly because we assume that both the growth rate of the population and GDP in future will decrease and reach its equilibrium point.

4. Conclusion

To simplify and aggregate the model, some electricity generator variables have been simplified. We did not use stocks to describe the clean energy supply as other kind of supplies. It is taken to be a constant in our model because after doing research, the growth rate of the development of clean energy is relatively low in and does not change a lot every year. However, in reality the electricity system is much more complicated, and we may not separate them like what we did in this model.

Deviations exist since projections about the dates after year of 2013 are used in this model. This may not agree with what will happen in future, because no one can predict the exact numbers of future. There are various kinds of projections in different papers online since different person has different views, and we just picked the one we think is most authoritative.

Finally, to answer questions that have been mentioned above, we can conclude that electricity price has the largest effect on electricity shortage. In order to gain a sustainable development of electricity industry, government should less rely on coal by changing its energy consumption structure. Problems related to energy shortage and CO_2 emissions can be mitigated by investing more on clean energy and less on coal relied methods to generate electricity. Increasing the proportion of electricity imported from other provinces is also a good option for Shanghai government.

About the relation between electricity demand and GDP growth: Strongly increased immigration to the city caused by GDP growth, might lead to a large population and huge demand, exacerbate the energy shortage problem. While from the projections, GDP won’t keep on increasing so rapidly as nowadays, and will reach equilibrium after many years, so the shortage problem is gradually getting better with proper policies.

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Appendix

Key variables

Residential demand-supply difference: This is variable equals to residential demand divided by residential supply, so demonstrating the degree of electricity shortage.

Total CO_2 emissions every year: It is the sum of CO_2 emission intensity multiplied by the installed capacity of different kinds of generators.

Residential electricity demand: This variable take both urban and rural aspects of electricity demand into consideration. And the fraction of these two parts is determined by the urbanization level of the city.

Electricity price: This consists of two parts: the historical electricity price before the year 2013 and the projected electricity price from then on.

Total electricity supply: This variable is equal to the sum of electricity supply generated by Shanghai itself and that imported from other provinces.

Growth rate of efficient generator (Same as other generators)

Urbanization level: This is the proportion of population in cities or towns, relative to the overall population.

Stocks

Variables can be modeled as stocks if the bathtub metaphor can be applied to them. They can accumulate over time, the level can increase and decrease through an out flow.

Permanent residential population: The permanent residential population in Shanghai city is modeled as a stock, because it changes significantly over time.

Installed capacity of gas-fired generator: The Installed capacity of gas-fired generators is a stock because the capacity of generators in the electricity system that are controlled by the government can be built up. After a while, there are new generators inflow and outflows of generators that are no longer used.

Installed capacity of conventional coal-fired generator: We separate the installed capacity of coal-fired generator in to conventional and efficient parts, since there is a huge difference between these two kinds of generators. The installed capacity of conventional coal-fired generators is much lower than that of efficient ones. Besides, the efficient type generates less CO_2 emissions in comparison to conventional generators.

Important equations and their explanation

Table 1 Important equations

Permanent residential population	INTEG(births+"immigrants-emmigrants"-deaths)
Electricity price	IF THEN ELSE(Time<2014, historical electricity price, projected electricity price)
Rural electricity demand	permanent residential population*rural electricity demand per capita*(1-urbanization level)
Urban electricity demand	permanent residential population*urban electricity demand per capita*urbanization level
Residentialdemand-supply shortage	residential electricity demand/residential electricity supply
Residential electricity supply	ratio of residential sector*total supply
Total supply	electricity supply by Shanghai +imported electricity supply from other provinces
Electricity supply by Shanghai	"conventional coal-fired electricity supply" +"efficient coal-fired electricity supply" +"gas-fired electricity supply" +clean energy electricity supply
Growth rate of efficient generator	IF THEN ELSE(Time<2014, historical growth rate of efficient generator, projected growth rate of efficient generator)
CO_2emission by efficient coal-fired generator	"CO2 intensity emitted by efficient coal-fired generator"*installed capacity of efficient coal fired generator
Total CO_2 emission every year	CO2 emission by conventional coal fired generator+CO2 emission by gas fired generator+CO2 emission by efficient coal fired generator
Efficient coal-fired electricity supply	"efficient coal-fired operating time"*installed capacity of efficient coal fired generator

Simulation Model

The complete simulation Model is shown in Fig. 11 below.

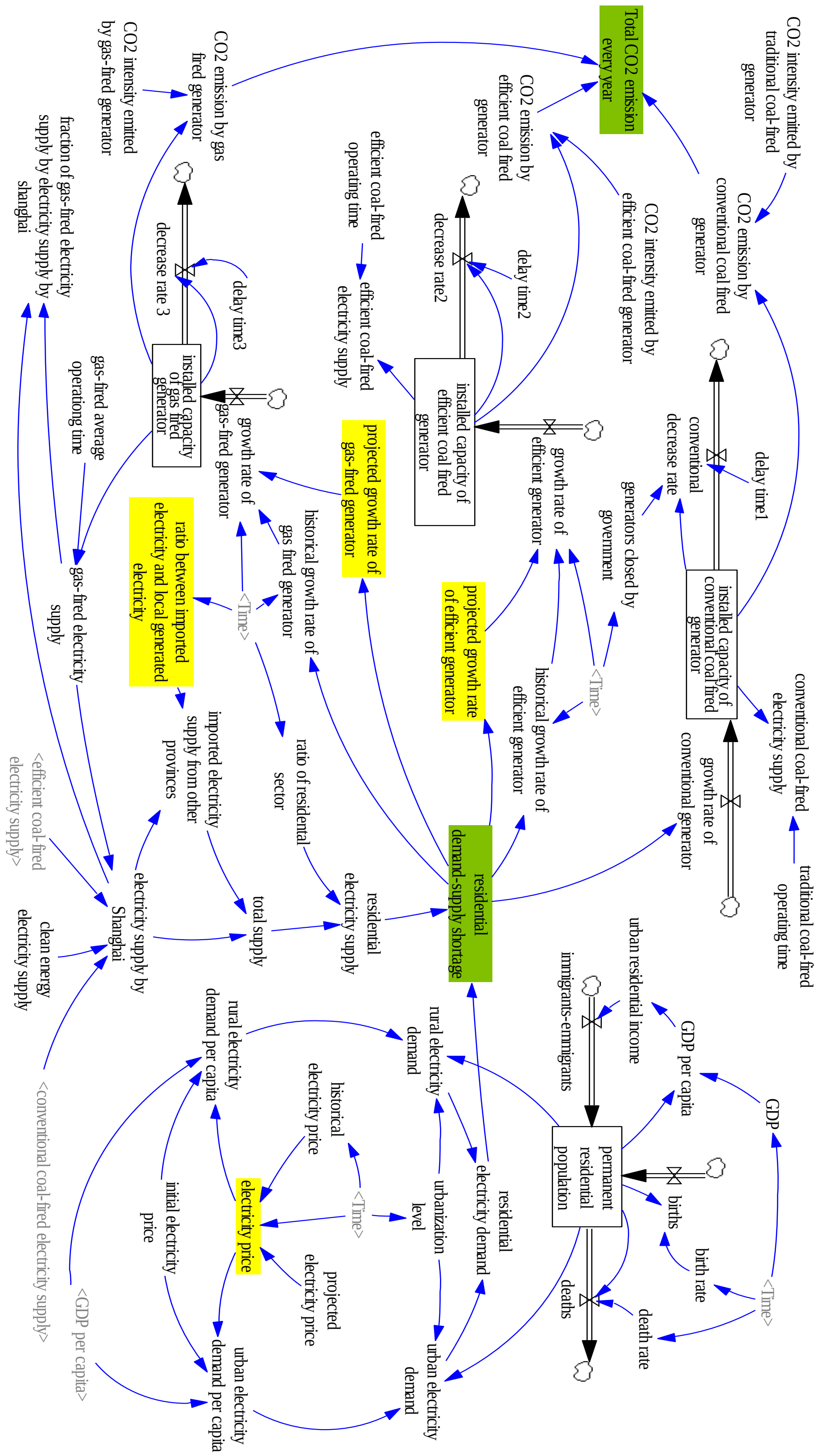

Figure 11, Simulation model