Modeling Oscillatory Shortage of Electricity Generating Capacity in China：A System Dynamics Approach

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Abstract

China has experienced a persistent shortage of electricity generating capacity since the late 1960s. This capacity shortage is mainly due to the shortage of thermal generating capacity. However, the shortage of thermal generating capacity has not been stable. There were several ups and downs in the shortage of thermal capacity while functioning capacity always fell behind desired capacity. System dynamics modeling was used to study the problem and endogenous causes for the oscillatory capacity shortage were analyzed. It was found that failure to take into account the capacity under construction can explain the oscillations in the shortage of capacity, while capacity shortage can be attributed to ignorance of construction time when deciding construction start so that capacity under construction was not big enough to increase functioning capacity in the presence of 3 years' construction time. Underestimates of desired capacity and underestimates of capacity depreciation were also part of the reasons for capacity shortage. The policy option of managing the stock of capacity under construction was recommended to both eliminate the oscillations in the capacity shortage and reduce the shortage. It was found that the policy was robust subject to long construction time. It was suggested in the paper that National Development and Reform Commission (NDRC) update their estimates of GDP growth rate, electricity intensity growth rate and capacity depreciation on a quarterly basis so as to reduce capacity shortage. However, capacity shortage becomes larger as GDP grows faster. Introducing more market effect into electricity price so that electricity price could be higher in the presence of electricity shortage could be an effective solution to improve electricity efficiency, thus offsetting fast growth in GDP a bit and thus reducing the capacity shortage, if the price elasticity in China is big enough.

Key words: *electricity industry, electricity generating capacity; thermal capacity, electricity cycles, electricity shortage, electricity price, electricity intensity, electricity efficiency, system dynamics*

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1 Introduction

Since the late 1960s, China has experienced large-scale shortage of electricity. There was a consensus that the shortage of electricity in the 1960s and 1970s was due to the intensive economy at that time. Intensive economy was known as high input, high consumption and low efficiency. Growth in economy was purely owed to increasing resource, i.e. more labor and more capital, rather than improvement in technology or productivity. Many high electricity-consumption industries generated a very high electricity demand, while the construction of electricity generating capacity lagged far behind. In 1978, China went through a reform and began to open up to the whole world. After that until 1997 when Asian Financial Crisis broke out, China had witnessed an unprecedented economic growth rate (GDP grew at a growth rate of 9% every year on average from 1978 to 2003, while growth rate from 1953 to 1978 was 4.8% (Gui and Huo 2006)), which led to an even higher electricity demand.

However, investment in electricity generating capacity was stagnant. The government was the only one to invest, distribute and sell electricity until 1985. Electricity price was set just to compensate capacity depreciation and cost to produce unit electricity, taking no account of revenue and reproduction on an extended scale (Wang 2006). In 1985 Chinese government came out with provisional regulation on encouraging fund-collecting to build electricity power plant and multi electricity price. It allowed more types of investors, including Chinese-Foreign Equity Joint Ventures, Stock Companies, Local Government and enterprises, which introduced more ways of financing for the construction of generating capacity. At the same time, it allowed different electricity prices at different stages of a power plant. There were 3 stages: startup, time to pay back the loan (10 years usually), and time after loan is paid (Wang 2006). Electricity generating companies sell the electricity at a highest price at the startup stage, because generators usually tend not to work stably so the cost at this stage is the highest. During the years to pay loan, although the investors have to pay the loan for each unit of electricity produced, things begin to run smoothly so the cost of unit electricity is largely reduced. Therefore, at this stage, they are allowed to sell electricity at a relatively higher price but not as high as the startup stage. Once the load is paid back, electricity price will be adjusted lower. Some observers believed that this regulation worked well to motivate investment in electricity capacity construction. As shown in Figure 1, the annual growth rate of total installed capacity was about 5% from 1980 to 1985 and about 10% after 1985. Due to the increase in the total installed capacity, the shortage of electricity was much alleviated since the beginning of the 1990s. However, it didn't turn the situation of electricity shortage around.

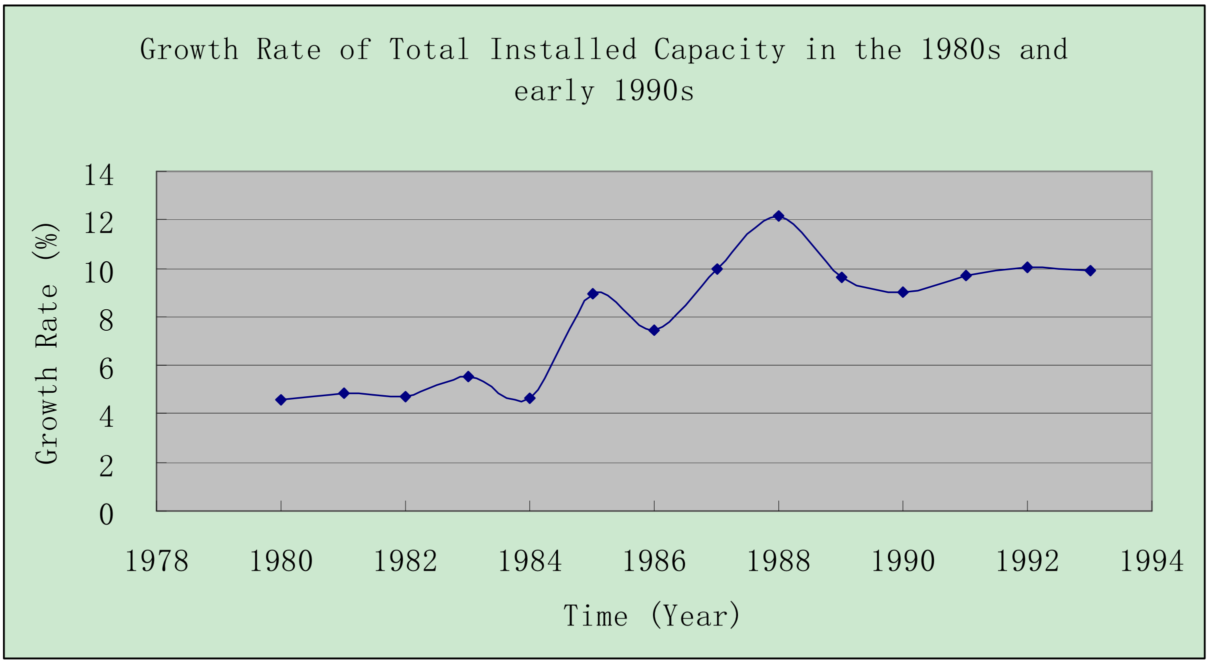


Figure 1 Growth Rate of Total Installed Capacity from 1980 to 1993

Source: State Power Information Network
China Electric Power Information Center
Hydro and thermal power composition in both installed capacity and electricity generation from 1952 to 2001
http://www.sp.com.cn/zgdl/dltj/d0104.htm

In the late 1990s, slower growth in electricity demand temporarily closed the shortage gap as the Asian Financial Crisis aggravated the economic growth in China (DRCNET 2005). See the growth rate of GDP, electricity consumption and electricity generating capacity in Figure 2. The three curves almost kept in phase all the time. Starting from 1994 the GDP growth rate in China was on the cycle of decrease, but the growth rate went down to even less than 10% from 1997 to 2000. The growth rate of electricity consumption was also on the downward tendency and even lower than GDP growth rate from 1995 to 1999. So it was with electricity generating capacity, which was even higher than the growth rate of electricity consumption. The moderate growth rate in electricity demand gave time for electricity capacity construction to catch up. The power plants that had been started several years ago were finished during these years. Years from 1996 to 1999 witnessed an annual growth rate of electricity capacity at 8.5%, while the electricity consumption grew correspondingly at a growth rate of 5% on average.

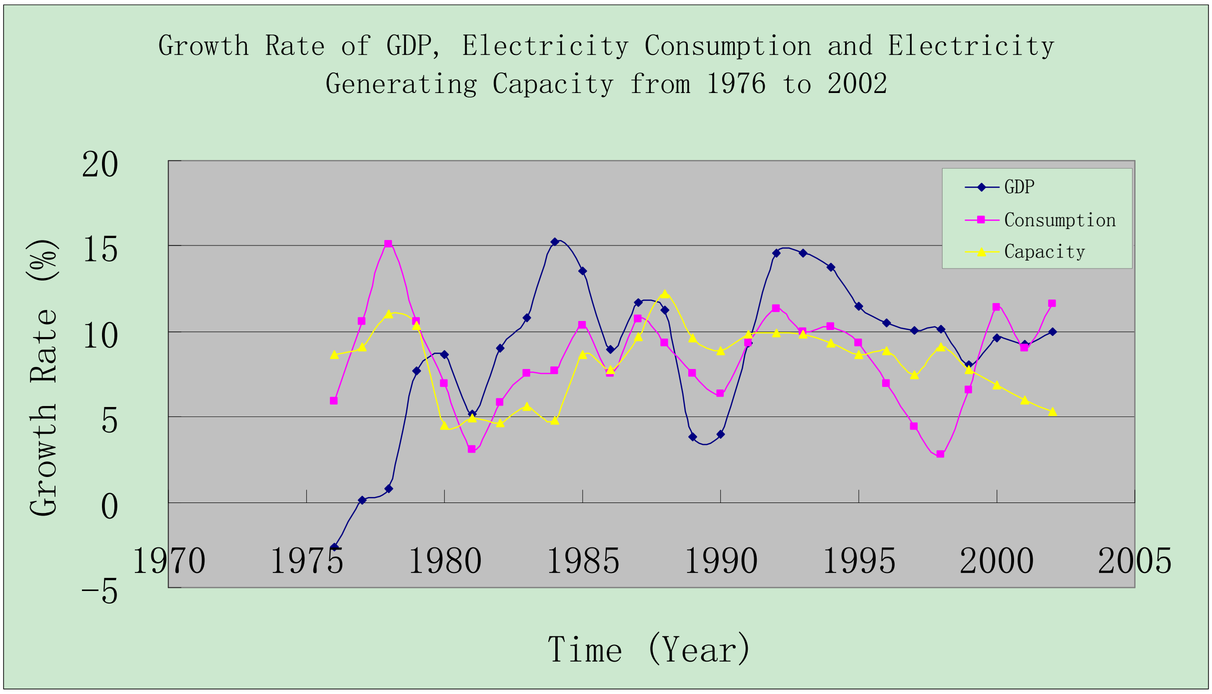


Figure 2 Growth Rate of GDP, Electricity Consumption and Electricity Generating Capacity from 1976 to 2002

Source: National Bureau of Statistics of China (2007)
Gross Domestic Product
http://www.stats.gov.cn/tjsj/ndsj/2007/indexch.htm
Global Econ Data
China, GDP deflator, 1980~2006
http://www.econstats.com/weo/C035V021.htm
(He, Zhao et al. 2006)
The Study of the Relationship between Power Industry and National Economy Growth in China

A short-term electricity surplus may have existed, but it was short-lived and an explanation will be discussed in Section 3. Five years later in 2002, the problem of electricity shortage appeared again and even aggravated. On one hand, alleviation of electricity shortage gave an impression that there was enough electricity to use. As a consequence, heavy industry, steel producing and machinery, developed rapidly from 2000. The heavy industries were electricity-intensive, which underlined a huge amount of electricity demand in the future. On the other hand, this alleviation put the decision makers of electricity capacity construction, the National Development and Reform Commission (NDRC), in an over-optimistic mood, which became less motivated to construct new power plants (DRCNET 2005). In 1998, only 10.47 Gigawatt of capacity was constructed, while more than 20 Gigawatt were constructed on average before 1997. In 1999 and 2000, less than 6 Gigawatt was started construction each year (Yi 2006).

The NDRC is a department of the State Council of the People's Republic of China, which was originally founded in 1952 named as State Planning Commission. Then in 1998 it was renamed as State Development Planning Commission. In 2003, it incorporated some functions of former Economy Policy Reform Office of the State Council and the State Economic and Trade Commission, and became what it is now. It is a macro-control department responsible for important economic and social development policies, overall balance and guiding the overall reform of the economic system.

As for electricity industry, its mission is: to study the strategic objectives and deployment of power system development (including development and power grid Development); to study how power system interacts with other departments in the national economy, etc. Power system planning in general can be divided into short-term, medium-term and long-term planning. Short-term planning is generally about five years. It aims to as accurately as possible foresee the demand of both electricity capacity and electricity generation and to balance the capacity and electricity generation every year. It is responsible for the construction of electricity capacity and annual investment of capacity.

As shown in Figure 2, GDP growth rate increased again after 2000. In 2002, China experienced another severe electricity shortage, which reached its summit in 2004. According to the rough estimate made by dispatching department of grid companies, in 2002, there were 12 provinces in China suffering from this electricity shortage. Gap in generating capacity was 20.35 Gigawatt on average. It turned to 24 provinces and 30 Gigawatt in 2003. In 2004, the whole China was suffering from severe lack of electricity, and the gap in generating capacity reached 35 Gigawatt. In 2005, things got better, the gap in generating capacity 25 Gigawatt (DRCNET 2005). The persistent gap between electricity demand and supply was evident again.

The shortage of electricity caused problems to economy. Industries had to shut down their machines in those days of limited electricity, which caused a huge economic loss to investors and local government. As a whole, GDP in China was also largely harmed due to electricity shortage. Take Zhejinag province, one of the most developed economies in China for example. In 2004, Zhejiang Province was short of electricity by more than 75 Terawatt hours, which caused an economic loss of more than 100 billion CNY (Li 2004). In the perspective of people’s lives, people had to restrain themselves from many night activities. Even during daylight hours, they could not full utilize their home appliances. Students above preliminary school had to light up candles in order to read and study. The whole of China really suffered.

The paper first examines the characteristic problematic behavior of China's electricity industry. Then a system dynamics model is developed and used to discover the structure which might be responsible for the problematic behavior. Some policy options were also developed.

2 Literature review

There has been much research addressing the electricity problems in China. Some researchers argued over the characterization of the problem, whether it was electricity shortage, or electricity surplus, or cycles of alternating electricity shortage and surplus. Among these researchers, some also gave their hypotheses about the causes for whatever problem they addressed. However, they either agreed on a cause which I have different views on, or there was disagreement among themselves about their hypotheses. Still, there are some papers talking about policies that can be adopted to avoid electricity shortage and make the electricity industry better in China.

Let us discuss the 3 categories of argument one by one. First, there is disagreement about what the problem really was. In the Seasonal Analysis Report for China's Industries *(zhongguo hangye jidu fenxi baogao)* (DRCNET 2005), it is believed that China's electricity industry has experienced cycles of electricity shortage and surplus since the late 1960s, driven by economic cycles. The ratio between electricity generating capacity and the capacity of electrical equipment was taken as an indicator of the cyclical behavior. Tan and Wang (2007) also believed there were cycles in the electricity industry and the cycles were closely connected to economic cycles. They used elasticity of electricity consumption/generation to GDP growth as the indicator. Elasticity circling around 1 indicates cycles in the electricity industry.

However, in the paper Power Shortage and Water Power Development in Sichuan (*sichuan quedian yu fazhan shuidian*) (Zhu 2004), Zhu discussed what electricity shortage is and argued that whether electricity generation can meet the electricity demand can not be taken as a decisive indicator. There is still an electricity shortage if capacity margin is not enough. In the paper What's Electricity Shortage? (*jiujing shenme shi quedian?*), Zhu (2005) argued that China might have never had a real surplus of electricity so far. He pointed out that elasticity of electricity consumption/generation to GDP growth can not be regarded as objective indicator of whether electricity generating capacity is sufficient or not. Those who think there has been electricity surplus in history only according to the elasticity of electricity consumption/generation do not have a solid argument. Zhu believed there were two indicators which are reasonable, average working hours of generators and capacity margin rate, which has not been a documented feature of the electricity industry though. However, Zhu could not conclude what the problematic behavior was in China.

Other researchers have focused on only recent evidence of shortage. Yang (2004), Liu, Liao et al. (2005), Du and You (2007) and Ma and Xu (2006) all asserted a severe electricity shortage since 2002, which reached its summit in 2004. Their evidence was the gap of both electricity generating capacity and electricity generation in these years.

I agree with Seasonal Analysis Report for China's Industries by taking the ratio of electricity generating capacity and electricity consuming capacity as an indicator. The ratio exhibits cyclical behavior. However, that report did not check carefully whether the center of the cycles was within a normal range or not. By looking into that point, I found the ratio was oscillating around a center which was far less than the supposed-to-be normal index, less than 0.43, see Figure 9. As a result, I think there has been electricity shortage in addition to oscillatory behavior. Zhu made very good points, the basic of which this paper relies on. However, neither of those reports used quantitative measures. And those who thought the problem was electricity shortage focused only on the period since 2002. This paper fills in with quantitative measures by comparing the index of China with other countries, over a long time-scale.

As mentioned above, some of the people who pointed out the electricity problems in China gave their hypotheses about the causes for the problem they asserted. They fall into the second group. Those who agreed the problem was oscillation in the electricity industry almost shared the same hypothesis about the cause, which was economic cycles (DRCNET 2005; Tan and Wang 2007). When economy is growing fast, demand for electricity grows accordingly. Then the profitability of investing in electricity industry also grows, which brings rapid development of electricity industry. When economy slows down, demand for electricity also declines. Then it is less profitable to invest in electricity industry, when electricity industry comes to its recession. Therefore, the development of electricity industry is closely connected to economic development, exhibiting similar cyclical behavior as economy cycles. However, they believed the cycles in electricity industry were 3 or 4 years behind economy cycles due to the construction time.

I do not totally agree with the point of view that electricity cycles were driven by economic cycles. There might be some correlation between electricity cycles and economic cycles. However, cycles in the electricity industry could arise endogenously, i.e. electricity industry itself generates cycles, regardless of economic effect. In this paper, I would like to test my hypotheses for the cyclical behavior.

Among those who agreed the problem was shortage of electricity, there is disagreement regarding the reasons for the shortage. Yang (2004) concluded that there were four reasons: too rapid economic growth, shortfall of electricity capacity construction, weak electricity grid, and inadequate coal supply, since coal is the main source to generate electricity. The four sources all make sense, and Yang had given a wide categorization. However, in this paper, I only focus on the first two reasons: too rapid economic growth and shortfall of electricity capacity construction Because the former drives a high electricity demand and the latter leads to the shortage of electricity generating capacity, the two of which make the key aspects of electricity industry: electricity demand and supply. Electricity grid is potentially one of the most important parts of the electricity industry because it serves the transmission of electricity. However, it causes electricity shortage in a totally different way than electricity capacity does, which is not the focus of interest in this paper. Coal supply is also indispensable for a reliable electricity supply, especially in China, where thermal power accounts for a percentage more than 79% of the total electricity generation. However, this paper only concerns about the reasons for shortage from the perspective of electricity capacity. Indeed, a deep research into the electricity industry needs a comprehensive study of both electricity grid and coal supply. However, in this paper, I have left electricity grid and inadequate coal supply to the future research, which is also a potential limitation of this paper.

Liu, Liao et al. (2005) believed electricity shortage, to a large extent, can be attributed to low efficiency of using electricity. The electricity used per unit GDP in China is far more than that in developed countries. In this sense, the fast-growing GDP in China could have required much less electricity than it actually needed. A higher efficiency of using electricity therefore can greatly lower the electricity demand, as well as to narrow the gap between electricity generating capacity and the desired capacity. I will discuss it later in this paper.

Du and You (2007) believed the fact that price of electricity was exclusively determined by the government was a very important reason for electricity shortage. They said in the paper that even coal price was determined by the market, thus an insensitive price of electricity by the government drives investors to seek for cheap coal, which usually has no easy access, thus causing coal shortage to some extent. They argued again for the importance of coal, and suggested a complete electricity reform. They said even closely associating electricity price with coal price, coal shortage can only be alleviated in short time. And the only solution to solve coal shortage was the reform in the electricity industry. The pricing of electricity is a key issue in the problem of electricity shortage and I will try to evaluate the effect of electricity price in electricity demand later in this paper. However, pricing of coal is beyond the boundary of my research.

Ma and Xu (2006) added that imprecise forecast of electricity demand was also a reason for the long-term electricity shortage. Their hypothesis was that decision-makers made decisions according to the forecast of total electricity demand and that imprecise, often too low, forecast led to inappropriate decisions, which led to electricity shortage. Imprecise forecast of electricity demand might have caused electricity shortage. However, I would like to go deeper to study why the decision-makers made imprecise forecasts, and how to make a better forecast. I will also examine whether imprecise forecast of electricity demand was really a decisive cause for electricity shortage.

In a word, I do not totally agree that electricity cycles were caused by economic cycles, because cycles could arise endogenously. And I will test both hypotheses. I agree with the suggested reasons for electricity shortage by the literature, but I will not include all of them in my research and I will go deeper into some of the reasons that I include in the boundary of my research, such as too rapid economic growth, shortfall of electricity capacity construction, low efficiency of using electricity, imprecise forecast of electricity demand and electricity price elasticity of demand. For example, I will model the relationship between economic growth and electricity demand, and get quantitative measures about it.

Finally, there is much research concerning policies to deal with demand. Most of it focuses on load sharing, which is to shift some part of peak load to other hours when the load from customers is usually lower. This is the so-called Demand Side Management (DSM). The US is the first country in the world to adopt DSM, one aspect of which is load shifting, which is to reduce the peak load within 24 hours to avoid power shortage. This aspect of DSM can work well to remove power shortage within a day. However, it can not help when there is shortage of electricity that could be generated as a whole, because this aspect of DSM by load shifting did not reduce the total amount of electricity demand or increase total generation throughout a year. This is where my research can fill in, because what I am going to study is the electricity capacity shortage averaged over a year. The aim of my research is to help policy-makers make decisions about how much capacity to build, annually and in a macro scope. Another aspect of DSM is to improve the electricity-usage efficiency, in order to save energy. This is where my research can rely on but will go much deeper to model the efficiency, which is affected by electricity price. Then based on the model, I will evaluate how electricity price can improve the efficiency and thus reduce the electricity demand. In this sense, my research falls to the category of DSM but goes deeper, more tangible and detailed.

To sum up, this paper first examines what the real problem was in the electricity system, based on the disagreement by the literature before. Then the paper focuses on the endogenous causes for the cycles in the electricity industry, rather than finding exogenous causes. For the causes which are regarded reasonable for the shortage of electricity, the paper leaves some of them and narrows down the boundary of research in order to go deeper into some of the causes. Finally, in order to compensate one aspect of DSM which focuses on dealing with daily electricity demand, the paper looks at decision-making in a macroscopic view, dealing with annual total electricity demand. At the same time, the paper relies on another aspect of DSM about improving the efficiency of using electricity, but goes much deeper in the field.

Regarding the methodology adopted in this field, I am going to use system dynamics. And this is not the first attempt to model energy problems with system dynamics methodology. Ford (2002) used system dynamics modeling to study the boom and bust in power plant construction in California. Ford argued that competitive electricity markets were prone to the cycles of boom and bust that appear in commodity market. Arango (2006) argued in his PhD dissertation that oscillations in the electricity systems could arise from the internal structure of the system. He used a system dynamics model and designed an experiment with the model underlying. When an investment lag treatment was added, cyclical tendencies exhibited in the electricity generating capacity and electricity price. Ford and Arango both successfully used system dynamics to illustrate the potential for endogenously generated cycles in deregulated electricity markets. In the paper, I will use System dynamics to study the cycles in China's electricity industry, which is regulated, and the long-term electricity shortage in China. Therefore, I will explore both supply and demand side dynamics in this paper, which is an extension of preceding research.

3 Defining the problem dynamically

The main problematic behavior over time--the dynamic problem to be addressed in this paper is the average shortage of thermal electricity generating capacity, from 1980 to 2005. Why the focus is thermal capacity shortage is due to the fact that thermal generation accounts for more than 79% of total electricity generation in China. Plus, thermal generators are more reliable than hydro power, which is subject to natural conditions, and more flexible than nuclear power in terms of capacity utilization rate. One can increase the utilization rate of thermal generators easily to satisfy the soaring demand, not beyond the maximum limit of course. Therefore, the shortage of total electricity capacity can be attributed to the shortage of thermal capacity. Later in the paper, all references to capacity should be understood as references to thermal capacity. The unit for generating capacity is Watt, or some equivalent units, such as Gigawatt and Terawatt. Refer to Appendix A further for background information about the electricity industry.

Average capacity shortage

= Desired capacity – functioning capacity (1)

Where, desired capacity is the capacity that would have been needed to satisfy the electricity demand when generating capacity is used at its sustainable utilization rate (measured in Gigawatt hour per year). Functioning capacity is the capacity that has been finished and is available to generate electricity.

In reality, generators have to work within a certain range of utilization rate, in order to stay in good condition, which can be called a sustainable utilization rate. If generators are kept working beyond the sustainable utilization rate, their performance, i.e. reliability, efficiency will be decreased and they will be more prone to break down.

Sustainable utilization rate is interpreted as sustainable hours of generators have been working over a year, i.e. average working hours of generators shares the concept of "sustainability" and there should be a sustainable range of average working hours for generators. We take upper limit of this sustainable range as the benchmark hours, beyond which generators are not supposed to work; or if they do, are not working in a sustainable way. And desired capacity is electricity demand that is supposed to be met by thermal generators divided by the benchmark hours. However, data about electricity demand is unavailable in reality and it is estimated by electricity consumption, which is also electricity generation. See the equation of desired capacity below.

$$\text{Desired capacity} = \frac{\text{thermal generation}}{\text{benchmark hours}} \tag{2}$$

Average capacity shortage is actually the gap between desired capacity and functioning capacity. See the behavior in Figure 3, which is called a reference mode. Reference mode is a graphical description of dynamic problem, which is gap between desired capacity and functioning capacity over time.

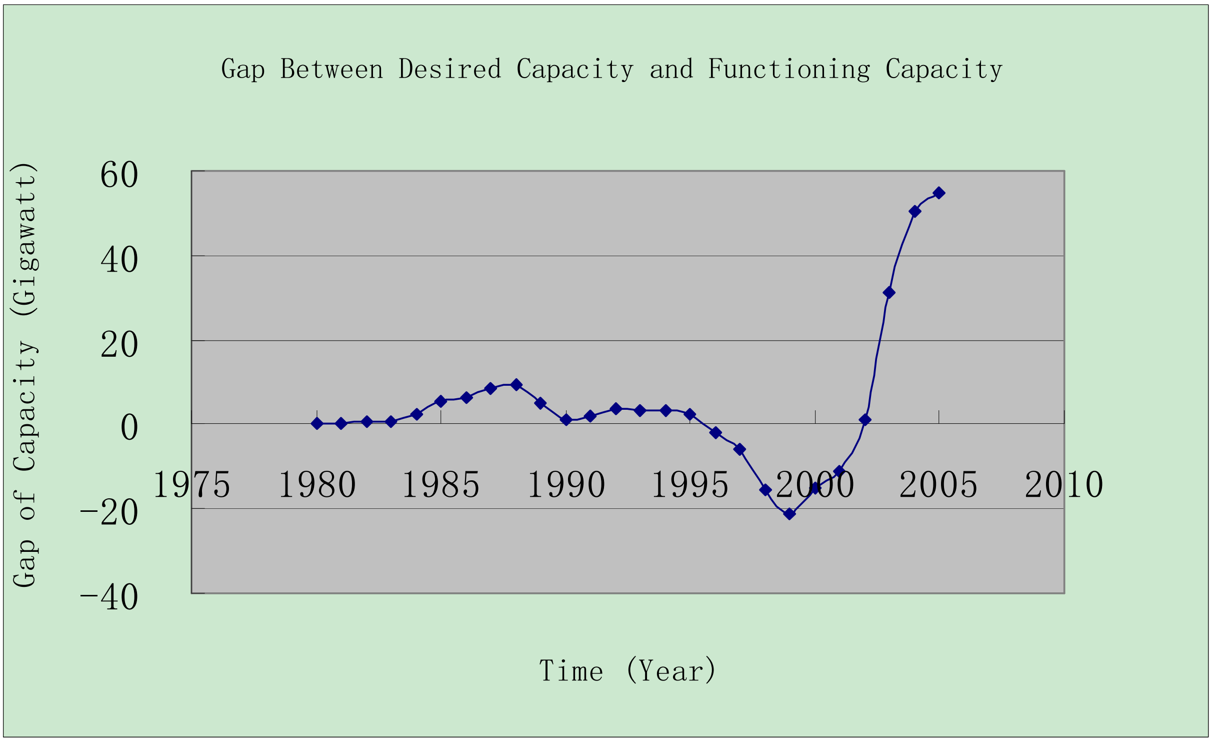


Figure 3 Gap Between Desired and Functioning Capacity in China

Source: Energy Information Administration, United States
World Conventional Thermal Electricity Installed Capacity, January 1, 1980-January 1, 2005
http://www.eia.doe.gov/emeu/international/electricitycapacity.html
World Net Conventional Thermal Electricity Generation, Most Recent Annual Estimates, 1980-2006
http://www.eia.doe.gov/emeu/international/electricitygeneration.html

Figure 3 is derived according to equation (1) and (2), with data about thermal generation and functioning capacity available. However, it is also based on an assumption that the average working hours of thermal generators is supposed to be no more than 5000 hours, the benchmark hours mentioned above, which will be explained later in the section.

We can see oscillations in the reference mode. Plus, the gap between desired capacity and functioning capacity has been bigger than 0 most of the time, which indicates capacity shortage. However, the oscillations seem to have become bigger and bigger over time. In order to get insight into it, I will analyze the reference mode in the following.

Actually, the reference mode shown in Figure 3 is a combination of 3 characteristic behaviors, exhibited by 2 other variables. The historical behaviors of these 2 variables are also reference modes, which give more ways to look at the dynamic problem.

The first one is exponential growth in the functioning capacity, see Figure 4.

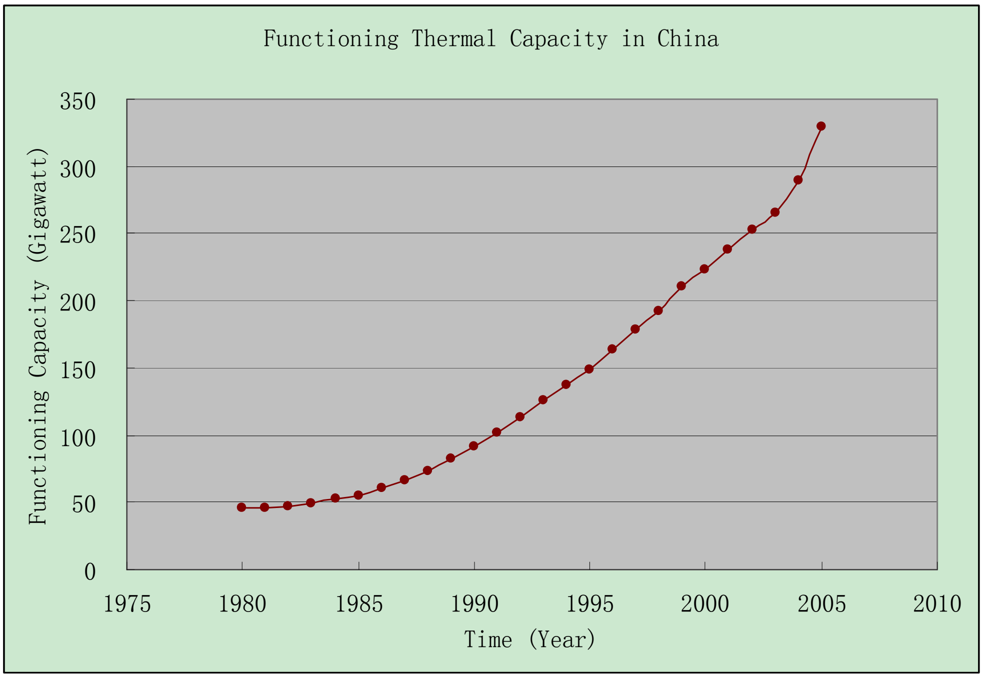


Figure 4 Functioning Thermal Capacity in China

Source: Energy Information Administration, United States
World Conventional Thermal Electricity Installed Capacity, January 1, 1980-January 1, 2005
http://www.eia.doe.gov/emeu/international/electricitycapacity.html

The second one is oscillation in the average working hours of thermal generators, which is consistent with the oscillations in Figure 3. See Figure 5 below.

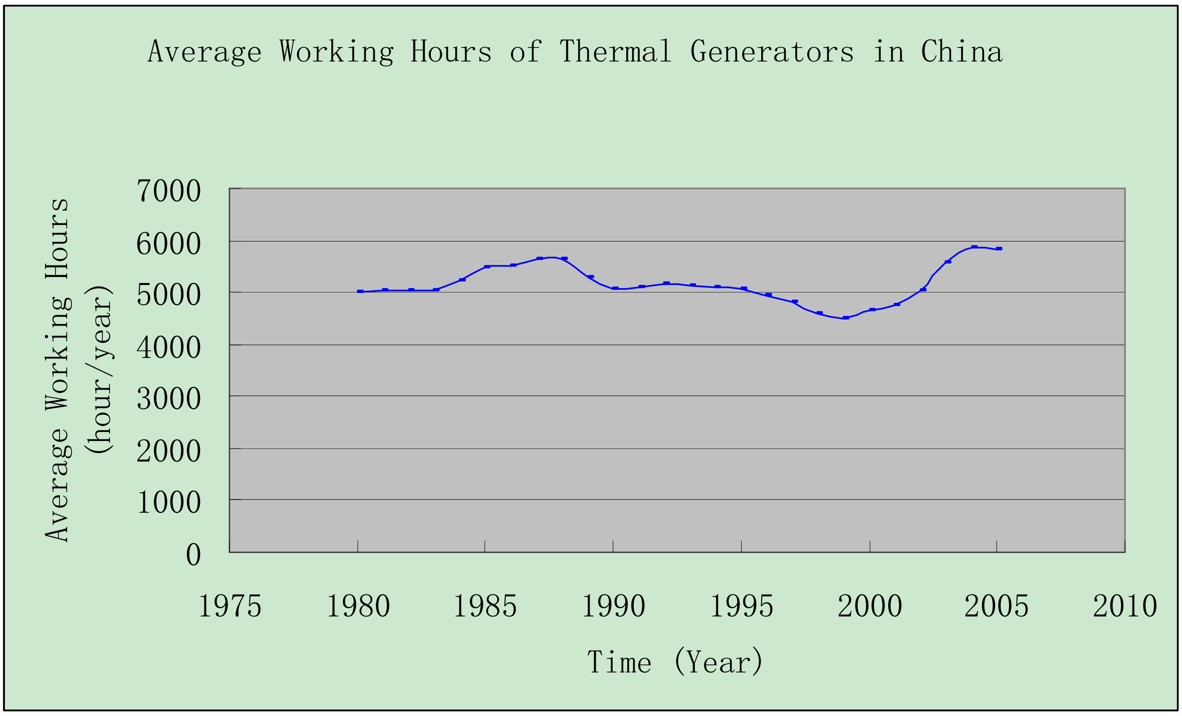


Figure 5 Average Working Hours of Thermal Generators in China

Source: Energy Information Administration, United States
World Conventional Thermal Electricity Installed Capacity, January 1, 1980-January 1, 2005
http://www.eia.doe.gov/emeu/international/electricitycapacity.html
World Net Conventional Thermal Electricity Generation, Most Recent Annual Estimates, 1980-2006
http://www.eia.doe.gov/emeu/international/electricitygeneration.html

From Figure 5 it is not difficult to see that average working hours of thermal generators were above 5000 hours most of time, only less from 1997 to 2001. This is consistent with Figure 3, where gap between desired capacity and functioning capacity has been above 0 most of time. This indicates the third characteristic behavior in the reference mode is short of goal, which can be called sluggish adjustment. Sluggish adjustment is the inability to arrive at a designated goal (Saeed 1998). The goal in this case is the desired capacity.

In conclusion, there are 3 reference modes for the dynamic problem to be addressed in this paper. The characteristic behaviors in the reference modes shown in Figure 3, Figure 4 and Figure 5 are exponential growth, oscillations and sluggish adjustment. The dynamic problems to be addressed in this paper are oscillations and sluggish adjustment over time.

In the following, I will first explain why the reference mode in Figure 3 can be broken into the reference mode in Figure 4 and Figure 5.

First, definitions of some abbreviation letters:

T: thermal electricity generation

C: capacity

G: gap between desired and functioning capacity

H: average working hours

Suppose the annual thermal electricity generation of the i th year is T_i ($1980 \le i \le 2005$), the thermal capacity of the i th year is C_i ($1980 \le i \le 2005$), gap between functioning and desired thermal capacity in the i th year is G_i ($1980 \le i \le 2005$), and average working hours of thermal generators in the i th year is H_i ($1980 \le i \le 2005$).

Then $G_i = \frac{T_i}{5000} - C_i$

While $T_i = C_i * H_i$,

So $G_i = \frac{C_i * H_i}{5000} - C_i = C_i(\frac{H_i}{5000} - 1) = \frac{C_i}{5000} * (H_i - 5000)$

So G_i can be broken up into C_i and (H_i -5000). Therefore the characteristic of G_i is the combination of C_i and (H_i -5000). G_i is shown in Figure 3, C_i is shown in Figure 4 (exponential growth), and H_i is shown in Figure 5 (oscillation and short of goal), from which (H_i -5000) is easy to get.

Then in the following, I will answer the questions left unanswered or at least not answered to the detail above:

1. Why shortage of total generating capacity can be attributed to shortage of thermal capacity?
2. How comes the 5000 hours as the limited average working hours?

Why shortage of total generating capacity can be attributed to shortage of thermal capacity?

First, in China, thermal power accounts for a very large percentage, more than 79%, see Figure 6. It's a dominating source of electricity. Although hydro power has been growing rapidly, not as fast as thermal power though, there is a limit to the growth. It is estimated by the International Energy Outlook 2006 (Energy Information Administration 2006) that the total electricity generating capacity in China will reach 1186 Gigawatt in 2020, while it is stated in

General Situation of Water Resources in China (China Electric Power Information Center) that the total exploitable hydro power capacity is 378 Gigawatt. This means hydro power capacity will account for no more than 31.8% of the total generating capacity even if all the hydro power resources in China has been exploited.

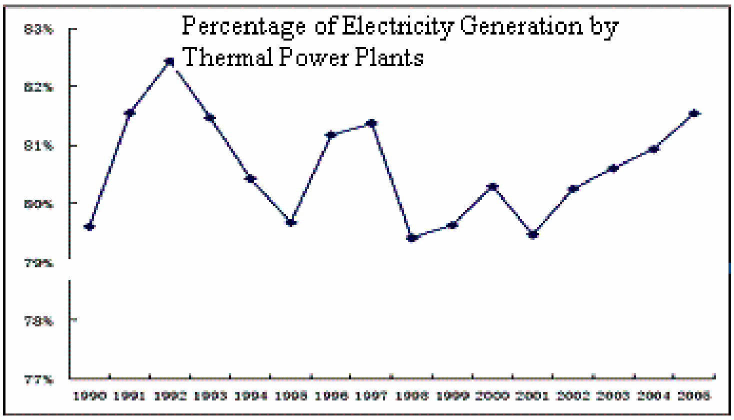


Figure 6 Percentage of Electricity Generation by Thermal Power Plants in China

Source: China Market Research Report Network
Change in the Percentage of Electricity Generation by Thermal Power Plants in China (1990 2005)
http://www.chinahyyj.com/news/w_2007050909139862513.html

Second, electricity generation by hydro power plants and nuclear power plants can not be extended when needed to. One can not force hydro power generators to produce electricity when there is no enough water level in the dam, no matter how urgently electricity is desired. Likewise, nuclear power generators, which account for 2.12% of China's electricity generation in 2005 (Energy Information Administration 2005), work at a nearly fixed utilization rate, which is determined by the nuclear fuel given. And it is difficult to adjust the utilization rate of nuclear generators once the nuclear fuel is given. Therefore, whenever there is electricity shortage, thermal capacity is the only one possible to adjust. In this sense, shortage in the total generating capacity can be attributed to shortage in thermal power capacity.

No more than 5000 hours

Now I will justify the assumption of "no more than 5000 hours", which serves as an important criterion of whether there is capacity shortage or surplus. Let us first define what capacity utilization rate is.

Capacity utilization rate, as its name implies, is the ratio of actual output to the potential output of a capacity. But potential output can be defined in two ways. One is the "engineering" or "technical" definition, according to which potential output represents the maximum amount of output that can be produced in the short-run with the existent stock of capital. Thus, a standard definition of capacity utilization is the (weighted) average of the ratio between the actual output of capacity to the maximum that could be produced per unit of time, with existing plant and equipment (Johanson 1968). Obviously, "output" could be measured in physical units or in market values, but in this paper it is measured in watt or Gigawatt, i.e. physical units. However, as output increases and well before the absolute physical limit of production is reached, most firms (electricity generation companies) might well experience an increase in the average cost of production (even if there is no change in the level of plant & equipment used). For example, higher average costs can arise, because of the need to operate extra shifts, undertake additional plant maintenance, and so on. This is why an alternative approach, sometimes called the "economic" utilization rate, is used to measure the ratio of actual output to the level of output, beyond which the average cost of production begins to rise. In this case, surveyed firms are asked by how much it would be practicable for them to raise production from existing plant and equipment, without raising unit costs (Berndt and Morrison 1981).

Take US for example, in the Federal Reserve Board (US) estimates of capacity utilization for a given industry, the capacity utilization rate is equal to an output index (seasonally adjusted) divided by a capacity index. The Federal Reserve Board's capacity indexes attempt to capture the concept of sustainable maximum output – the greatest level of output a plant can maintain within the framework of a realistic work schedule, after factoring in normal downtime and assuming sufficient availability of inputs to operate the capital in place (Federal Reserve Statistical Release). In a word, the capacity utilization rate is actually the “economic” utilization rate mentioned above. Therefore, by dividing the actual average working hours of thermal generators by the capacity utilization rate in American electric industry, we get the maximum sustainable average working hours of thermal generators. However, data about yearly capacity utilization rate is unavailable. What is available is the average capacity utilization rate in the American electric industry from 1992 to 2007. We can therefore get a rough estimate of maximum sustainable average working hours of thermal generators in US by dividing the actual average working hours of thermal generators by the average capacity utilization rate in American electric industry, see Table 1.

Table 1 Maximum Sustainable Average Working Hours of Thermal Generators in US

Year	Maximum Sustainable Average Working Hours	Year	Maximum Sustainable Average Working Hours
1980	4554.87	1993	4749.07
1981	4412.32	1994	4760.70
1982	4038.40	1995	4774.52
1983	4093.85	1996	4817.36
1984	4239.00	1997	4969.37
1985	4267.45	1998	5210.00
1986	4182.74	1999	5176.21
1987	4376.55	2000	5185.51
1988	4566.39	2001	4863.26
1989	4682.94	2002	4566.91
1990	4597.64	2003	4351.62
1991	4565.14	2004	4371.04
1992	4595.93	2005	4433.50

Source: Energy Information Administration, United States
World Conventional Thermal Electricity Installed Capacity, January 1, 1980-January 1, 2005
http://www.eia.doe.gov/emeu/international/electricitycapacity.html
World Net Conventional Thermal Electricity Generation, Most Recent Annual Estimates, 1980-2006
http://www.eia.doe.gov/emeu/international/electricitygeneration.html
Industrial Production and Capacity Utilization
Table 7 Capacity Utilization, Percent of capacity, seasonally adjusted
Federal Reserve Statistical Release

Note: Assuming the capacity utilization rate of thermal power plants is the same as the other type of power plants in US, which is 86.7% on average from 1972 to 2007.

We can get Figure 7 directly from Table 1, which is easier for us to get the maximum sustainable working hours of thermal generators.

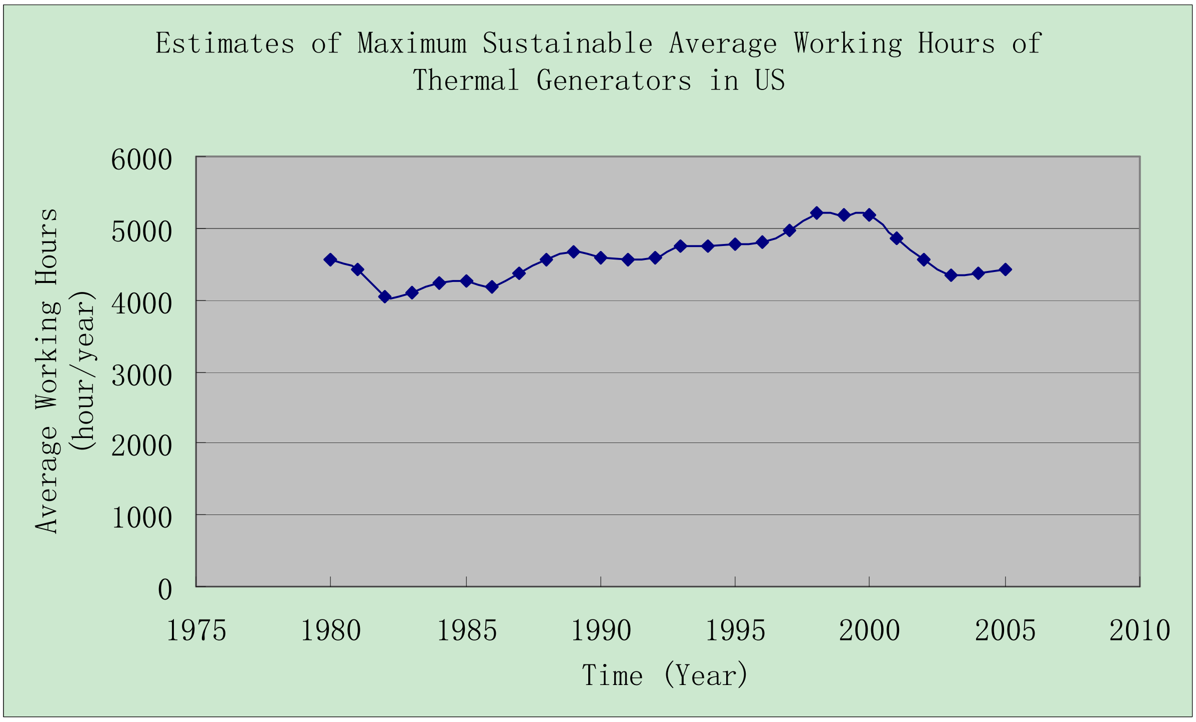


Figure 7 Estimates of Maximum Sustainable Average Working Hours of Thermal Generators in US

It is obvious in Figure 7 that maximum sustainable working hours of thermal generators in US has been stably among 4000~5000 hours, while most of time it is less than 5000, except 3 years from 1998 to 2000. Therefore, it is not a haste to say the maximum sustainable average working hours of thermal generators in US is no more than 5000 hours. As known to us all, US have been playing a leading role in almost all the technological fields in the world. In the mean while, the electricity industry in developed countries on average is more advanced than that in developing countries, including China. Therefore, it is logical to expect the maximum sustainable average working hours of thermal generators in China to be no more than 5000 hours.

In order to make the conclusion that there has been shortage in the thermal capacity more solid, the paper develops some implicit indicators of electricity shortage in the following in the absence of explicit indicators (exact desired thermal capacity).

1. Actual average working hours

Actual average working hours of thermal generators every year is an important indicator of whether capacity is sufficient. As above mentioned, there has not been an absolute way in the world to calculate exactly the maximum sustainable average working hours. Therefore, this paper will resort to comparing the actual average working hours of thermal capacity in China and some other developed countries.

As shown in Figure 8, comparison was made between China (CH), United States (US), Canada (CA), Denmark (DA), Netherlands (NL), United Kingdom (UK), Japan (JA) and Ireland (EI), all of them with a percentage of electricity generation by thermal plants ranging from 63% to 87%, while for China is 81.04%, according to Energy Information Administration. See Figure 8.

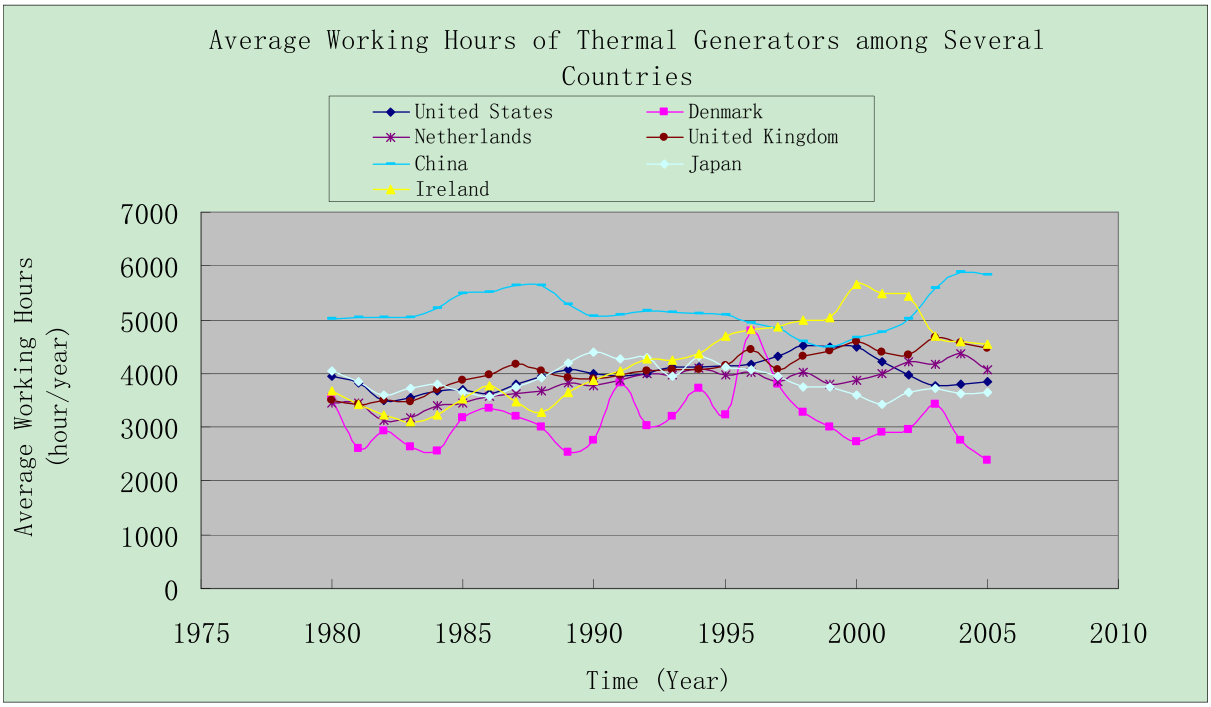


Figure 8 Average Working Hours of Thermal Generators among Several Countries

Source: Energy Information Administration, United States
World Conventional Thermal Electricity Installed Capacity, January 1, 1980-January 1, 2005
http://www.eia.doe.gov/emeu/international/electricitycapacity.html
World Net Conventional Thermal Electricity Generation, Most Recent Annual Estimates, 1980-2006
http://www.eia.doe.gov/emeu/international/electricitygeneration.html

As shown in Figure 8, except Ireland, in which average working hours of thermal generators exceeded that of China in some years, average working hours of thermal generators in China were always more than other countries, except that around 1999, the average working hours decreased and reached its nadir, which was around 4500 hours.

In a word, it is not in a haste to say that average working hours of thermal generators in China were more than the world average, which to some extent indicates a shortage of electricity generating capacity.

In the meanwhile, as shown in Figure 8, the world average working hours of thermal generators seems to be around 4000 hours. Therefore, taking 5000 hours to be the criteria of whether there is capacity shortage or not is a conservative act.

2. Electricity generating capacity VS Capacity of electricity-consuming equipment

The ratio of electricity generating capacity to capacity of electricity-consuming equipment is also an important indicator of whether there is electricity shortage or surplus, as referred to Seasonal Analysis Report for China's Industries (DRCNET 2005). Unfortunately, this ratio is not used in statistics in other countries of the world. It is believed by DRCNET that when the ratio is more than 0.45 (DRCNET, 2005), there is a surplus of electricity, and a shortage is believed to exist when the ratio is less than 0.45. For most of the years from 1981 to 2001, the ratio is less than 0.45. See Table 2 and Figure 9. (Here the electricity generating capacity is the total generating capacity, rather than thermal capacity only, and capacity of electricity-consuming equipment is also the total capacity. The same concept of "total capacity" also applies to capacity margin to be discussed later. This is because it does not make sense to assume that some electricity-consuming equipment uses only thermal electricity or hydro electricity. However, to use total capacity here does not change the conclusion because shortage in total generating capacity indicates shortage in thermal capacity, as discussed above.)

Table 2 Capacity of Electricity Generating Capacity VS Capacity of Electricity-Consuming Equipment

year	electricity generation capacity (10 million watt)	capacity of electricity-consuming equipment (10 million watt)	ratio
1981	6913	16040	0.43
1982	7236	17240	0.42
1983	7644	18635	0.41
1984	8012	19846	0.40
1985	8705	21258	0.41
1986	9382	23411	0.40
1987	10090	26095	0.39
1988	11550	28614	0.40
1989	12664	30859	0.41
1990	13789	34741	0.40
1991	15147	36726	0.41
1992	16653	39858	0.42
1993	18291	42983	0.43
1994	19989	46017	0.43
1995	21722	49047	0.44
1996	23654	52645	0.45
1997	25424	55310	0.46
1998	27729	59395	0.47
1999	29877	64449	0.46
2000	31932	72935	0.44
2001	33861	83148	0.41

Source: State Power Information Network
China Electric Power Information Center
Ratio of electricity generating capacity over capacity of electrical equipment from 1980 to 2001
http://www.sp.com.cn/zgdl/dltj/d0102.htm

Figure 9 is derived directly from Table 2, which makes it easier to read and see the tendencies of changing.

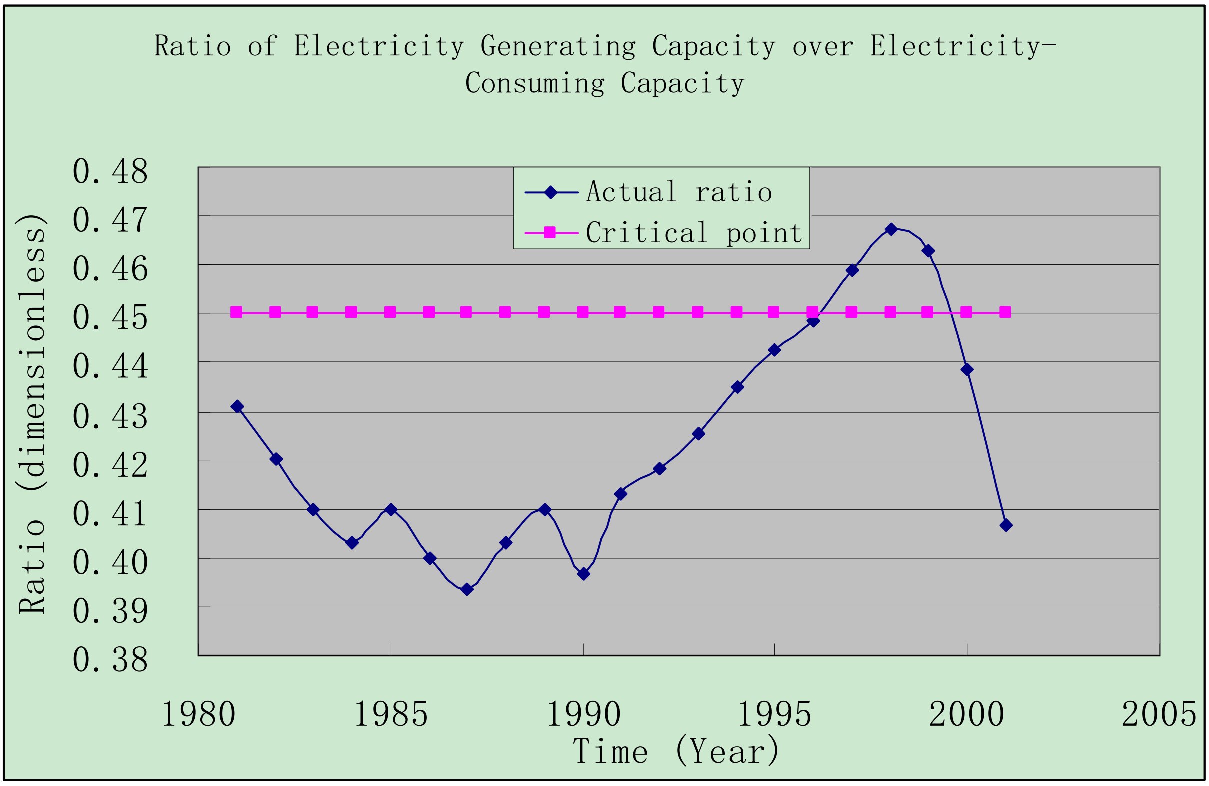


Figure 9 Ratio of Electricity Generating Capacity over Electricity-Consuming Capacity

By putting the graph of ratio and graph of average working hours into one graph, we can find there's consistency between them. In order to make a good comparison, average working hours of thermal generators is standardized instead of the original data. The standardization is first dividing average working hours by 9000 hours in order to make it dimensionless and the ratio (standardized average working hours) between 0.5 and 1. Then 1 minus the ratio is taken as the standardized average working hours of thermal generators, so that the two curves can run in the same direction, making it easier to examine the two graphs. See Figure 10.

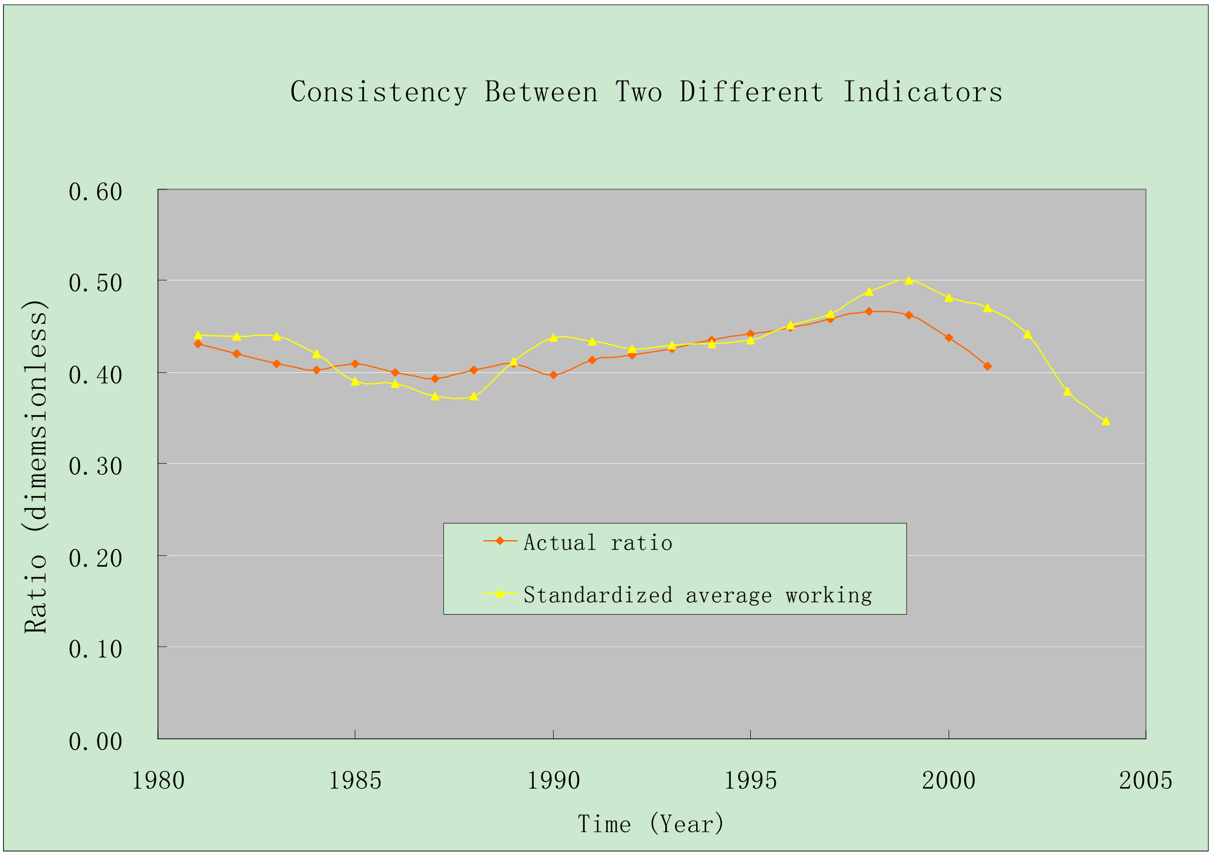


Figure 10 Consistency Between Two Different Indicators

As shown in Figure 10, the two curves almost overlapped each other and the trend of the two curves is almost the same.

3. Capacity margin

Capacity margin is another important indicator of whether the existing capacity is enough to ensure a reliable electricity supply, according to Zhu (2005).

Capacity margin can be described as the capacity required to ensure that the expected demand of the system is met even under situations of unexpected failure of generation during system peak demand or unusual or unanticipated increases in demand. Capacity margin rate is capacity margin over peak load in a year.

$$\text{Capacity margin rate} = \frac{\text{reliable generating capacity - annual peak load}}{\text{annual peak load}} * 100\% \qquad (3)$$

Capacity margin rate has already been calculated as an important index in several countries, such as Australia, Canada, Demark, Finland, Ireland, Italy, Spain, United Kingdom and United

States. Figure 11 is the capacity margin in Contiguous US from 1995 to 2006, which is above 15% most of the time.

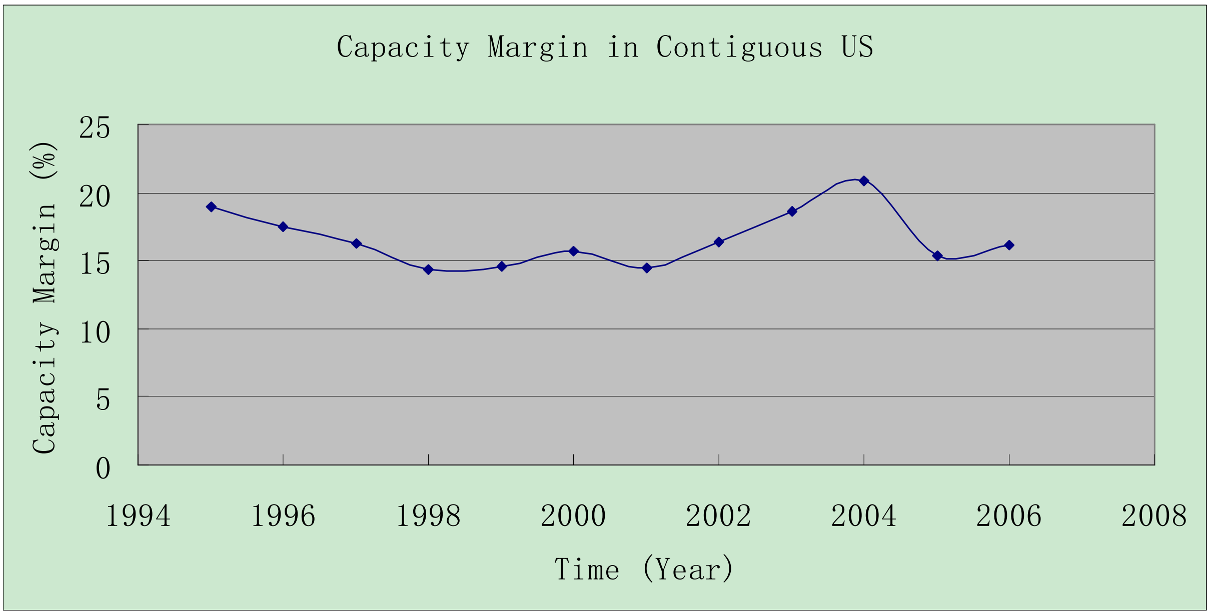


Figure 11 Capacity Margin Rate in Contiguous US

Source: Energy Information Administration, United States
Electric Power Annual 2006
Net Internal Demand, Capacity Resources, and Capacity Margins by North American Electric Reliability Council Region, Summer, 1995 through 2006
http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

In China, capacity margin has not been a documented feature of the electricity industry. There's no official document regulating reliable generating capacity and annual peak load, so it is difficult to attain data about capacity margin rate.

However, some assumptions can be made about reliable generating capacity and peak load. Suppose reliable generating capacity is 80%~93% (China Electric Power Information Center) of the total installed capacity. Also, suppose peak load in every year is 35% (China Electricity Council 2005)~45% (The maximum percentage without making capacity margin negative, because according Figure 9, installed generating capacity is less than 45% of total capacity of electricity-consuming equipment.) of the capacity of electricity-consuming equipment.

Therefore, based on these assumptions,

Capacity margin rate

=

$$\frac{(80\% \sim 93\%) * \text{installed generating capacity} - (35\% \sim 45\%) * \text{electricity consuming capacity}}{(35\% \sim 45\%) * \text{electricity consuming capacity}} * 100\% \quad (4)$$

According to the electricity-generating and electricity-consuming capacity in Table 2, we got Figure 12.

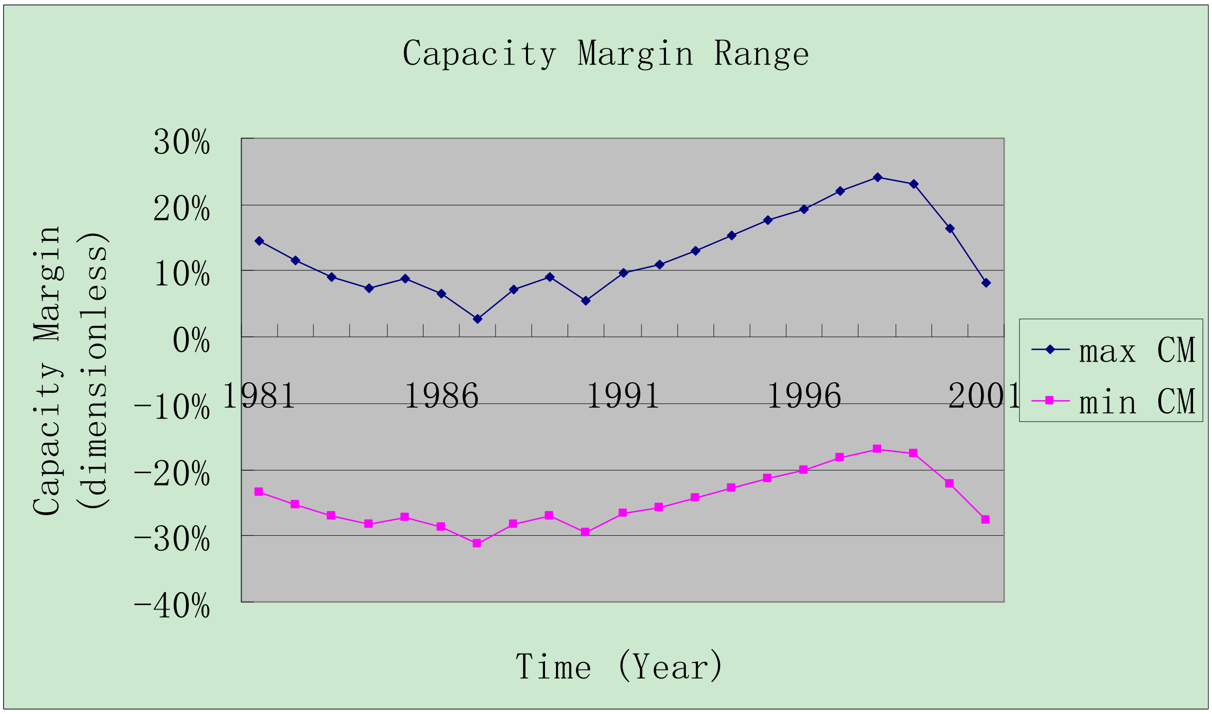


Figure 12 Maximum and Minimum Limit of Capacity Margin Rate in China

Source: State Power Information Network
China Electric Power Information Center
Ratio of electricity generating capacity over capacity of electrical equipment from 1980 to 2001
http://www.sp.com.cn/zgdl/dltj/d0102.htm
Main technical and economic index (1952-2001)
http://www.sp.com.cn/zgdl/dltj/d0105.htm
China Electricity Council
Annual report of electricity industry in 2005

As shown in Figure 12, the capacity margin rate in China is below 15% most of time, in some years even less than 10%. China's GDP has been growing at a higher rate than the US. Electricity demand has a large potential to increase, unlike US, whose electricity market has been mature for a long time. Therefore, China is supposed to have a bigger capacity margin rate than

US, in order to ensure a reliable domestic electricity supply. In the meanwhile, State Electricity Regulatory Commission, China (1994) regulates in Methods of Implementing Gird Coordination and Management Byelaw (*dianwang diaodu guanli tiaoli shishi banfa*), NO. 23 that the total capacity margin rate is not supposed to be less than 20%. Due to the rapid economic growth rate in China, capacity margin rate needs to be even higher than 20% in order to ensure a secure electricity supply and meet the roaring electricity demand.

We can combine the capacity margin in Figure 12 with the two other indicators discussed above, see Figure 13.

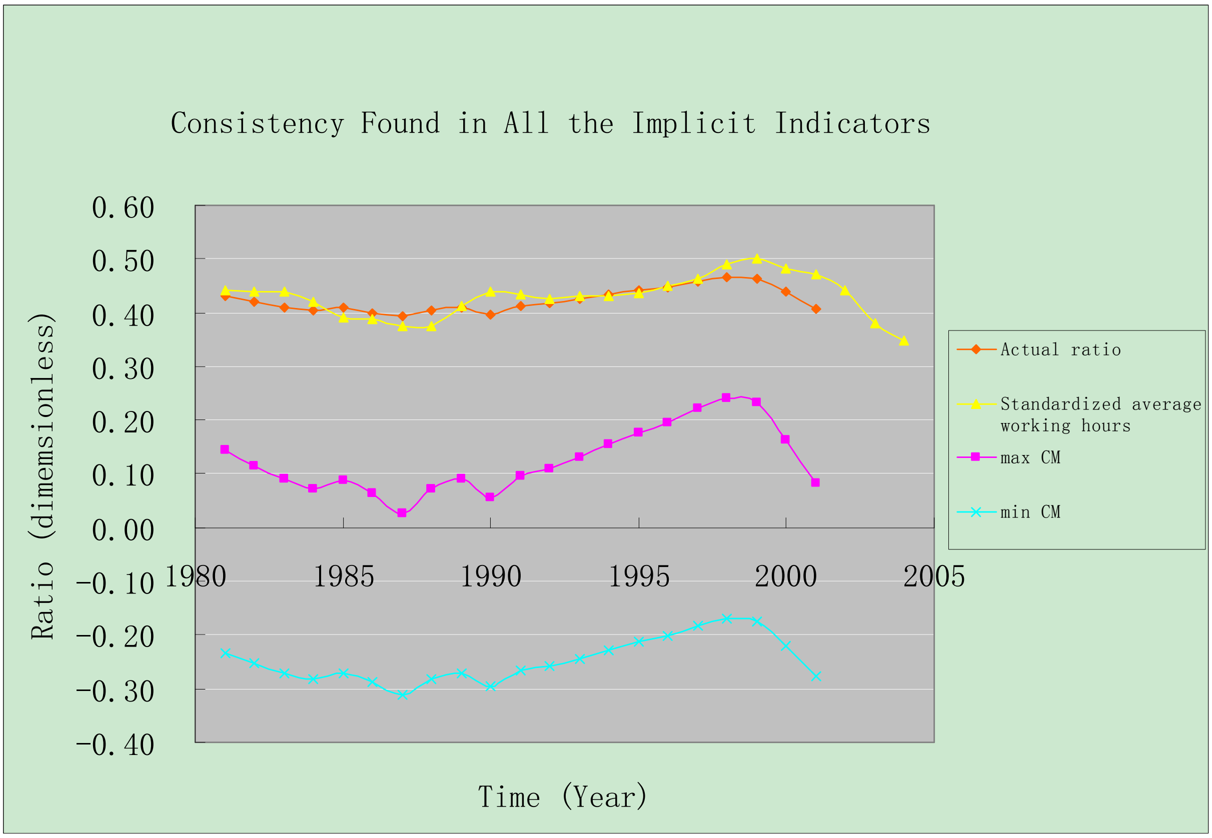


Figure 13 Consistency Found in All the Implicit Indicators

Therefore, there is evidence that China has experienced long-term electricity generating capacity shortage ever since 1980. Even if from 1997 to 2001 China was not suffering from severe shortage of electricity, electricity shortage still dominated in the history of China's electricity industries in the past few decades.

However, in order to gain a deeper insight into the whole problem, it is better to look at the data for indicators before 1980 also, starting from 1965. Since only data about average working hours is available, let us trace back to average working hours of thermal generators starting from 1965. See Figure 14. (Here, the focus is to discover the characteristic behavior in the average working hours of thermal generators in China.)

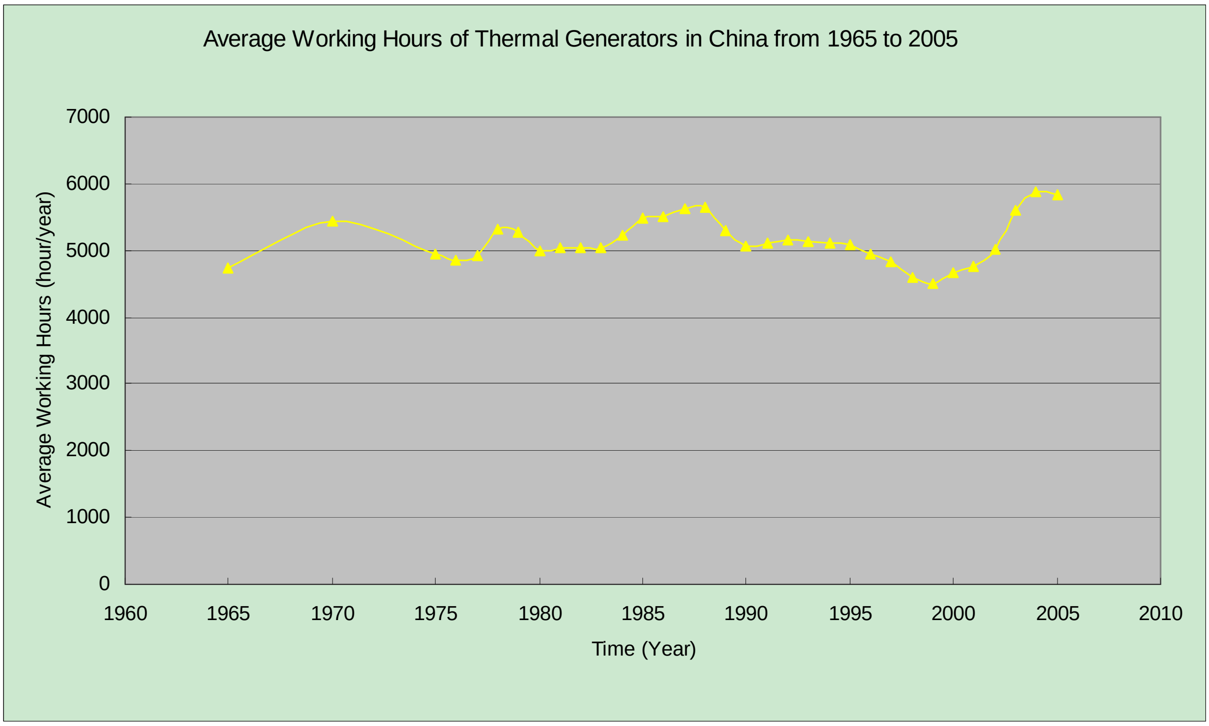
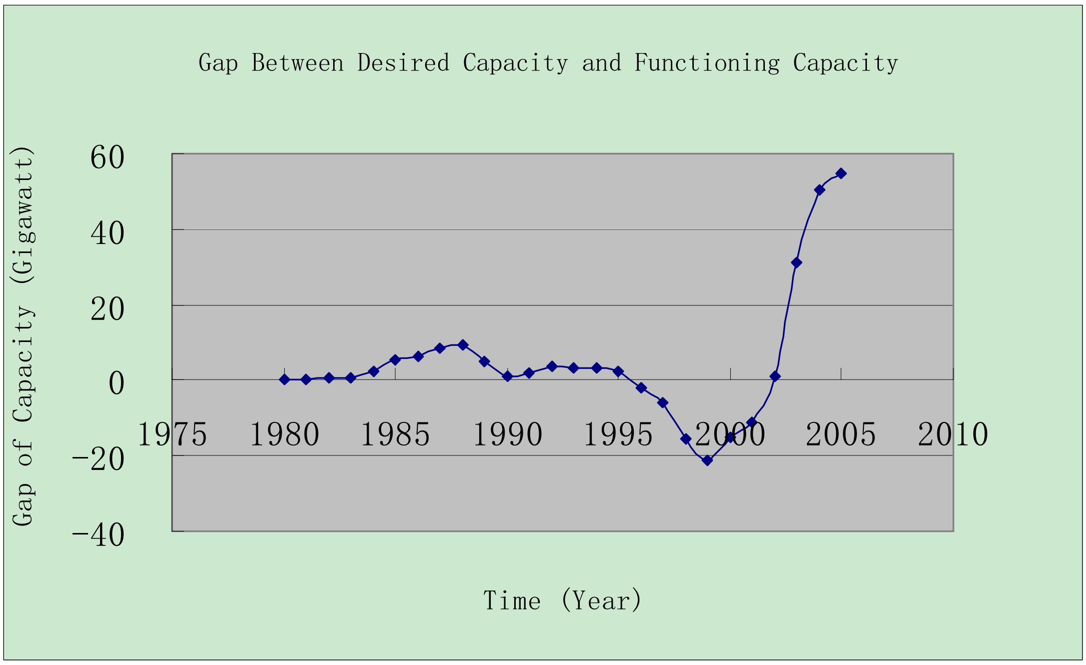


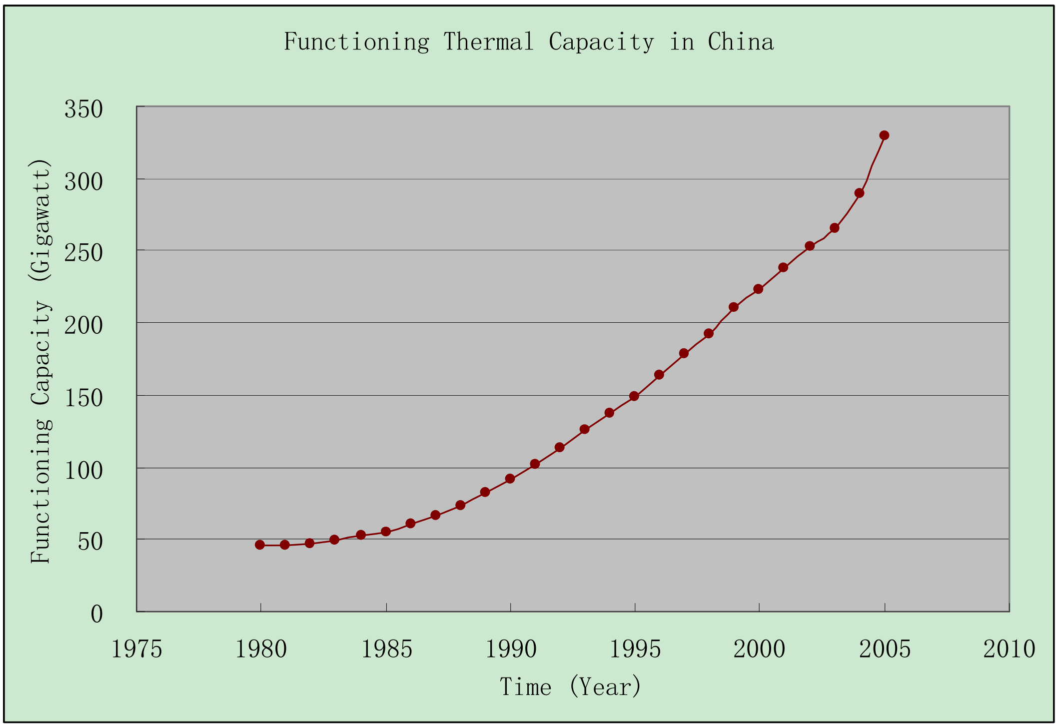
Figure 14 Average Working Hours of Thermal Generators in China from 1965 to 2005

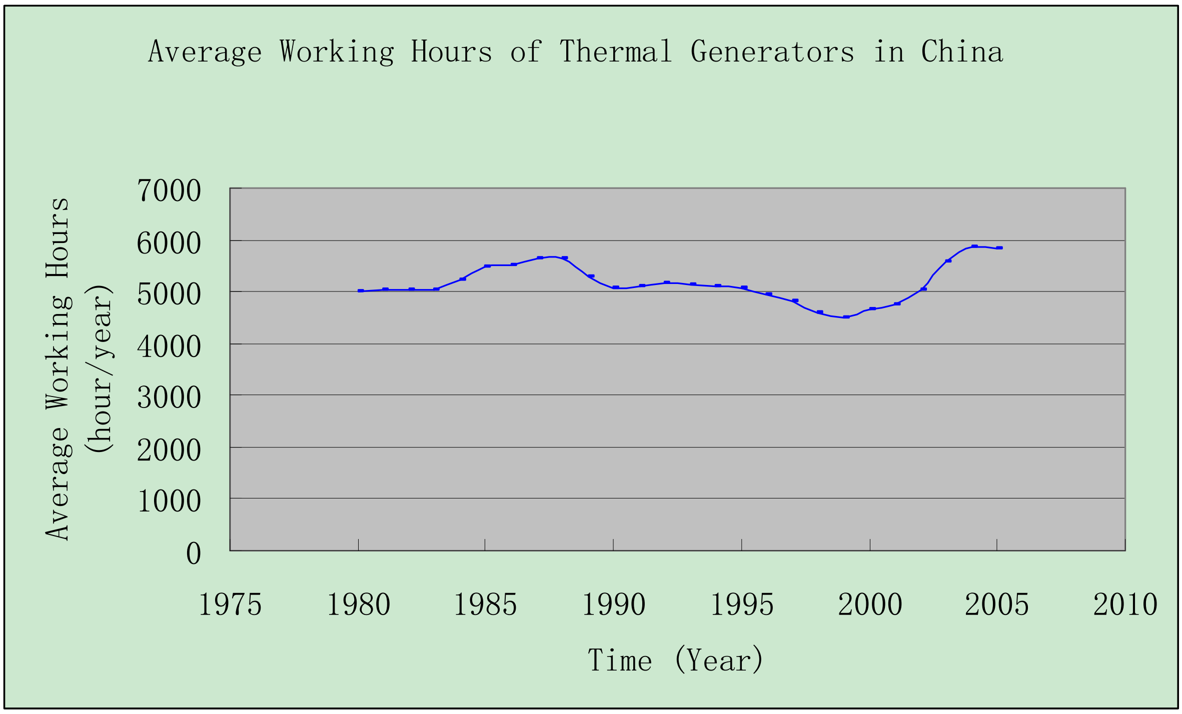
Source: State Power Information Network
China Electric Power Information Center
Hydro and thermal power composition in both installed capacity and electricity generation from 1952 to 2001
http://www.sp.com.cn/zgdl/dltj/d0104.htm
Energy Information Administration, United States
World Conventional Thermal Electricity Installed Capacity, January 1, 1980-January 1, 2005
http://www.eia.doe.gov/emeu/international/electricitycapacity.html
World Net Conventional Thermal Electricity Generation, Most Recent Annual Estimates, 1980-2006
http://www.eia.doe.gov/emeu/international/electricitygeneration.html

As shown in Figure 14, the center around which average working hours of thermal generators is oscillating is more than 5000 hours. Therefore, to this point, we can believe there has been long-term shortage in thermal capacity in China in the past decades.

However, what is shown in Figure 14 is for the purpose of further substantiating the reference modes which were discussed at the beginning of this section. The dynamic problem to be addressed is the gap between desired and functioning capacity, which could be expressed with the help of functioning capacity and average working hours of thermal generators. Thus here I repeat the reference modes of capacity gap, functioning capacity and average working hours. See graphs below.







4 Dynamic hypothesis

As shown in the reference modes above, there are oscillations in the gap between desired and functioning capacity. Plus, the gap has been non-negative most of the time. This reflects in the oscillations in the average working hours and they are above 5000 hours most of time. This section will offer a tentative explanation, a hypothesis for the problematic dynamic behavior, i.e. a dynamic hypothesis. The dynamic hypothesis will be given by both causal loop diagram and stock and flow diagram.

4.1 Causal loop diagram

As discussed before, the characteristic behaviors in the reference modes are oscillation, exponential growth and sluggish adjustment. A major counteracting feedback loop with significant delays could be responsible for oscillatory behavior (Sterman 2000). Exponential growth could be caused by a positive feedback loop, either endogenous or exogenous. As for sluggish adjustment, it could occur when the decision makers have a wrong goal, a goal that is lower than what it is actually. Sluggish adjustment can also occur when the counteracting feedback loops in the system are too weak to properly adjust the system to its goal. Let us first see the hypothesis for oscillation.

4.1.1 Oscillation

The major counteracting feedback loops in the electricity industry are shown in Figure 15.

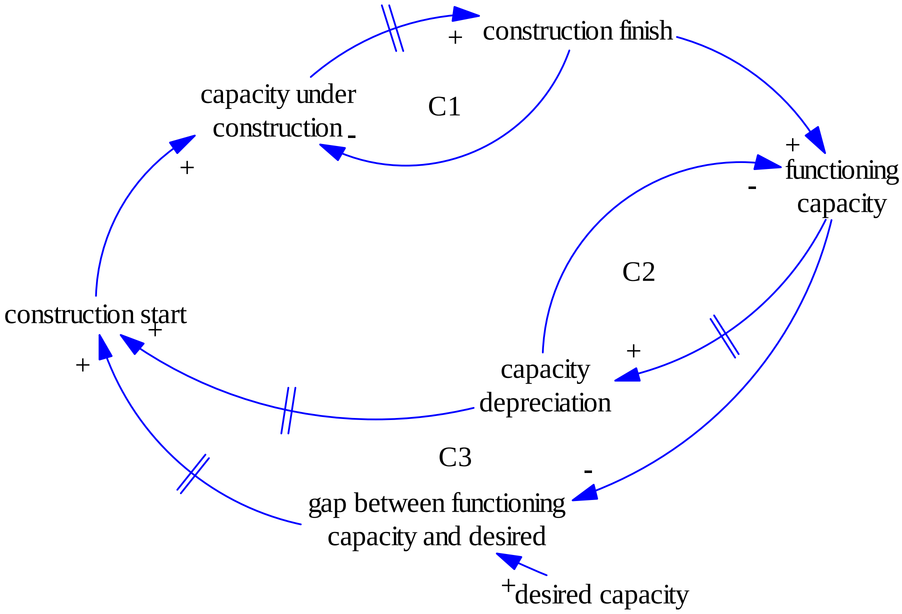


Figure 15 Causal Loop Diagram: Feedback Loops in the Capacity Construction Sector, including Structure Responsible for Oscillations in the Reference Mode

As shown in Figure 15, Loop C3 is a major counteracting feedback loop with more than one delay, which could cause oscillations in the reference mode. Usually NDRC compares the functioning capacity with desired capacity, and sees the gap between them. Then they will start constructing new capacity in order to close the gap. However, there is a big delay from the new capacity being constructed to the capacity being finished. The new capacity being constructed accumulates as the capacity under construction, which appears to be ignored by NDRC. NDRC keeps closing the gap according to their estimates about the gap, while ignoring some capacity is on the way to be delivered. Loop C3 has some similarity in Figure 16, the generic behavior and structure of oscillation. The structure in Figure 16 is also a major counteracting feedback loop with significant delays. Refer to the Appendix B about system dynamics principles.

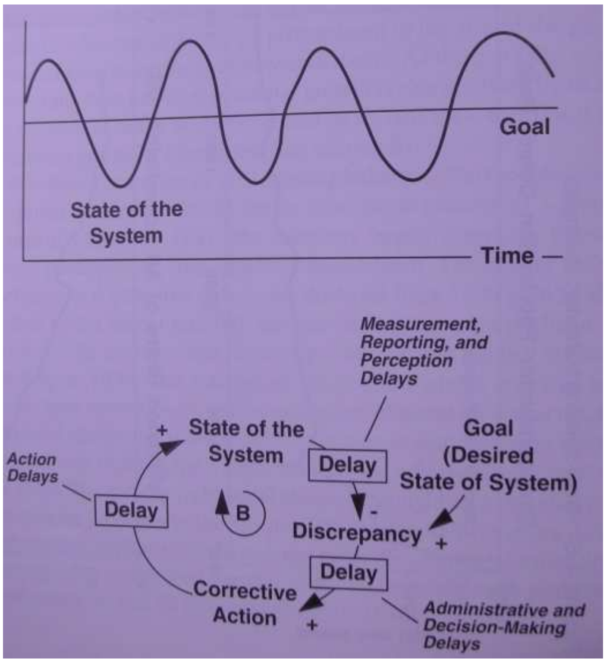


Figure 16 Oscillation: Structure and Behavior

Source: John D. Sterman
Business Dynamics Systems Thinking and Modeling for a Complex World
(Sterman, 2000)

4.1.2 Exponential growth

The exponential growth exhibited in the reference mode of functioning capacity could be caused by an exogenous positive feedback loop, GDP in this case. The loop driving GDP is not shown explicitly in the paper. However, GDP grows at some growth rate every year (Figure 18), which must be driven by a positive feedback loop. Exponential growth in GDP causes exponential growth in total electricity demand, which finally causes exponential growth in desired capacity, which is a goal of the construction system. Therefore, functioning capacity exhibited exponential growth.

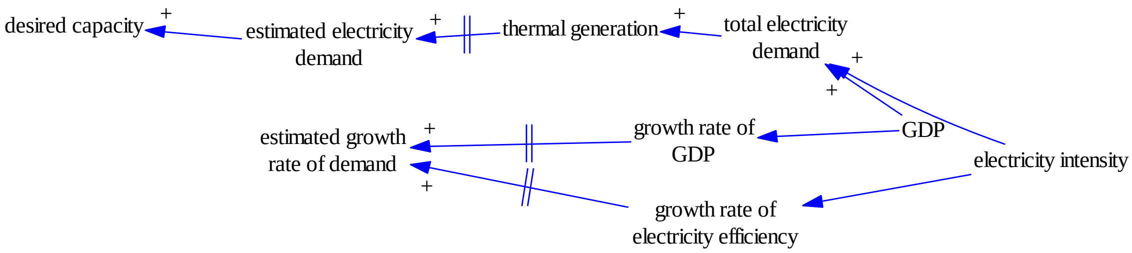


Figure 17 Causal Diagram: Structure Responsible for Exponential Growth in Reference Mode

See the real GDP in China in Figure 18. GDP exhibited exponential growth.

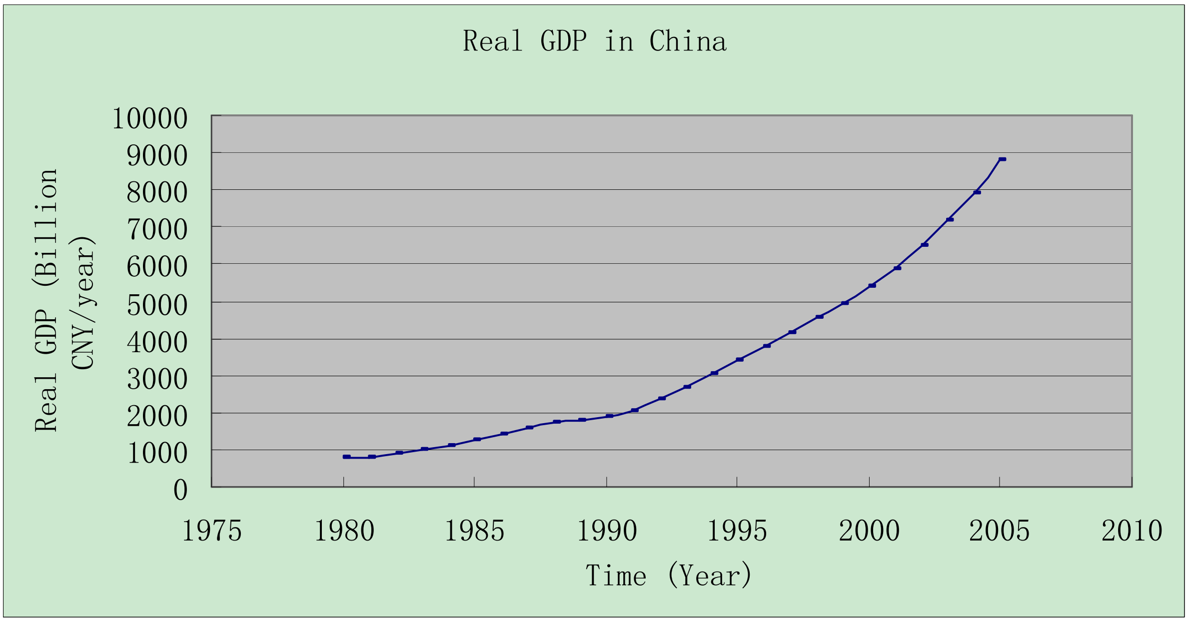


Figure 18 Real GDP in China from 1980 to 2005

Source: National Bureau of Statistics of China (2007)
Gross Domestic Product
http://www.stats.gov.cn/tjsj/ndsj/2007/indexch.htm
Global Econ Data
China, GDP deflator, 1980~2006
http://www.econstats.com/weo/C035V021.htm

4.1.3 Sluggish adjustment

Now let us move to sluggish adjustment. Sluggish adjustment is the inability to arrive at a designated goal, enough capacity in this case. It is a pervasive problem both in physical and social systems with inadequate feedback tracking discrepancy, although this phenomenon occurs together with other patterns (Saeed, 1998), oscillation in this case. Sluggish adjustment usually results from an inappropriate goal or a weak balancing feedback loop. Now let us combine Figure 16 and Figure 17 into one big causal loop diagram to see how sluggish adjustment occurs.

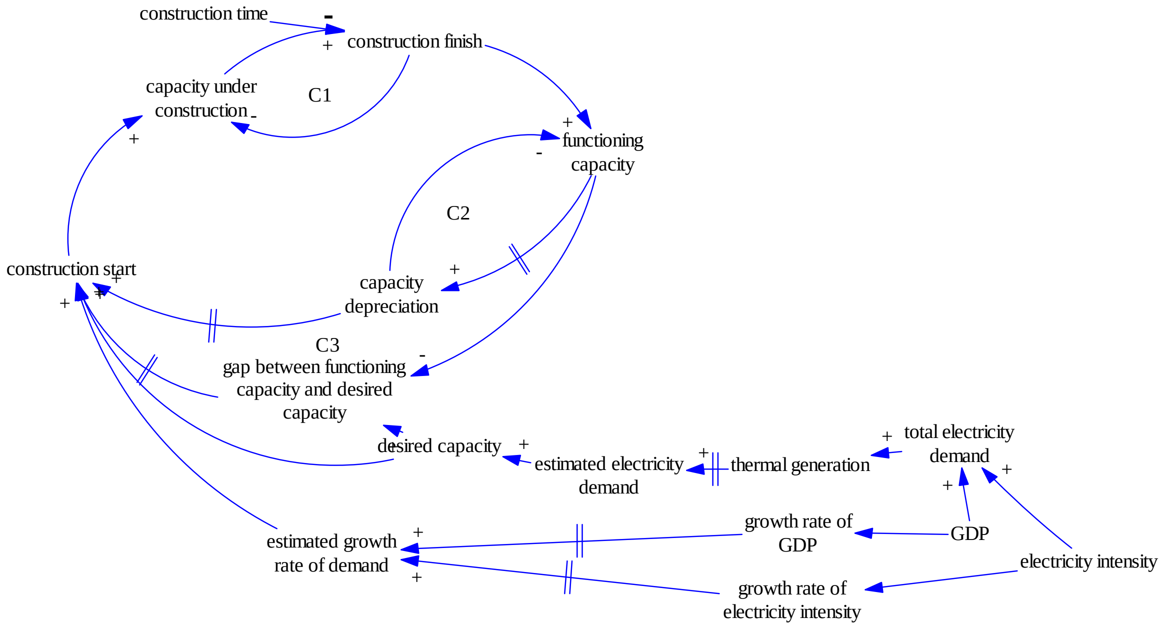


Figure 19 Causal Loop Diagram: Overall, including Sluggish Adjustment in Reference Mode

As shown in Figure 19, when GDP grows exponentially, it causes desired capacity to grow exponentially, eventually functioning capacity and capacity depreciation. In order to make functioning capacity keep up with desired capacity, capacity under construction should be big enough to ensure a big enough construction finish, which adds to functioning capacity. Since there is a delay (construction time) from capacity under construction to construction finish, the longer the construction time, the bigger capacity under construction should be and this requires big construction start. However, there is no causal relationship between the construction time and construction start in Figure 19. Therefore, ignorance of construction time when deciding construction start could be a reason for capacity shortage.

There is a delay from thermal generation to estimated electricity demand (desired capacity). There is also a delay from growth rate of GDP and growth rate of electricity efficiency to estimated growth rate of total demand, which is added to construction start. There is also a delay from capacity depreciation to construction start, so there is also an underestimate of capacity depreciation, especially when capacity depreciation is growing exponentially. Therefore, underestimates of demand and an underestimate of capacity depreciation could also be the reason for electricity capacity shortage.

Fast growth rate of China's GDP and improper electricity pricing mechanism add to the capacity shortage. When GDP grows rapidly, and it drives rapid growth in electricity demand if electricity intensity fail to decrease enough so as to offset part of the growth in GDP, which can be caused by inactive electricity price. The faster the growth is in GDP (electricity demand) and the slower growth in electricity intensity, the more it is possible to underestimate electricity demand (desired capacity) and capacity depreciation.

There is one thing to note that in Figure 19, there is no link from functioning capacity to thermal generation, which is due to the fact that thermal generation is driven by electricity demand, rather than functioning capacity. However, thermal generation is constrained by functioning capacity for sure. I will take this into account in the stock and flow diagram and model formulation part, so as to make the model robust under extreme conditions.

In conclusion, loop C3 could be responsible for oscillations in the gap between desired capacity and functioning capacity and in the average working hours of thermal generators in the past decades. Ignorance of construction time when deciding construction start could be the reason for capacity shortage. Underestimates about electricity demand (desired capacity) and capacity depreciation could also be part of the reasons for capacity shortage. Too fast growth in GDP and improper electricity pricing, which fails to reduce electricity intensity, add to the underestimates and thus add to capacity shortage.

Here is a boundary chart for the model developed in this paper.

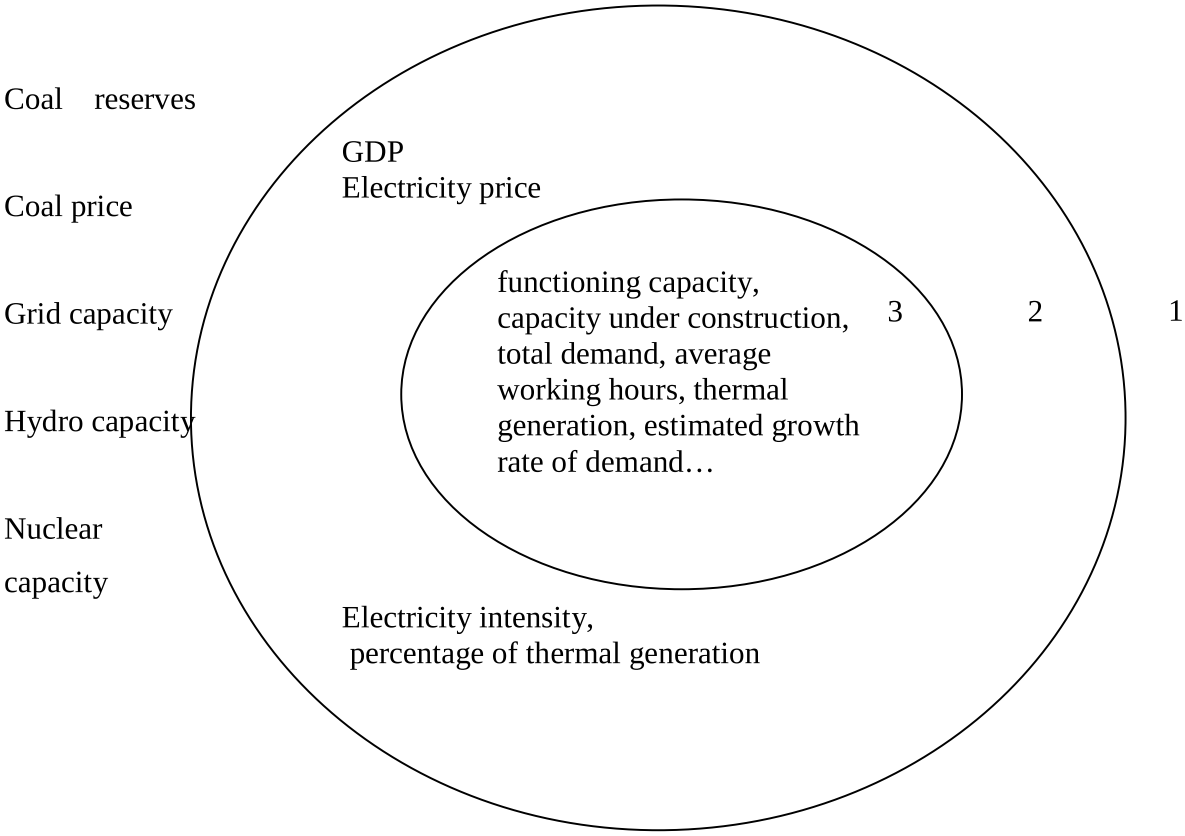


Figure 20 Boundary Chart of Studied System

Note: 1-beyond boundary; 2-exogenous variables; 3-endogenous variables

Table 3 lists all the variables that are out of boundary and exogenous variables and explains why. The endogenous variables will be left later in the section when I construct stock and flow diagram of the model.

Table 3 Explanation about Variables That Are Out of Boundary and Exogenous Variables

Variables out of boundary	**Why**
coal reserves	coal can not help when there is no generating capacity
Coal price	Coal price determines cost of electricity, which is beyond boundary
grid capacity	grid capacity does not produce electricity
hydro capacity	the focus of this paper is thermal capacity
nuclear capacity	the focus of this paper is thermal capacity
Exogenous variables	
GDP	GDP is affected by many factors which are beyond boundary
Electricity intensity	There is a trend for electricity intensity to decline over time, even without the effect of electricity price
Electricity price	Electricity price is hardly affected by the feedback from the model during the time period under study, from 1980 to 2005
percentage of thermal capacity	the percentage is very stable

4.2 Decision rules of electricity capacity construction

Before we move to the stock and flow diagram of the model, I will explain the decision rules of electricity capacity construction, to gain confidence in the causal loop diagrams discussed above and the model itself that will be discussed later in this section.

My hypothesis about how decision makers, the NDRC makes decisions is as follows, divided in several steps:

a) Forecast annual total electricity demand, which is based on past electricity consumption (Xu 2006). Then forecast the growth rate of demand and add to past electricity consumption so as to get electricity demand forecast, according to what Wang Yeping, General Manager of South Grid Company, which is one of two grid monopolies in China, said in his report to NDRC about 11th five-year plan and 2020 long-term target for electrical power industry (Wang 2003). The growth rate of demand is based on GDP growth and change in electricity intensity, according to Seasonal Analysis Report for China’s Industries *(zhongguo hangye jidu fenxi baogao)* (DRCNET 2005).

b) Decide how much demand has to be satisfied by thermal generators, according to the percentage of electricity generation thermal power accounts for.
c) Calculate the desired capacity of thermal generators based on the estimate of electricity demand and benchmark working hour of generators.
d) Calculate the gap between existing (functioning) capacity and desired capacity.
e) Average the depreciated generators in the past year and compensate the capacity in the next year.
f) Close the gap with some time period, at least implicitly, in mind.

NDRC does not invest directly in the capacity construction after 1985. Multiple types of investors, as discussed in Section 1, are those who invest directly. However, they need to apply to NDRC for the license to construct capacity. NDRC then decides whether to approve the application or not. The only drive for investors to invest capacity is the profitability of investment, which depends on potential electricity demand and the difference between electricity price and cost. However, NDRC does guide the investors to properly invest (close the gap between desired capacity and functioning capacity), through administrative or financial or tax measures, or even electricity price. But these measures are beyond the boundary of my research. Any way, NDRC has the capacity to control capacity construction start, making it more or less equal to their estimates of the gap of capacity.

There is great similarity in the decision rules and the generic structure of oscillation (Figure 16) and sluggish adjustment. The first 3 steps of decision-making are to find the goal of the generating capacity. Then comparing the functioning capacity with the goal gets the discrepancy, step d). Then decision makers decide how quickly to adjust the capacity to the goal, step f). This period of adjustment time and the time it takes for NDRC to coordinate with investors are the administrative and decision making delays. Then new capacity is started construction in order to close the gap. However, usually it takes about 3 years for a thermal power generator to be finished and start to generate electricity. This construction time is the action delay. Therefore, the decision-making rules are completely consistent with the generic structure of oscillation. However, whether the decision-making rules are consistent with the way NDRC really makes decisions needs to be tested through model validation, which will be discussed in the model validation part.

Regarding to sluggish adjustment, as discussed above, when deciding construction start, no thought is given to the time delays of construction (construction time) thus capacity under construction is not big enough to ensure the as fast growth in functioning capacity as in desired capacity. Continual underestimates in the growth rate of total electricity demand and capacity depreciation can also be the source of capacity shortage. Too fast growth in GDP and slow decline in electricity intensity, which could be caused by the ineffective pricing mechanism, drives fast growth in electricity demand, which adds to the underestimates.

In the following I will explain the origin of the causal loop diagrams, using stock and flow diagrams. It is explained in the same sequence as in causal loop diagram: structures responsible for oscillation, exponential growth and sluggish adjustment as a whole.

4.3 Stock & Flow Diagram

In this part, I will discuss stock and flow diagram in the exactly in the same sequence as causal loop diagram. First, I will give the stock and flow diagram of capacity construction sector, which includes the structure responsible for oscillations in the reference mode. Then I will give the stock and flow diagram of demand sector, which includes the structure responsible for exponential growth in functioning capacity. Afterwards, I will combine the two sectors into one and discuss why there is sluggish adjustment.

4.3.1 Oscillation

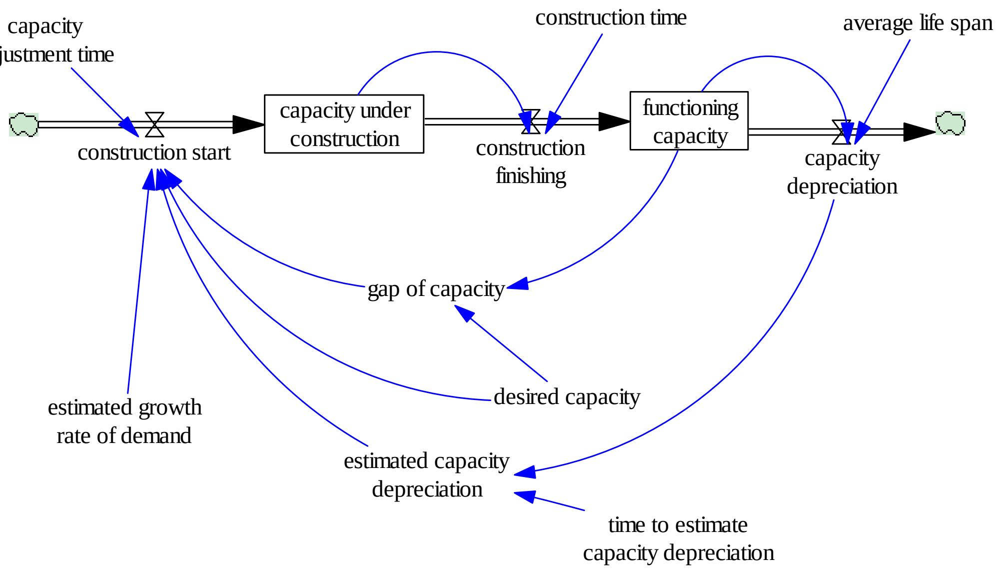


Figure 21 Stock and Flow Diagram: Capacity Construction Sector, including Structure Responsible for Oscillation in the Reference Mode

First I will explain the structure in Figure 21 step by step. Capacity can be seen as the equivalent of an accumulation of generators. So it can be conceptualized as a stock, the unit of which is Gigawatt. We call this stock of capacity functioning capacity, which is the capacity that has been finished and is ready to generate electricity. Every year there is some new capacity added to the stock, while at the same time some old capacity is depreciated, after an average life span.

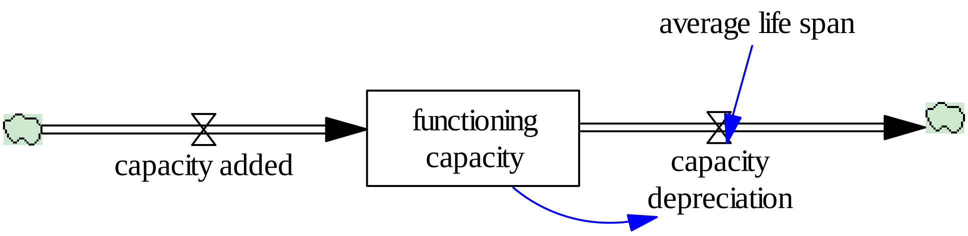


Figure 22 Stock and Flow Diagram of Capacity: One Stock

We can conceptualize another stock called capacity under construction, because it takes time to build capacity. All the capacity that is being constructed accumulates in this stock.

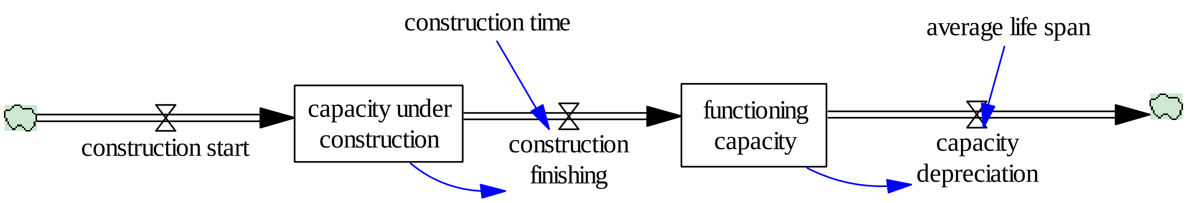


Figure 23 Stock and Flow Diagram of Capacity: Two Stocks

As mentioned above, we hypothesize that decision makers take the capacity that is depreciated into consideration when deciding construction start, i.e., the capacity depreciated has to be compensated afterwards; otherwise there would be steady state error. See Figure 24 below.

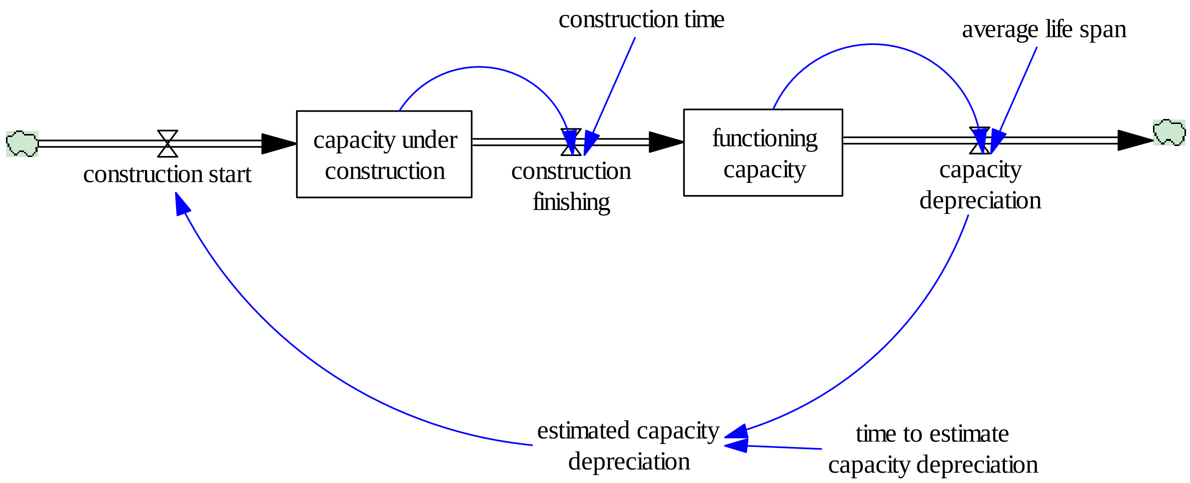
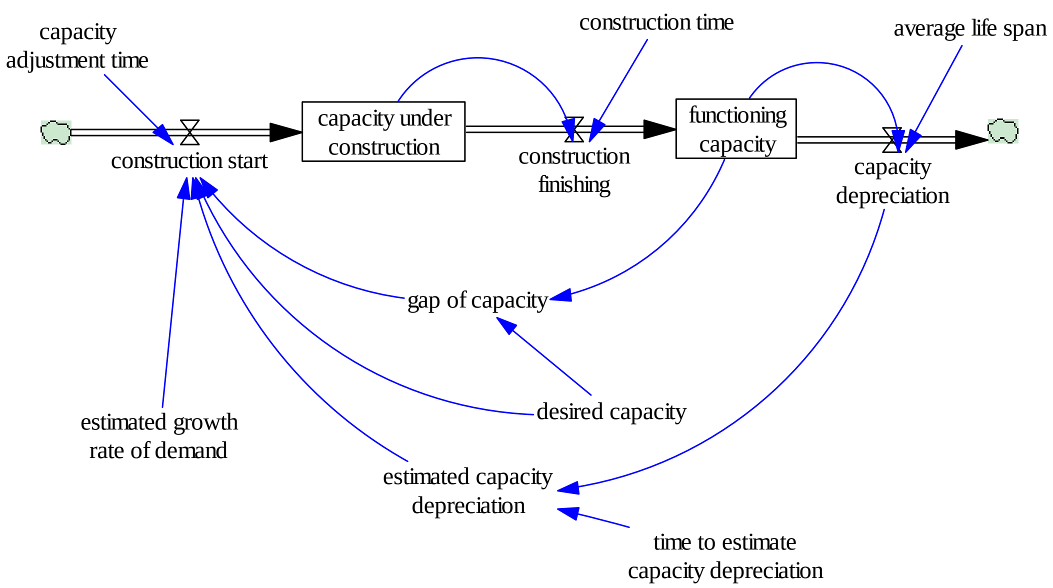


Figure 24 Stock and Flow Diagram of Capacity: Considering Depreciation

Our hypothesis is that construction start is driven by the gap between functioning capacity and desired capacity, because capacity has to keep up with desired capacity all the time, which is the goal of functioning capacity. The decision-makers compare what is available (functioning capacity) with what is needed (desired capacity) and calculate the discrepancy, then make a decision about how quickly to adjust the situation. When they decide construction start, they add to the growth factor of demand, which is the multiplication of desired capacity and estimated growth rate of demand. Until now, we finish the capacity construction sector, including structure that we hypothesize is responsible for oscillation in the reference mode. I will repeat it below and discuss about oscillations afterwards.



Ignorance about the stock of capacity under construction is the cause for oscillation in the reference mode, given capacity under construction is the main delay in the big feedback loop from construction start to functioning capacity to gap of capacity, which then feedbacks to construction start. However, one might argue that since it takes long to construct capacity, how can the NDRC ignore such a big stock? Well, this could be a good point, but there has been no literature, even some implicit clue about how NDRC treats the stock of capacity under construction. They might have a rough estimate about it but that does not necessarily mean they ever tried to manage the stock. Therefore, for the time being, I will leave it but will test it later.

4.3.2 Exponential growth

Now, let us show the stock and flow diagram of demand sector, which includes the structure responsible for exponential growth in functioning capacity, corresponding to Figure 17.

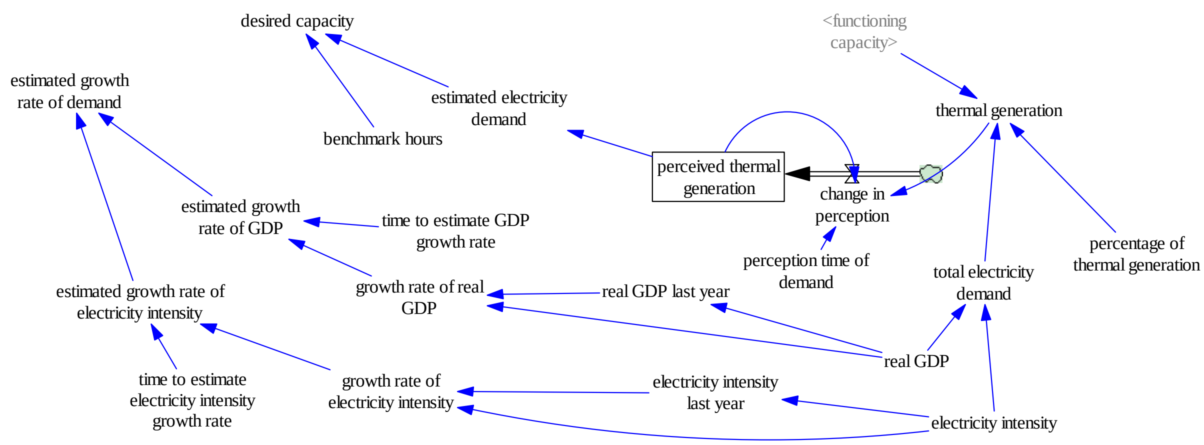


Figure 25 Stock and Flow Diagram: Structure Responsible for Exponential Growth in Reference Mode

As before, I will explain the structure in Figure 25 step by step. Desired capacity is derived from estimated electricity demand that is met by thermal generation, divided by benchmark working hours. Electricity demand is estimated according to past thermal generation. Thermal generation is driven by total electricity demand, and is a percentage of total demand, if functioning thermal capacity is sufficient to meet the demand. As discussed in causal loop diagram section, thermal generation is constrained by functioning capacity available. How the constraint works will be discussed later when Figure 25 and Figure 21 are combined into one. See Figure 26, from total demand to desired capacity.

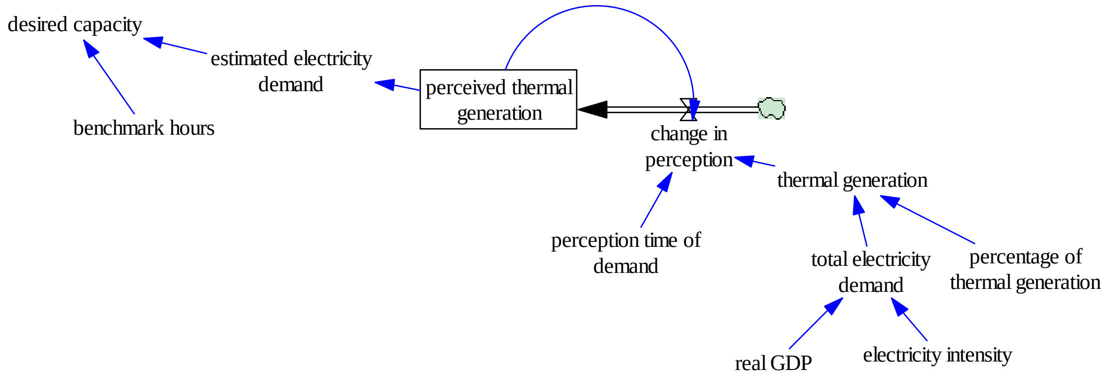


Figure 26 Stock and Flow Diagram: Desired Capacity

As shown in Figure 26, total electricity demand is determined by real GDP and electricity intensity, which is electricity demand per real GDP.

As discussed above, decision makers take into account the growth rate of demand when forecasting future demand. My hypothesis is that they add the growth rate of demand to construction start. But how they estimate the growth rate of demand? My hypothesis is that they estimate the growth rate of real GDP and electricity intensity first, and then estimate the growth rate of demand according to them. See Figure 27.

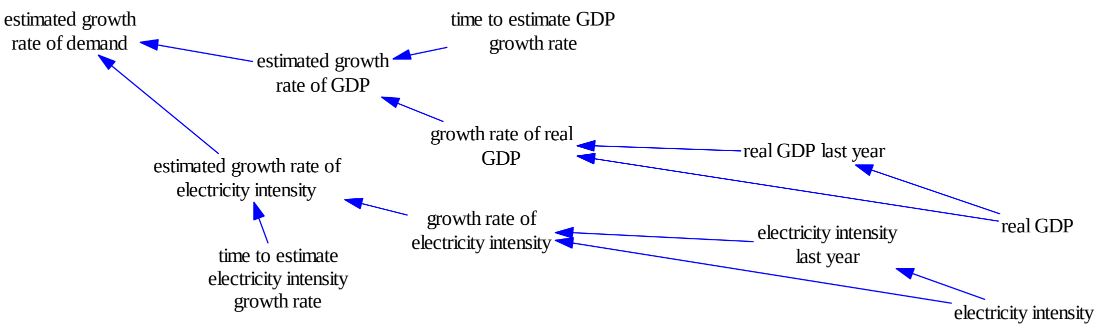


Figure 27 Stock and Flow Diagram: Estimated Growth Rate of Demand

There is an assumption made in Figure 27, which is that decision makers estimate the growth rate of real GDP and electricity intensity according to past growth rate. There is evidence that they figure out the past growth rate on a yearly basis, i.e. to compare real GDP over a time period with real GDP over the same period last year. The National Bureau of Statistics and the State Power Information Network both make such comparisons.

4.3.3 Sluggish adjustment

Now let us combine Figure 25 and Figure 21 to get the full stock and flow diagram, see Figure 28.

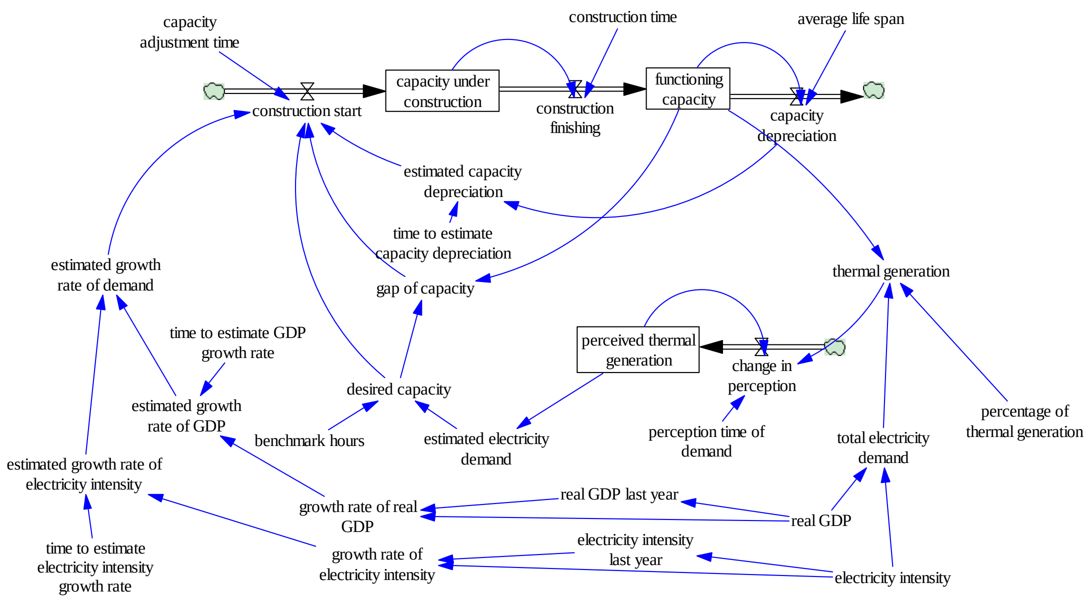


Figure 28 Stock and Flow Diagram: Over All, including Sluggish Adjustment in Reference Mode

First about functioning capacity, thermal generation and total electricity demand. Indeed, thermal generation is driven by electricity demand. However, it is also constrained by functioning capacity. When functioning capacity is not enough, managers will increase the capacity utilization rate of generators so that practically they will work more average working hours in order to meet electricity demand. It takes days or hours to adjust capacity utilization rate, depending on which type of thermal generators. But it can be regarded as instant over the time horizon I am studying, from 1980 to 2005. However, this is a limit to average working hours, i.e. its maximum can not exceed 8760 hours, which is the total hour in a year. Therefore, when average working hours that is needed to meet the demand is less than 8760 hours, electricity demand determines thermal generation. Otherwise, functioning capacity determines thermal generation. Thermal generation is actually a minimum of demand and capacity.

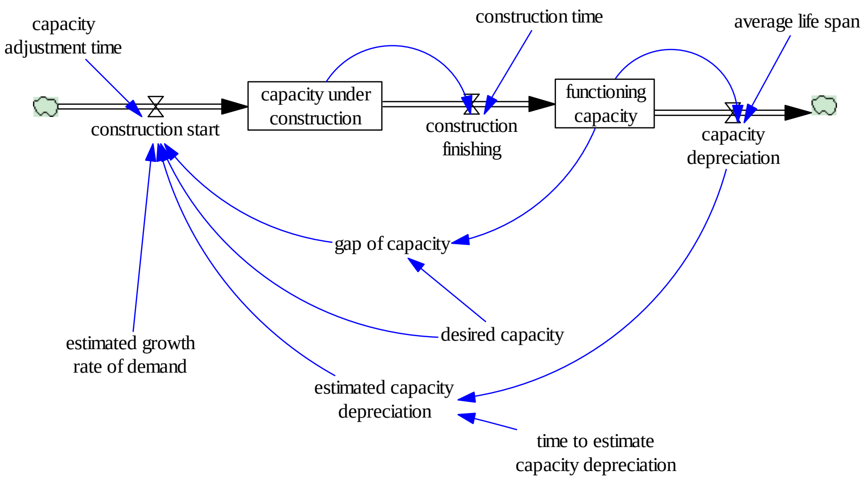
Now let us discuss the overall structure in Figure 28. Electricity capacity is always trying to keep up with total electricity demand, thus exhibiting exponential growth, which is exhibited in capacity depreciation as well. However, the electricity demand has been increasing all the time, due to the fast-growing GDP and slow decline in electricity intensity. Increasing demand drives desired capacity to be increasing all the time. On one hand, there could be always underestimates of total demand and capacity depreciation, which could be a reason for capacity shortage when deciding construction start. On the other hand, it takes time for capacity construction to be finished. Suppose at one moment functioning capacity catches up with desired capacity, it will be difficult for it to keep up with rising desired capacity, unless there is a big stock of capacity under construction, which keeps sending new capacity to the stock of functioning capacity. However, when deciding construction start, the time delay of construction (construction time) is not taken into account, thus making it impossible for functioning capacity to keep up with fast increasing desired capacity.

As discussed in the causal loop diagram section, major counteracting feedback loop C3, which includes the stock of capacity under construction, is the reason for oscillations in the reference mode. Tests about this will be made in model validation section. Now let us move to next section: model formulation.

4.4 Model Formulation

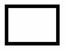
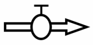
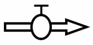
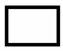
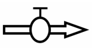
In this section, I will formulate the model, in the same sequence as in stock and flow diagram section, sector by sector.

1) **Capacity construction sector**



See the equations for this sector in Table 4.

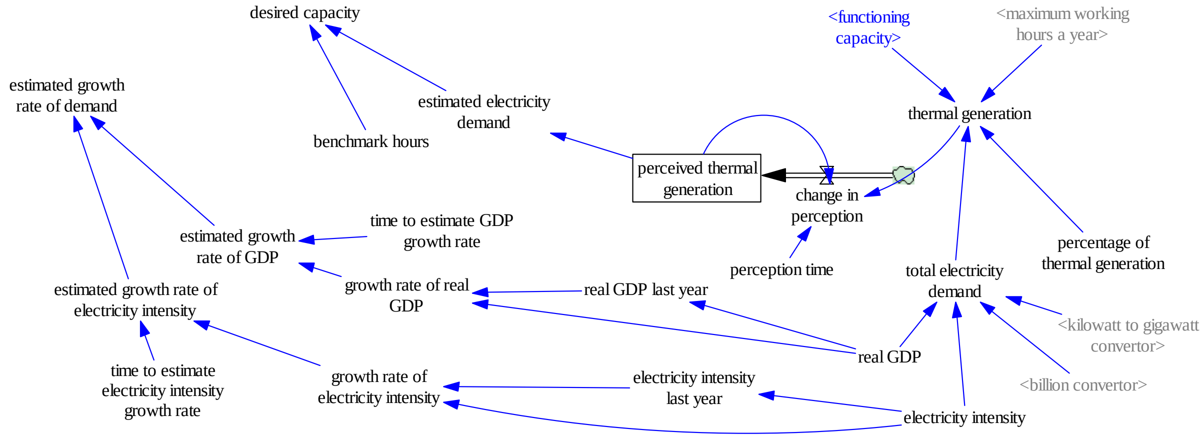
Table 4 Equations for Capacity Sector

Equations for capacity sector				
		Left Side of Equation	**Right Side of Equation**	**Units**
1		Capacity under construction	INTEG (+construction start-construction finishing, initial capacity under construction) INIT=initial capacity under construction	Gigawatt
2		Construction finishing	capacity under construction / construction time	Gigawatt /year
3		Construction time	3	year
4		Average life span	30	year
5		Capacity depreciation	functioning capacity /average life span	Gigawatt /year
6		Functioning capacity	INTEG(construction finishing - capacity depreciation , 45.551) INIT=45.551	Gigawatt
7		Gap of capacity	desired capacity - functioning capacity	Gigawatt
8		Time to estimate capacity depreciation	1	year
9		Estimated capacity depreciation	SMOOTH N (capacity depreciation , time to estimate capacity depreciation ,capacity depreciation , 1)	Gigawatt /year
10		Capacity adjustment time	1	year
11		Construction start	(gap of capacity + desired capacity * estimated growth rate of demand) / capacity adjustment time + estimated capacity depreciation	Gigawatt /year
12		Desired capacity	Demand sector	Gigawatt
13		Estimated growth rate of demand	Demand sector	Dmnl

Construction time is an estimate. Usually it takes 2 to 3 years to build a small-capacity thermal generator, 4-5 years for a big-capacity thermal generator. For the time being, I will just define it as 3 years and will run sensitivity tests about this estimate in the model validation section. Time to estimate capacity depreciation and capacity adjustment time are my assumptions, according to the aim of NDRC, which is to make annual investment of capacity. Average life span is according to my field research (Zhou 2008)

Now let us move on to the demand sector.

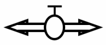
2) **Demand sector**



Here functioning capacity is also included in the sector, just to make the equation of thermal generation realistic, as discussed before. See the equations for demand section in Table 5.

Table 5 Equations for Demand Sector

Equations for demand sector				
		Left Side of Equation	**Right Side of Equation**	**Units**
1	○	Desired capacity	estimated electricity demand/benchmark hours	Gigawatt
2	○	Estimated growth rate of demand	(1+estimated growth rate of GDP) *(1+estimated growth rate of electricity intensity)-1	Dmnl
3	○	Estimated growth rate of GDP	SMOOTH N(growth rate of real GDP, time to estimate GDP growth rate , growth rate of real GDP , 1)	Dmnl
4	○	Estimated growth rate of electricity intensity	SMOOTH N(growth rate of electricity intensity, time to estimate electricity intensity growth rate, growth rate of electricity intensity ,1)	Dmnl
5	○	Time to estimate electricity intensity growth rate	1	year
6	○	Time to estimate GDP growth rate	1	year
7	○	Total electricity demand	electricity intensity/kilowatt to gigawatt convertor*real GDP*billion convertor	Gigawatt *hour/year
8	○	Thermal generation	min(total electricity demand*percentage of thermal generation, functioning capacity* maximum working hours a year)	Gigawatt *hour/year
9	□	Perceived thermal generation	INTEG (change in perception, thermal generation) INIT=thermal generation	Gigawatt /year
10	○	Perception time of demand	0.25	year

11	○	Growth rate of real GDP	(real GDP-real GDP last year)/real GDP last year	Dmnl
12	○	Growth rate of electricity intensity	(electricity intensity-electricity intensity last year)/electricity intensity last year	Dmnl
13	○	Real GDP last year	DELAY N(real GDP, 1, real GDP, 12)	Billion *CNY/year
14	○	Electricity intensity last year	DELAY N(electricity intensity, 1 , electricity intensity, 12)	Kilowatt *hour/CNY
15	○	Real GDP	Data file	Billion *CNY/year
16	○	Electricity intensity	Data file	Kilowatt *hour/CNY
17	○	Percentage of thermal generation	0.8	Dmnl
18		Change in perception	(thermal generation-perceived thermal generation)/perception time of demand	Gigawatt *hour/year /year
19	○	Estimated electricity demand	perceived thermal generation	Gigawatt *hour/year
20	○	Benchmark hours	5000	Hour/year
21	○	Maximum woking hours a year	8760	Hour/year
22	○	Kilowatt to gigawatt convertor	1e+006	Kilowatt /Gigawatt
23	○	Billion convertor	1e+009	Dmnl /Billion

All the parameters in Table 5 are all assumptions. But I do have confidence in the assumption about perception time of demand. I searched carefully about this perception time, and found we do have seasonal analysis reports of electricity industry. In these reports, decision makers always summarized what have happened in the electricity industry in the past season:

mainly the relationship between electricity demand and supply, electricity price etc, and made forecast about the relationship between electricity demand and supply for the rest of the year (DRCNET 2005; DRCNET 2007). Therefore, a quarter of a year might be a good assumption about perception time. Percentage of thermal generation is an approximation of what really is (between 0.79 to 0.82). Regarding benchmark hours, we discussed much about it in Section 3 and we will test it in model validation part.

So far, we have finished model formulation and will run the model and do the tests in Section 5.

5 Model validation and policy tests

First, I will see whether the model can replicate the reference modes. Then I will run structure and behavior tests to see whether the behavior is consistent with my hypothesis, and therefore lends support to it. After that, I will run extreme condition tests to make sure my model is robust even under extreme conditions. Then I will run parameter sensitivity test to make sure the model is not sensitive to the parameters I am not sure about, as well as to see to which parameters that can be controlled by my client the model is sensitive so as to gain hint about policy suggestions. In addition to policy parameters, I will test the policy of adding a new structure to the model to see how it works.

5.1 Reference Mode Replication Test

In this part, I will show the behaviors of variables of interest, and compare them with their reference modes.

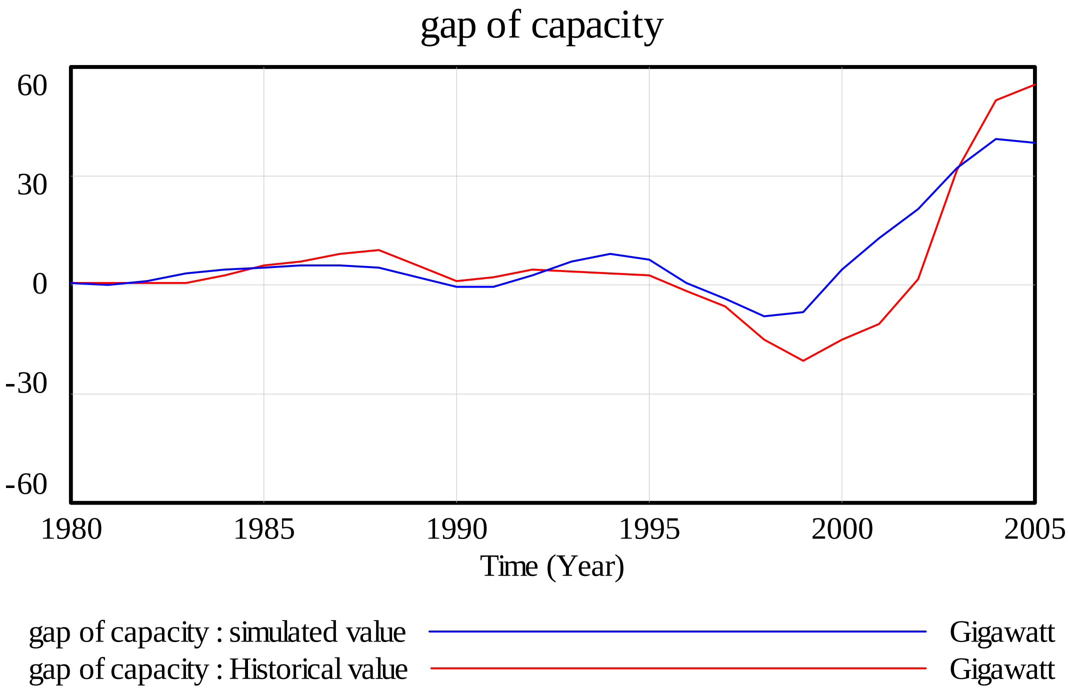


Figure 29 Reference Mode Replication Test: Gap of Capacity

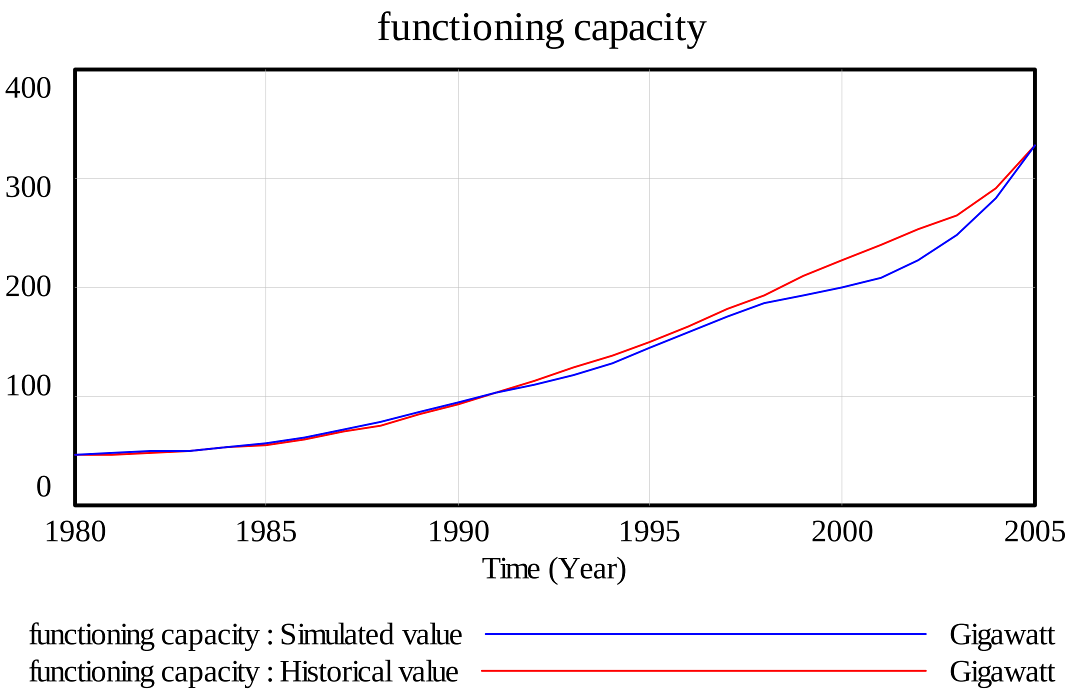


Figure 30 Reference Mode Replication Test: Functioning Capacity

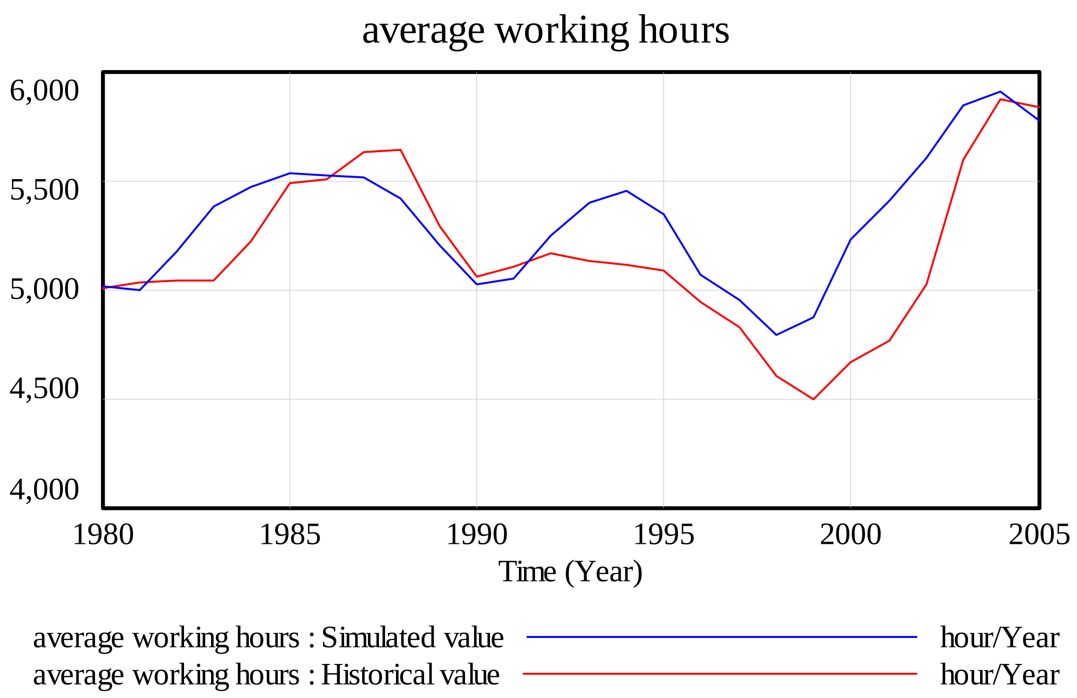
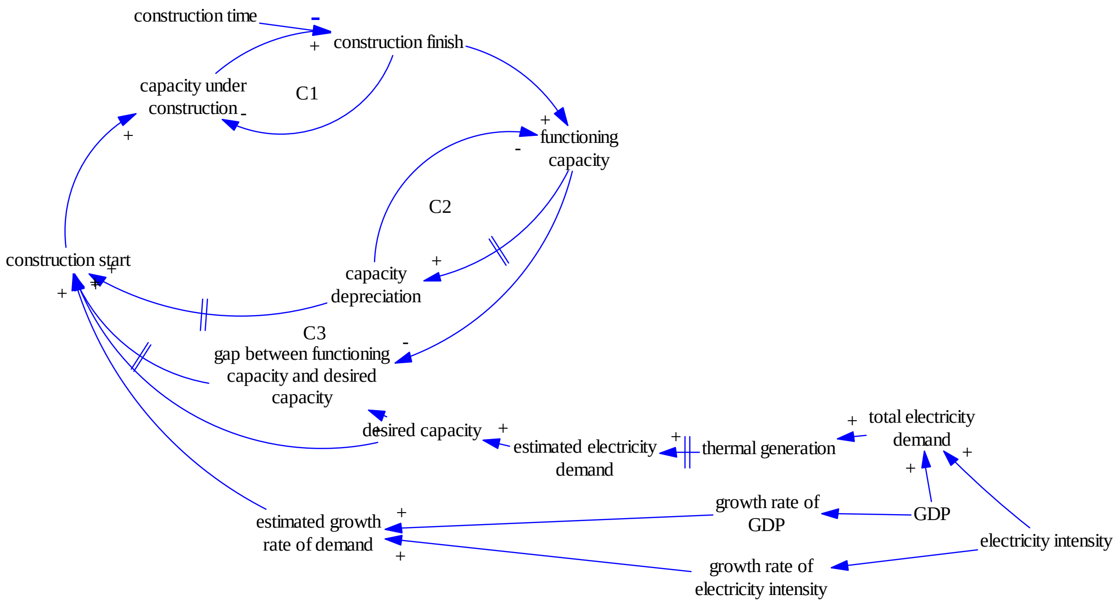


Figure 31 Reference Mode Replication Test: Average Working Hours

As shown above, the model can roughly replicate the reference modes, especially the characteristic behaviors in the reference modes.

5.2 Structure and Behavior Tests

In this part, I will test my hypotheses about the dynamic problem. First, I will test whether counteracting feedback loop C3 is the reason for oscillation in the reference mode. Then I will test whether exponential growth in GDP is the reason for exponential growth in functioning capacity. I will leave the rest of tests to the parameter (policy parameter) sensitivity test part and policy test: (1) whether underestimates about electricity demand and capacity depreciation have been the reason for electricity shortage; (2) whether ignorance of construction time when deciding construction start causes capacity shortage; (3) whether fast growth in GDP and improper pricing mechanism adds to the shortage. Below I repeat the overall causal loop diagram.



I) Hypothesis about oscillation

My hypothesis is that Loop C3 is the reason for oscillations in the reference modes (gap between desired capacity and average working hours). I will test this hypothesis by cutting loop C3 and compare the behavior of the model with the behavior before C3 is not cut. I will call the behavior of the model before C3 the business as usual run, when parameters and structures are those which replicate the reference mode.

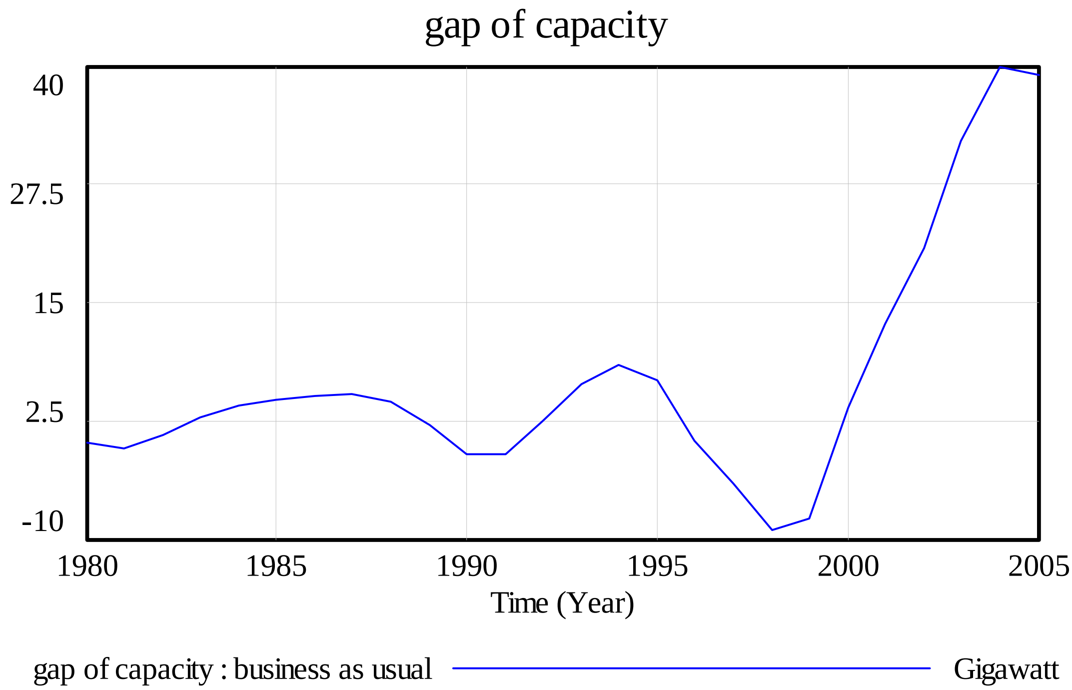


Figure 32 Structure and Behavior Test: Oscillations in Gap of Capacity

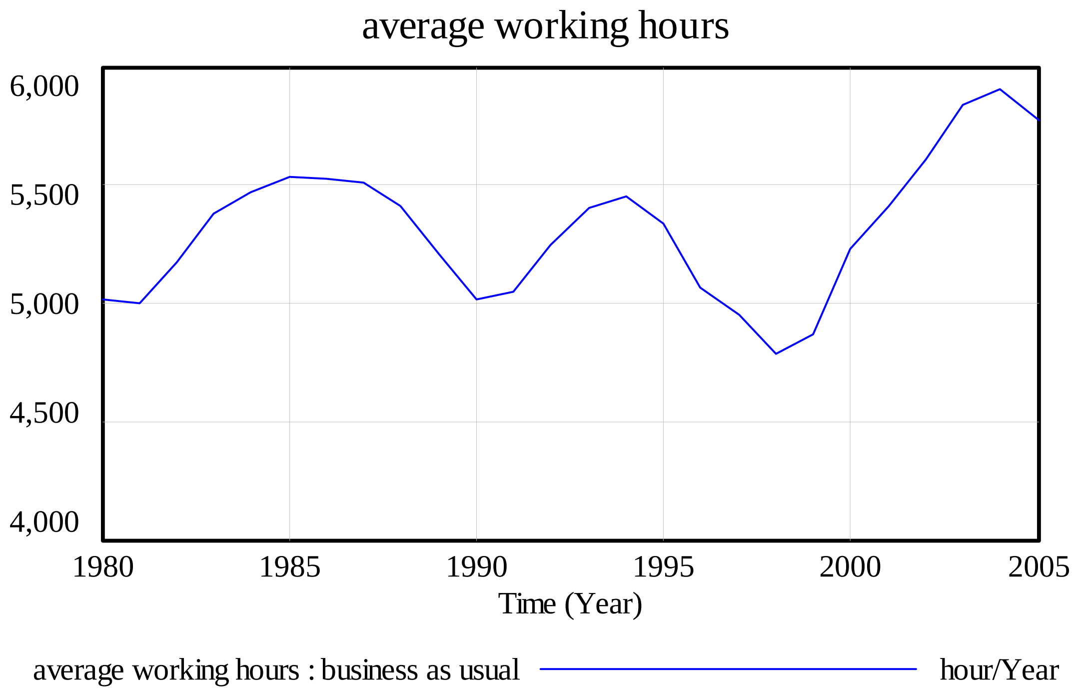


Figure 33 Structure and Behavior Test: Oscillation in Average Working Hours

First, I will cut the loop of C3, by making adjustment time extremely big, say 1e+009, to see whether the oscillations in the reference modes will disappear. See Figure 34 and Figure 35 below.

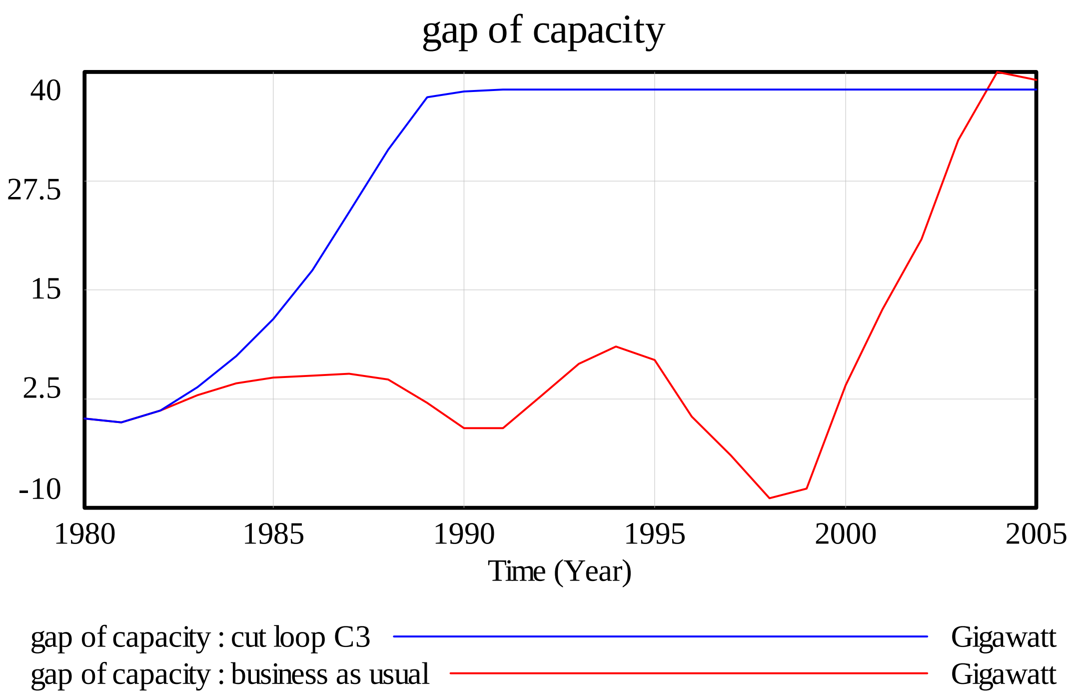


Figure 34 Structure and Behavior Test: Gap of Capacity, Cut Loop C3 and Business as Usual

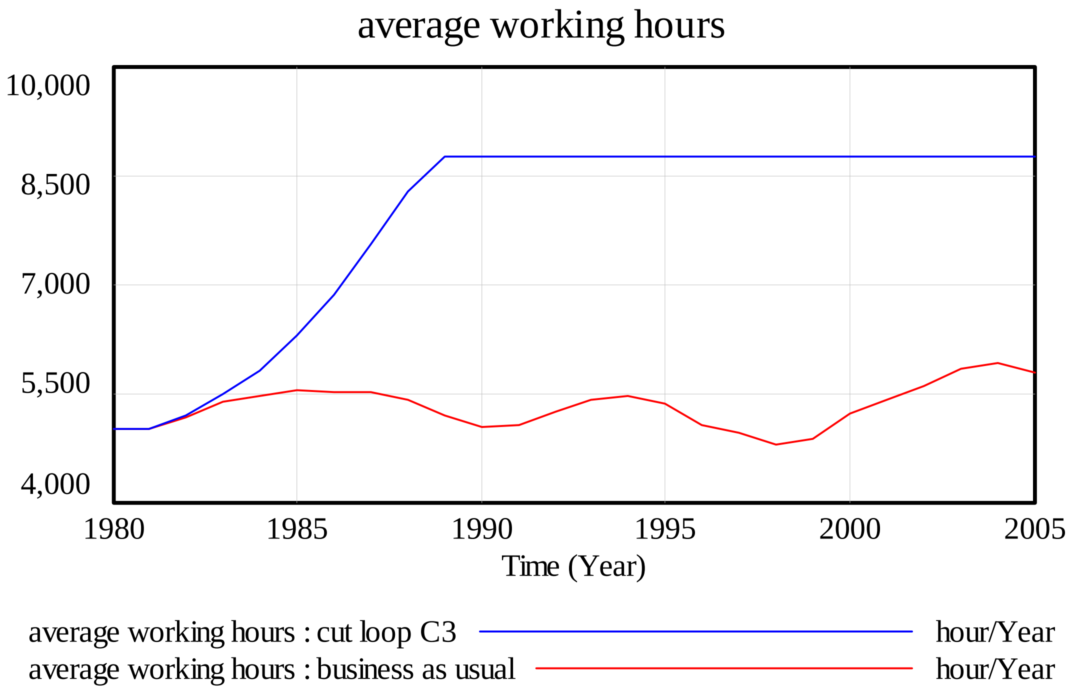


Figure 35 Structure and Behavior Test: Average Working Hours, Cut Loop C3 and Business as Usual

As shown in Figure 34 and Figure 35, both gap of capacity and average working hours showed no oscillations after cutting loop C3. Therefore, the behavior is consistent with my hypothesis, and therefore lends support to it. Since the absence of the loop eliminated the behavior, I can infer that the presence of the loop contributes to the behavior.

As discussed in literature review, there is argument that cyclical behavior in the relationship between electricity supply and demand is driven by economic cycles. I will test it by making real GDP constant. Suppose real GDP equals to 1000 billion CNY per year all the time. See the behavior of gap of capacity and average working hours.

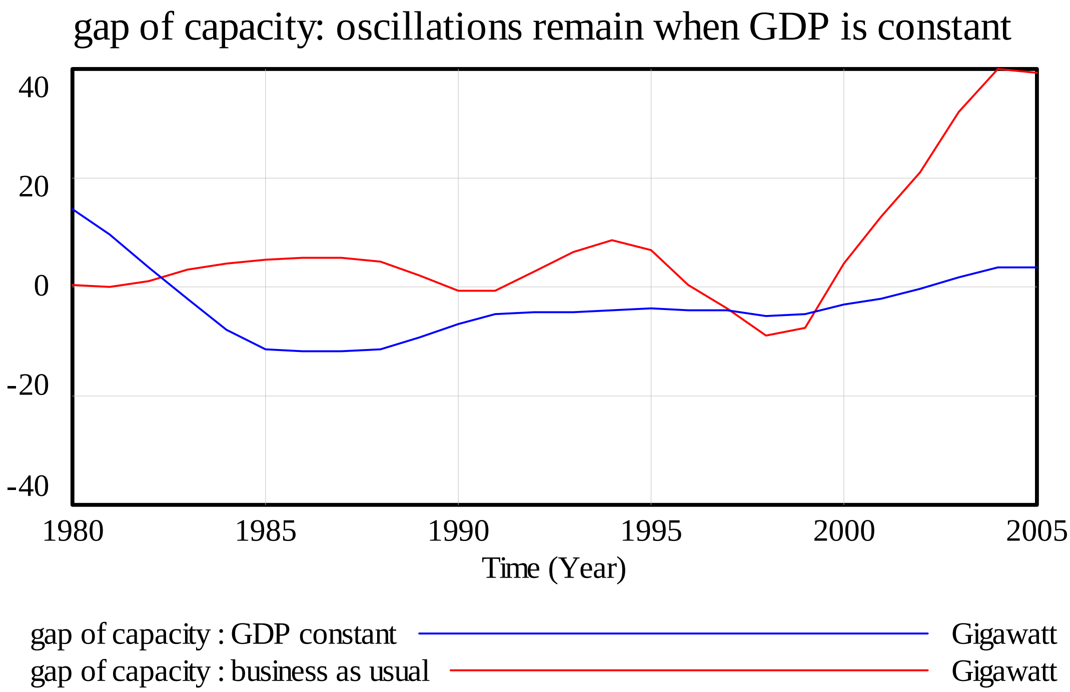


Figure 36 Structure and Behavior Test: Gap of Capacity, Oscillations Remain even when GDP is Constant

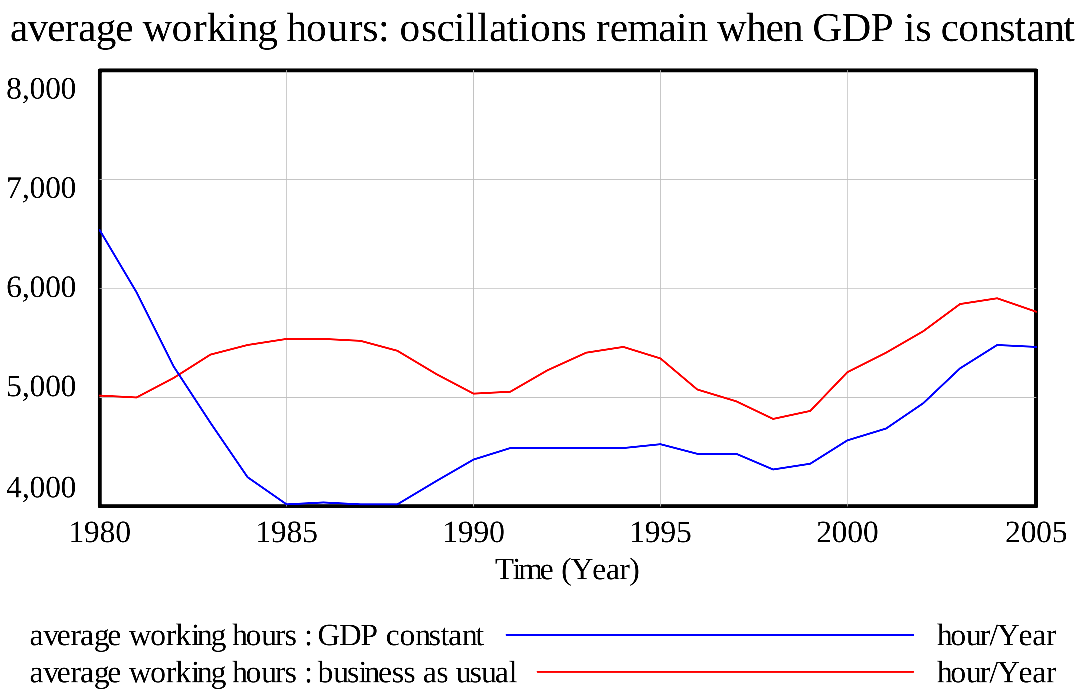


Figure 37 Structure and Behavior Test: Average Working Hours, Oscillations Remain even when GDP is Constant

As shown in Figure 36 and Figure 37, gap of capacity and average working hours still exhibit cyclical behavior even when GDP stays constant all the time. This indicates that cycles in the reference mode could arise endogenously, even without exogenous economic cycles. Therefore, there is the potential at least to reduce the cycles by managing the endogenous process, managing the stock of capacity under construction in this case, which will be discussed in the policy test part.

II) Hypothesis about exponential growth

My hypothesis is that exponential growth in functioning capacity, as well as amplifying amplitude in the cycles in the gap of capacity, is driven by exogenous GDP, which is exponentially growing. Assuming GDP is constant (cutting the exogenous positive feedback loop), see the behavior of functioning capacity in Figure 38.

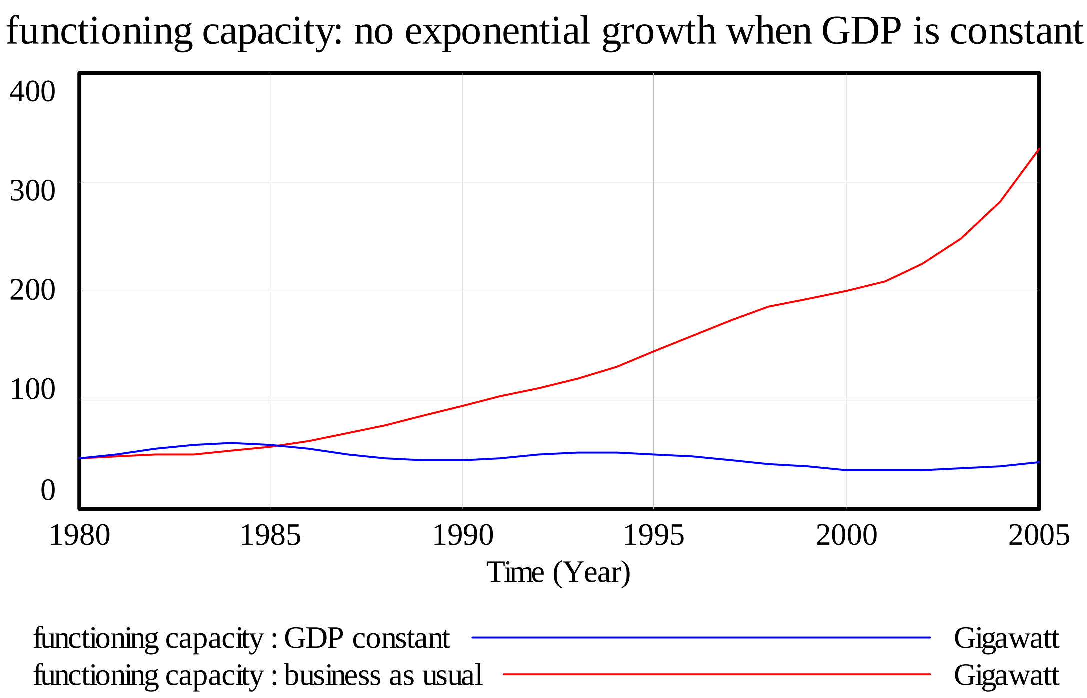


Figure 38 Structure and Behavior Test: Functioning Capacity, No Exponential Growth when GDP is Constant

As shown in Figure 38, functioning capacity does not show exponential growth in the GDP constant run at all. Instead, there is a decline in the functioning capacity, which is driven by the decline in electricity intensity, i.e. improvement in electricity efficiency, which brings decline to total electricity demand.

So far, we have finished structure and behavior tests. By cutting the loops hypothesized to be responsible for the characteristic behaviors in the reference mode, we can build even more confidence in my hypotheses in Section 4. Now let us move to extreme condition tests.

5.3 Extreme Condition Tests

I) Assume functioning capacity is 0 all the time, by setting initial functioning capacity = 0, initial capacity under construction =0 and total demand =0. See thermal generation in Figure 39.

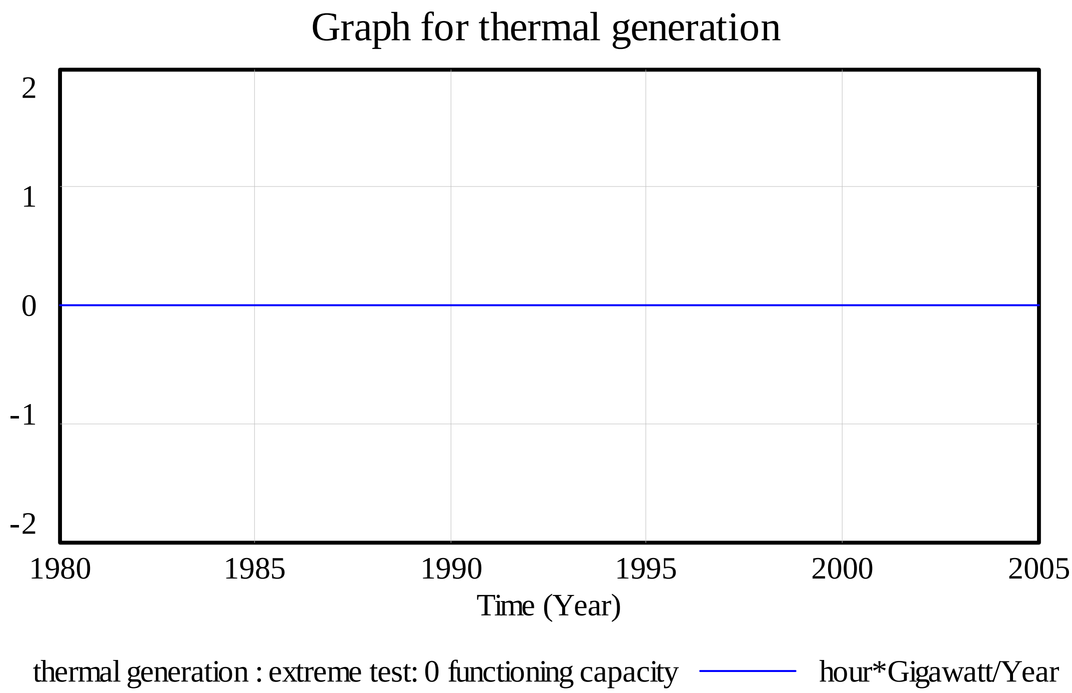


Figure 39 Extreme Condition Test: Thermal Generation when Functioning Capacity=0

As shown in Figure 39, when functioning capacity equals to 0 all the time, there is no thermal generation at all. In the real world, when there is no capacity, there is supposed to be no electricity generation as well. Therefore, the model behaves in a realistic way under this extreme condition test.

II) Suppose it takes 1 trillion years to construct capacity, see functioning capacity and thermal generation.

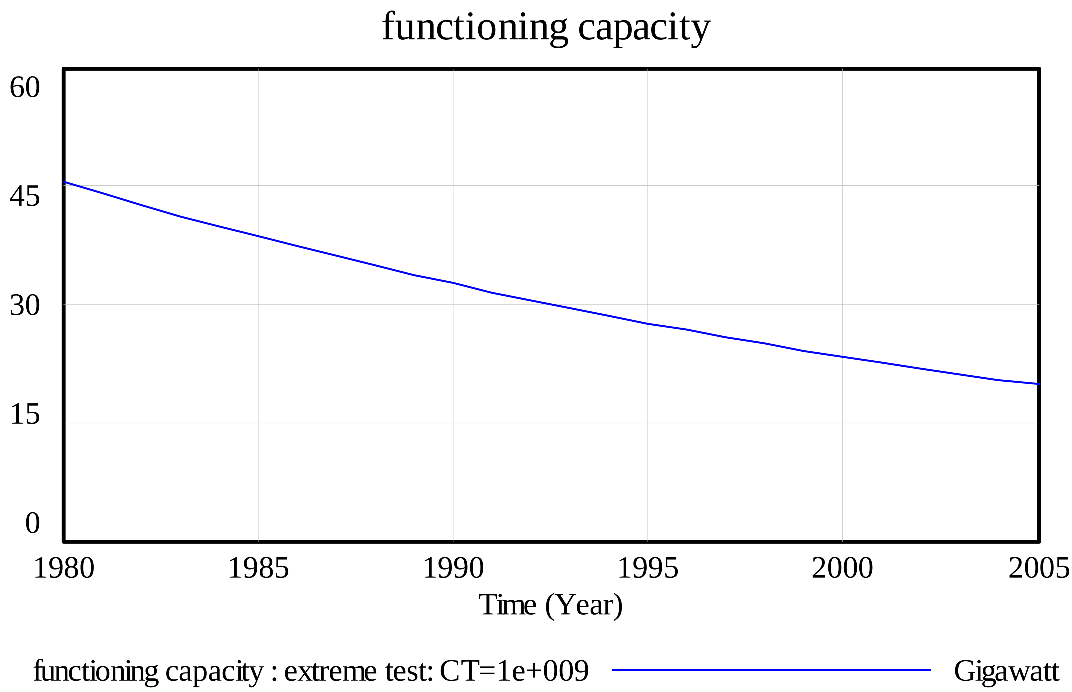


Figure 40 Extreme Condition Test: Functioning Capacity when Construction Time=1+009

As shown in Figure 40, functioning capacity exhibits an exponential decay, because there would be almost no new capacity added to this stock, while 3.3% of capacity depreciates every year. In the real world, when there is a 3.3% annual rate of decline, the capacity should be cut in half in about 21 years, according to the "rule of 70". This is consistent with what is shown in Figure 40 (around the year 2001, the capacity is cut half as the initial value.).

See thermal generation in Figure 41. Thermal generation first increases as demand increases, but afterwards, when functioning capacity is no longer sufficient to satisfy demand, thermal generation decays as functioning capacity does, which is realistic.

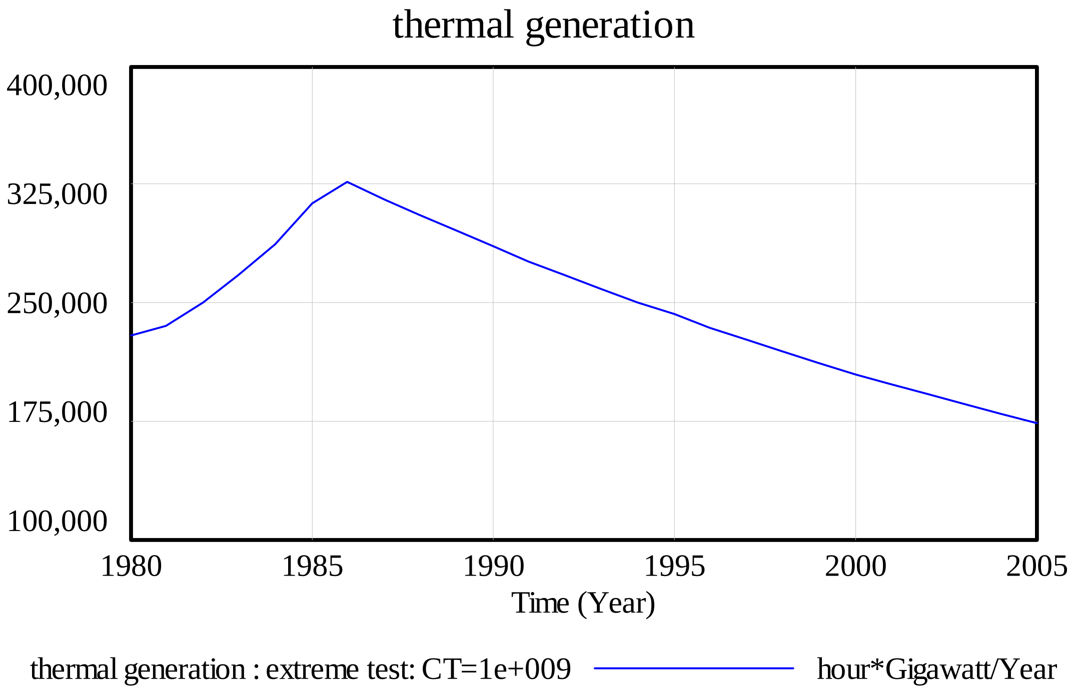


Figure 41 Extreme Condition Test: Thermal Generation when Construction Time=1+009

III) Suppose total electricity demand =0 all the time, see functioning capacity, construction start, capacity under construction, construction finish and thermal generation.

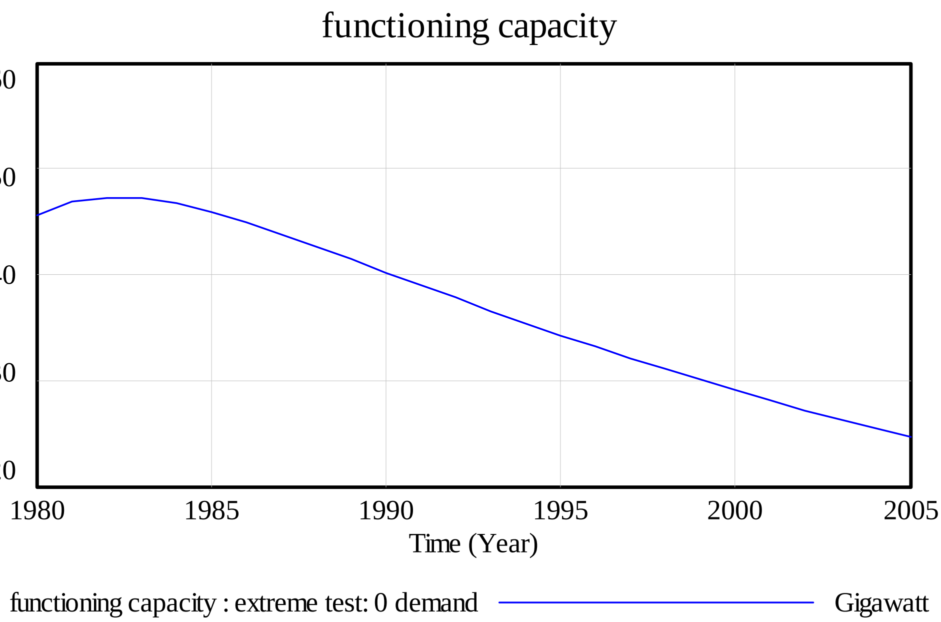


Figure 42 Extreme Condition Test: Functioning Capacity when Total Electricity Demand=0

As shown in Figure 42, when total demand equals to 0, functioning capacity first increases because there is still some capacity in the pipeline. But afterwards functioning capacity starts to decline because of the 3.3% of capacity depreciation. This is consistent with what is expected in the real world.

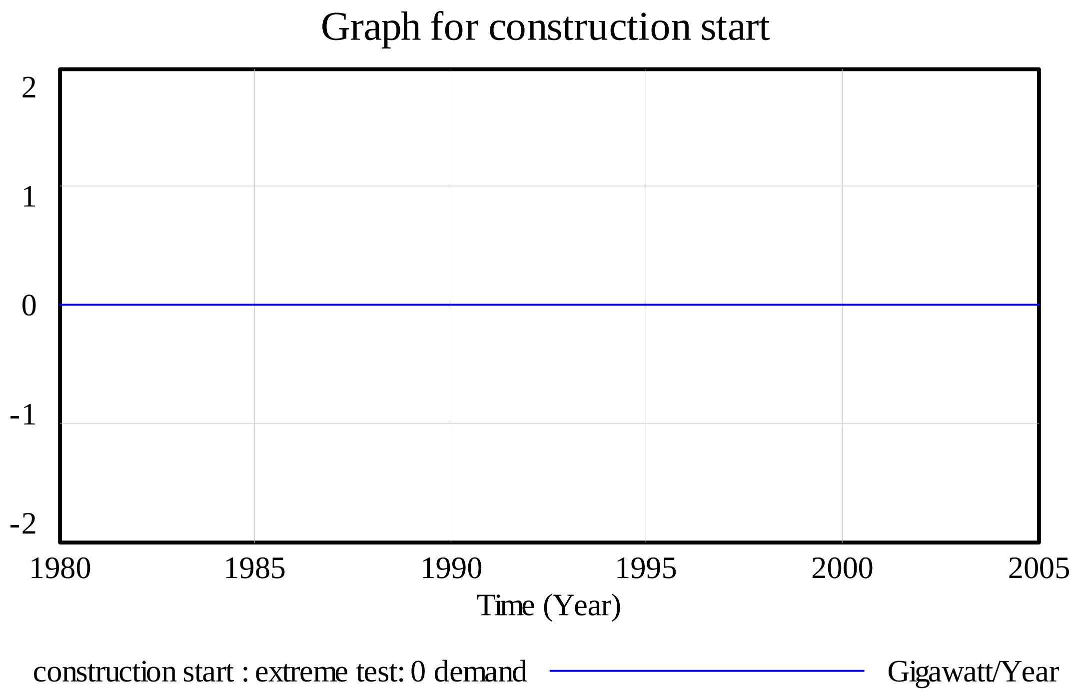


Figure 43 Extreme Condition Test: Construction Start when Total Electricity Demand=0

In reality, if there is no demand, there will be no need to start construction (construction start equals to 0), as shown in Figure 43.

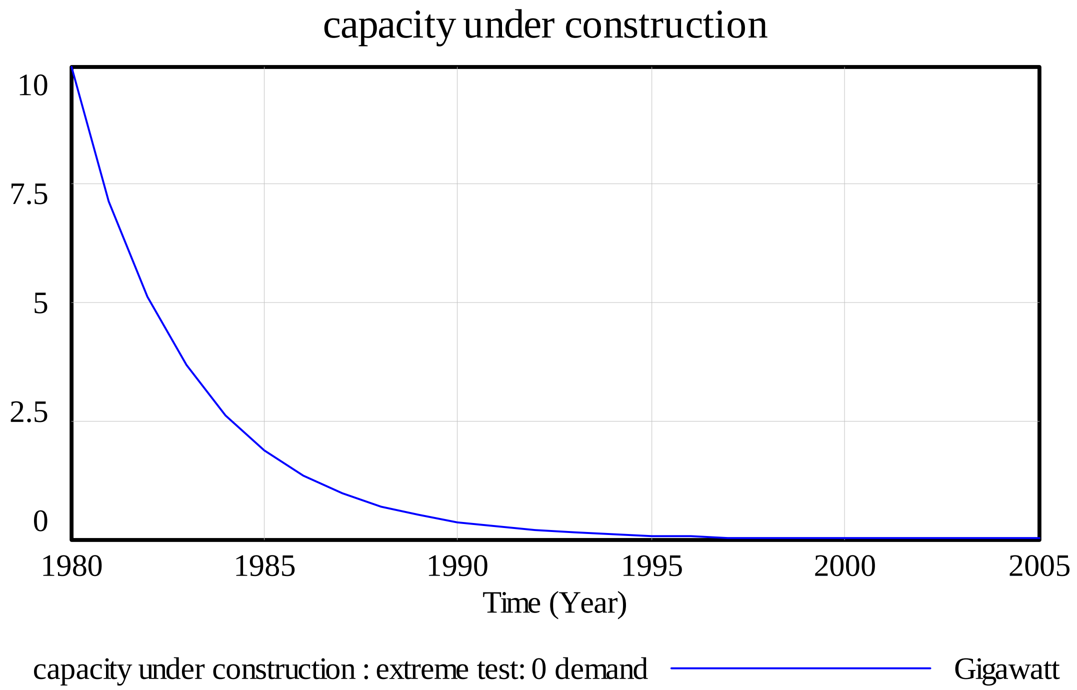


Figure 44 Extreme Condition Test: Capacity under Construction when Total Electricity Demand=0

In the real world, when there is no demand, then construction start equals to 0 all the time, the capacity initially in the pipeline will be sent to the functioning capacity gradually (deducted from capacity under construction). The more the capacity under construction is, the more capacity will be sent every year. When capacity under construction approaches 0, the capacity that will be sent to functioning capacity will also approach 0. In any case, capacity under construction will never go negative. As shown in Figure 44, the stock of capacity under construction exhibits an exponential decay until 0, which is as expected in the real world.

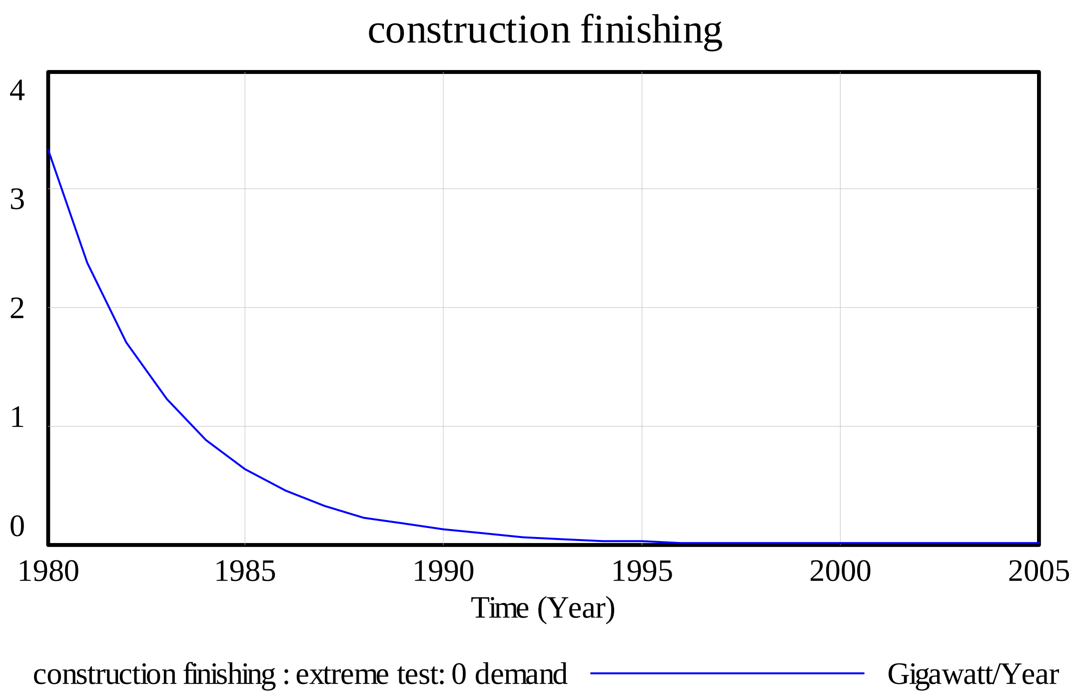


Figure 45 Extreme Condition Test: Construction Finishing when Total Electricity Demand=0

Construction finishing is proportional to capacity under construction. It will decay as capacity under construction but will never go negative. The graph shown in Figure 45 is just as expected in the real world.

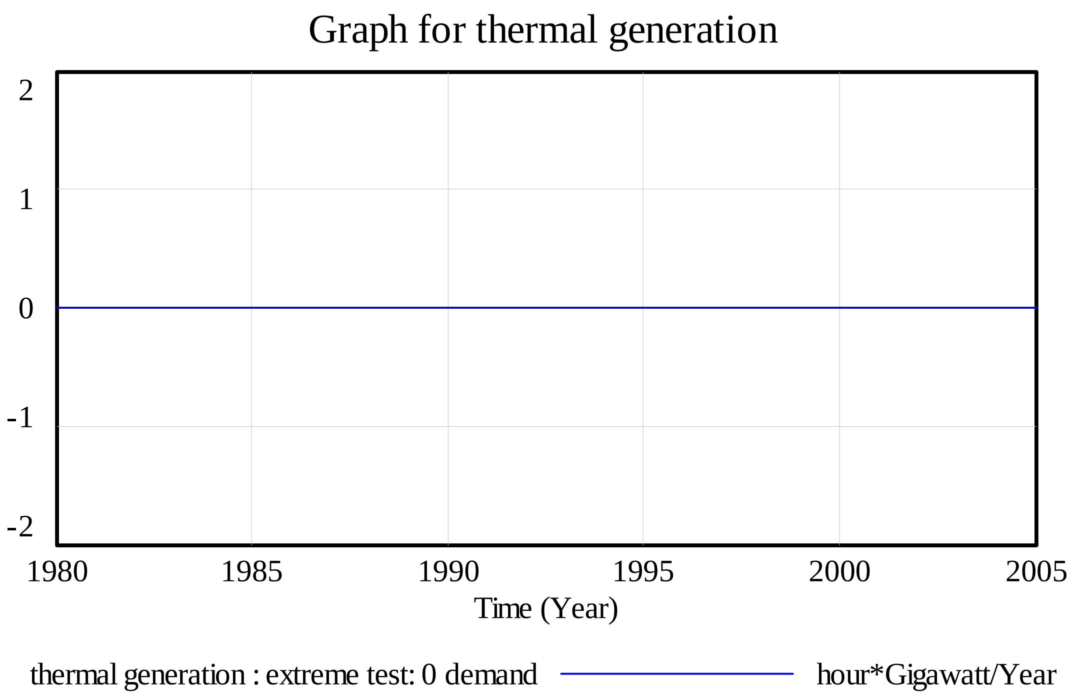


Figure 46 Extreme Condition Test: Thermal Generation when Total Electricity Demand=0

When there is no demand, there would be no electricity generation, regardless of the capacity available. The graph shown in Figure 46 is consistent with what is expected in the real world.

Until now, according to my knowledge, extreme tests are ok and the model is robust under extreme conditions. Now let us move to parameter sensitivity test.

5.4 Parameter Sensitivity Test

As mentioned in the model formulation part, there are some parameters that I am not sure about, or make estimates of. There are also some variables that are in the hand of NDRC (policy parameters) and I would like to see whether the model is sensitive to them so that I could give some strategic hint about policy suggestions. Table 6 lists all the parameters and differentiates them.

Table 6 List of Parameters to Run Sensitivity Tests On

parameters	have confidence	Not sure about or make estimate of	Policy parameters
Capacity adjustment time		√	√
time to estimate capacity depreciation		√	√
perception time of demand	√		√
construction time		√	
time to estimate GDP growth rate		√	√
time to estimate electricity intensity growth rate		√	√
benchmark hours		√	√

First I run the sensitivity tests on all the parameters that I am not sure about or make estimate of, just to build further confidence in the model. It turns out that the model is not sensitive to any of them except capacity adjustment time. Table 7 lists the sensitivity results of all the parameters that the model is not sensitive to (I test the behaviors of all the 3 variables of interest: gap of capacity, functioning capacity and average working hours and the conclusion is the same. Here I choose gap of capacity only as the responsive variable.). I will discuss the sensitivity test of adjustment time later.

Table 7 List of Sensitivity Results of All the Parameters That the Model is not Sensitive To

parameters	Range of change	Percentage change	Responsive change (on average)
time to estimate capacity depreciation	0.083~1	91.7%	1.16%
construction time	2~5	100%	12.7%
time to estimate GDP growth rate	0.083~1	91.7%	7.37%
time to estimate electricity intensity growth rate	0.083~1	91.7%	5.04%
benchmark hours	4800~5500	14%	3.51%

Note: percentage change is calculated by dividing the absolute change of parameters' change range by the value of the parameters assumed in the model. Average responsive change is calculated by dividing the absolute change of gap of capacity under upper and lower bound of parameters by the absolute length of scale of business as usual run.

Now let us look at the sensitivity test of capacity adjustment time and I will show the behavior of functioning capacity and gap of capacity. As shown in Figure 47, functioning capacity is numerically sensitive to capacity adjustment time. The upper bound of sensitivity runs is when capacity adjustment time =0.5 year. When capacity adjustment time=0.5, functioning capacity in model run is close to its reference mode before 1999 but starts to go beyond reference mode by the end of the time scale under study. And the cyclical behavior in functioning capacity is much more obvious than in the reference mode, due to the aggressive adjustment. In this sense, 0.5 year is not a good assumption about capacity adjustment time. The lower bound of sensitivity runs is when capacity adjustment time=2 years. When capacity adjustment time=2, functioning capacity in model run is much lower than its reference mode. As discussed in the model formulation section, NDRC makes annual investment and balances electricity generation and electricity capacity on a yearly basis, 1 year could be a good assumption about capacity adjustment time.

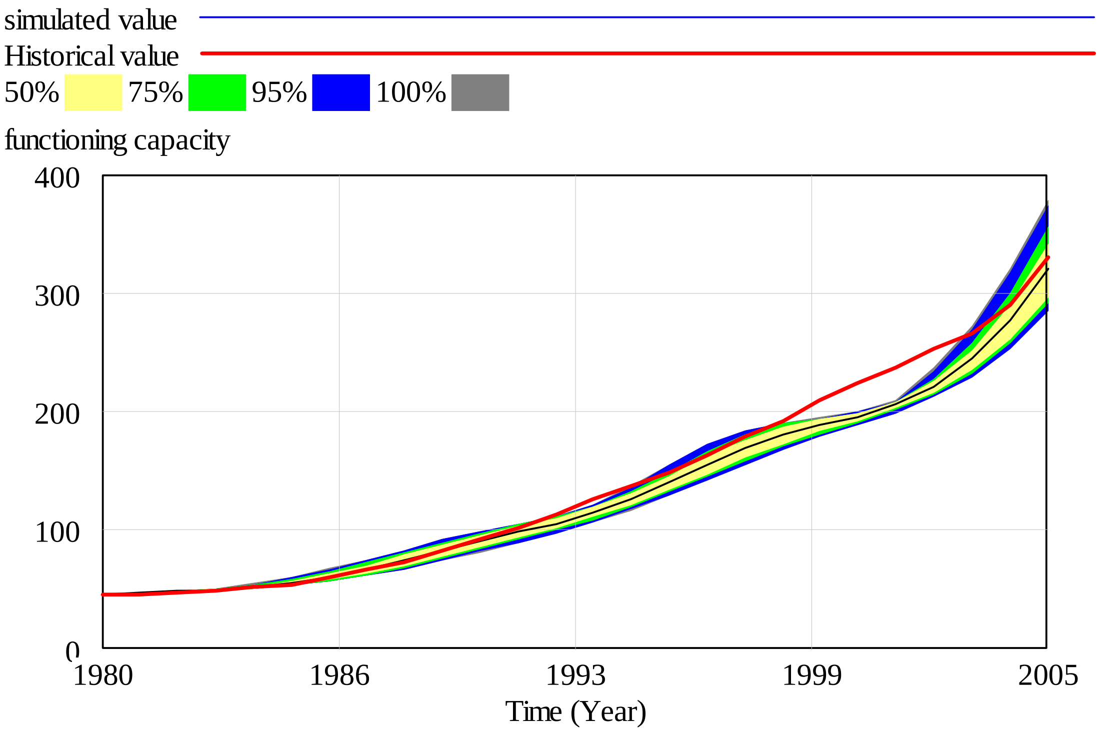


Figure 47 Parameter Sensitivity Test: Functioning Capacity, Capacity Adjustment Time=0.5~2

The same conclusion can be derived from the behavior of gap of capacity, as shown in Figure 48.

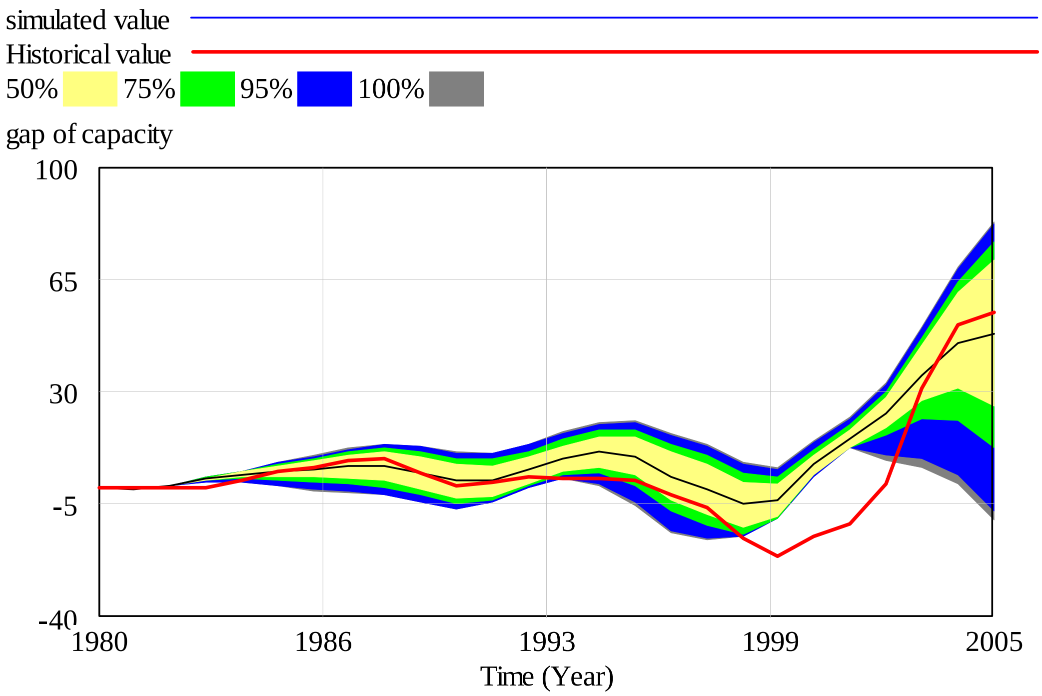


Figure 48 Parameter Sensitivity Test: Gap of Capacity, Capacity Adjustment Time=0.5~2

Most of variables that I am not sure about or make estimates of do not have big effect on the model. The model is sensitive only to capacity adjustment time but it is found in Figure 47 and Figure 48 that my assumption about capacity adjustment time before was realistic.

Now let us move to the sensitivity tests of policy parameters, most of which have been done above, except perception time of demand. I did the sensitivity test of this policy parameter and found that the model was not sensitive to it, although a smaller perception time of demand did improve the behavior of the model. Therefore, underestimates of demand due to the current perception time of demand could be a cause for capacity shortage. However, changing perception time of demand is not an effective policy suggestion.

Regarding other policy parameters, the model is not sensitive to 4 of them, as shown in Table 6: time to estimate GDP growth rate, time to estimate electricity intensity growth rate, time to estimate capacity depreciation, and benchmark hours. I also run the sensitivity test about the first 3 time parameters together, which have something to do with underestimates of total demand and underestimates of capacity depreciation. Still the model is not sensitive to them together. Indeed, reducing these 3 parameters reduces underestimates and reduces gap of capacity, which indicates that underestimates of total demand and underestimates of capacity depreciation could be part of the reasons for capacity shortage. However, the fact that the model is not sensitive to them indicates that they are not effective policy parameters, at least under the current decision rules.

As discussed above, the model is sensitive to capacity adjustment time, which is also a policy parameter. From Figure 47 and Figure 48 we know that if policy makers decide to close the gap between functioning capacity and desired capacity in 0.5 year, then the gap will oscillate around 0, which means capacity shortage can be removed. However, aggressive adjustment causes more oscillations in the system. On the other hand, since the NDRC's mission of electricity industry is to balance annual electricity demand and supply, the suggestion of more aggressive adjustment is not feasible. Therefore, let us stick to the 1-year capacity adjustment time.

Let us summarize the discussion about policy parameters above in this: under current decision rules, there are no effective policy suggestions about all the parameters, except capacity adjustment time. However, a smaller capacity adjustment time is not feasible for NDRC. It seems the model has reached its bottleneck under current decision rules, which might call for a change in the decision rules. We have talked much about ignorance of construction time when deciding construction start before and said we would leave it to policy test part. Now let us move to structural policy test.

5.5 Policy Test

In this part, I will add a new structure to the model, which takes construction time into consideration when deciding construction start. As discussed in Section 4, ignorance of construction time when deciding construction start results in not big enough the stock of capacity under construction, which makes it impossible for functioning capacity to keep up with desired capacity, in the presence of 3 years' construction time. Therefore, what we can do is manage capacity under construction by taking construction time into consideration. Let us make the goal of capacity under construction a function of construction time and adjust capacity under construction to the goal, which adds to construction start.

Usually, managing capacity under construction aims to make the flows flowing the system are all equal, so the goal of capacity under construction is the estimated capacity depreciation times construction time (Sterman 2000). However, in this case, functioning capacity is increasing all the time, so the goal of capacity under construction (desired capacity under construction) should take into consideration the growth in functioning capacity in addition to estimated capacity depreciation in order to ensure exponential growth in functioning capacity.

Let us make the equation of desired capacity under construction as follows:

Desired capacity under construction= (estimated capacity depreciation + desired capacity*estimated growth rate of demand/capacity adjustment time) * construction time

Unit consistency:

Gigawatt = (Gigawatt/year + Gigawatt * dimensionless / year) * year = Gigawatt

When deciding the part of construction start as a result of managing capacity under construction, it is also necessary to add to the growth rate of electricity demand, because desired capacity under construction is also growing exponentially.

Time to adjust capacity under construction should be 1 year, in order to make capacity under construction catch up with its increasing goal every year so that it can always send enough new capacity as desired to functioning capacity,.

See the modified model structure in Figure 49.

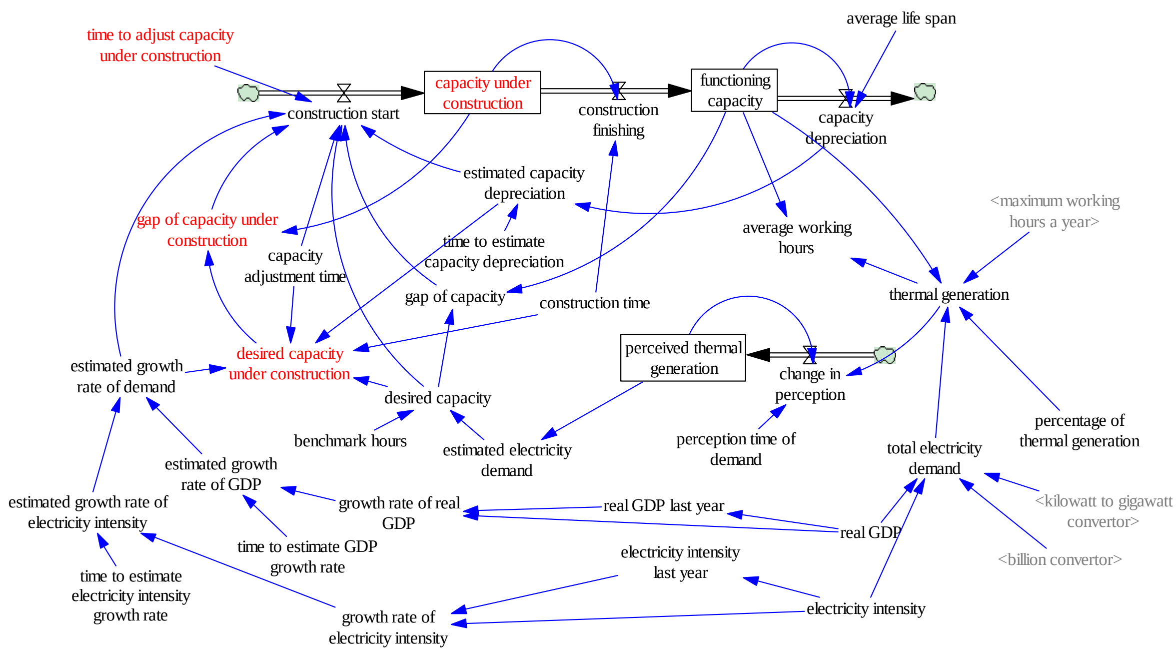


Figure 49 Policy: Adding the Management of Capacity under Construction

Now let us look at the behavior of gap of capacity, functioning capacity and average working hours, Figure 50, Figure 51 and Figure 52.

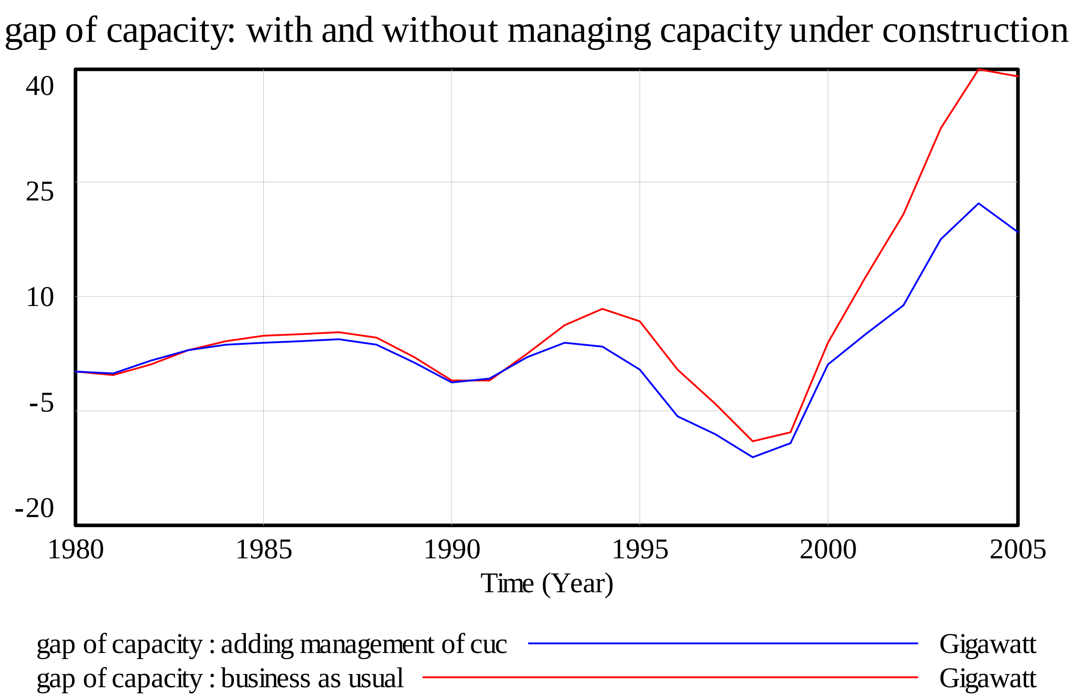


Figure 50 Policy Test: Gap of Capacity, With and Without Adding Management of Capacity under Construction

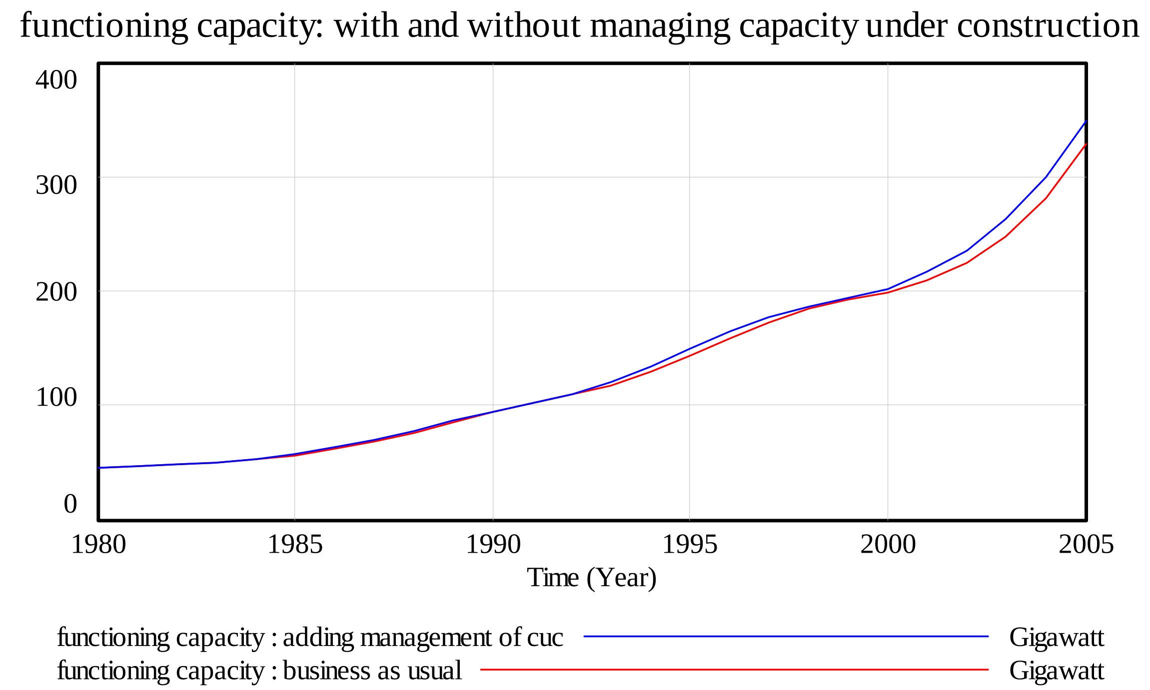


Figure 51 Policy Test: Functioning Capacity, With and Without Adding Management of Capacity under Construction

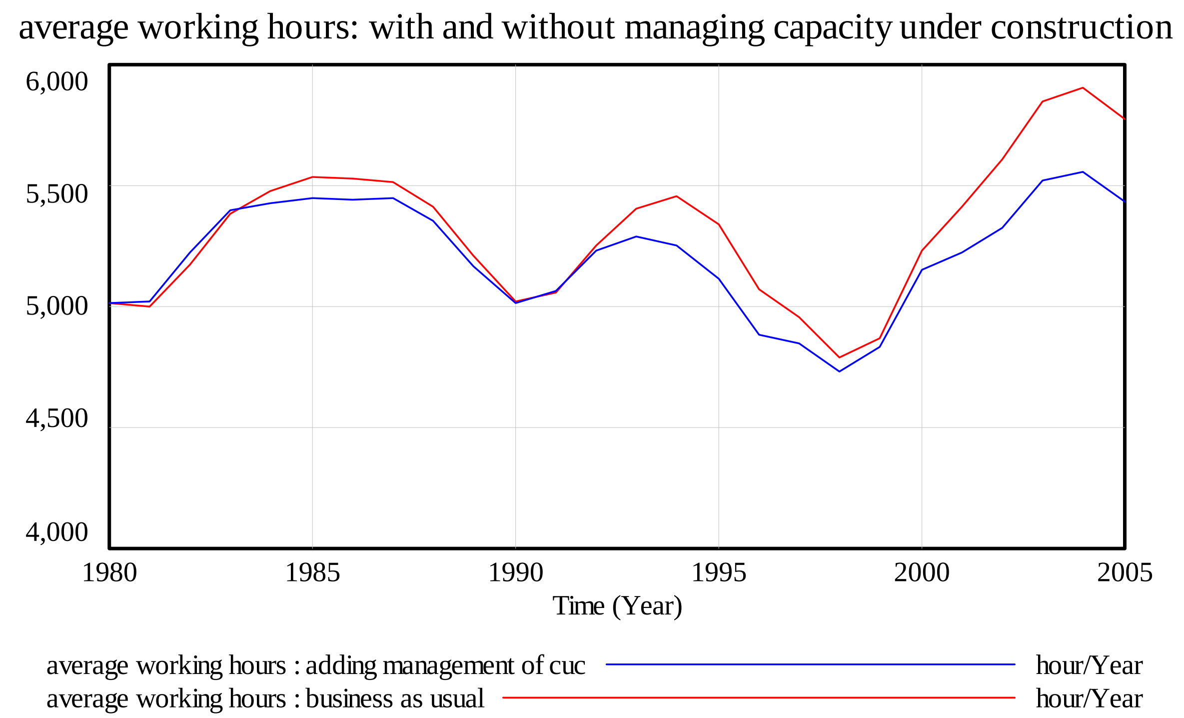


Figure 52 Policy Test: Average Working Hours, With and Without Adding Management of Capacity under Construction

As shown in Figure 50, Figure 51 and Figure 52, there is big improvement in the behavior of the model after adding the structure of managing capacity under construction. On one hand, taking into consideration the construction time when deciding desired capacity under construction greatly reduced the gap of capacity and average working hours. On the other hand, management of capacity under construction also reduces the oscillations in the gap of capacity and average working hours, which will be shown again later when running sensitivity test about GDP growth rate.

Regarding the feasibility of this policy, I am optimistic. Indeed, managing the stock of capacity under construction is completely new to NDRC. However, just because it is new, it might be easier for NDRC to adopt it than changing their old habit of merely closing the gap of existing capacity.

After introducing this policy of managing capacity under construction, I would like to run the sensitivity tests of the 5 policy parameters again because there might be more policy options after making the structural change. My finding is that after managing capacity under construction, the model is more sensitive to these two time parameters: time to estimate GDP growth rate (0.25~1 year) and time to estimate electricity intensity growth rate (0.25~1 year). Figure 53 shows the sensitivity test result of the two parameters together, after adding the management of capacity under construction. The model is numerically sensitive to these two parameters. In reality, it is also feasible to update the estimates of GDP growth rate and electricity intensity growth rate on a quarterly basis, just as updating estimates of demand. Therefore, it is recommended that NDRC update the estimates of GDP growth rate and electricity intensity growth rate more often, say on a quarterly basis.

Figure 54, Figure 55 and Figure 56 shows the result of updating the estimates of GDP growth rate and electricity intensity growth rate on a quarterly basis in addition to the policy of adding management of capacity under construction, compared to adding management of capacity under construction alone and business as usual run. Updating the estimates about growth rate on a quarterly basis in addition to managing capacity under construction turns out to be an effective policy, in terms of both reducing the oscillations in the reference modes and reducing gap of capacity and average working hours of thermal generators.

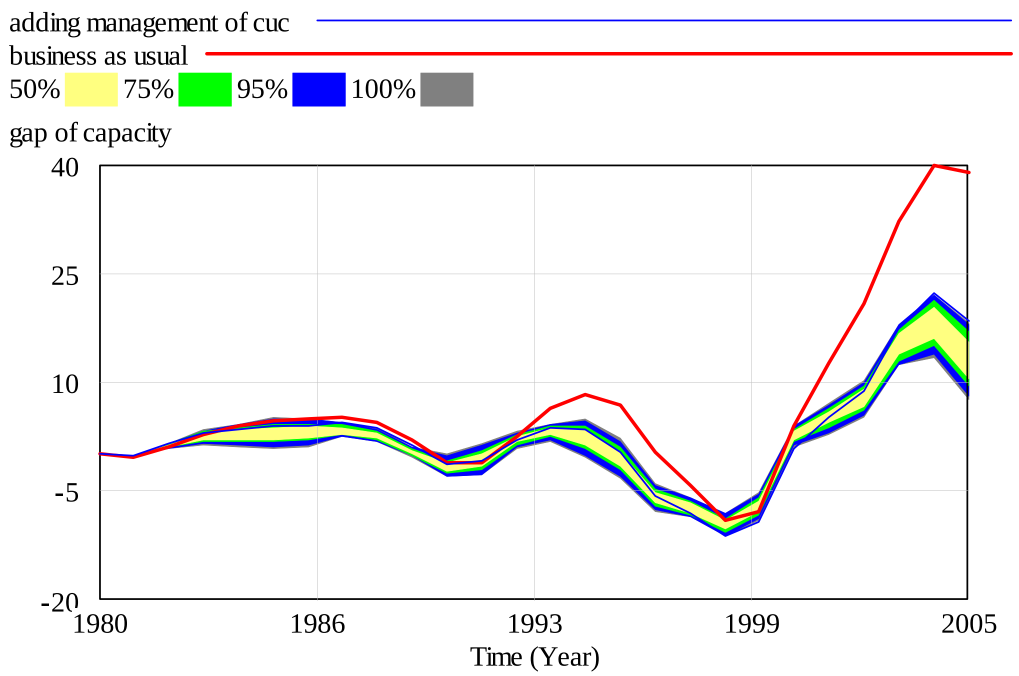


Figure 53 Policy Sensitivity Tests of Two Policy Parameters together: Time to Estimate GDP Growth Rate and Time to Estimate Electricity Intensity Growth Rate, after Adding Management of Capacity under Construction

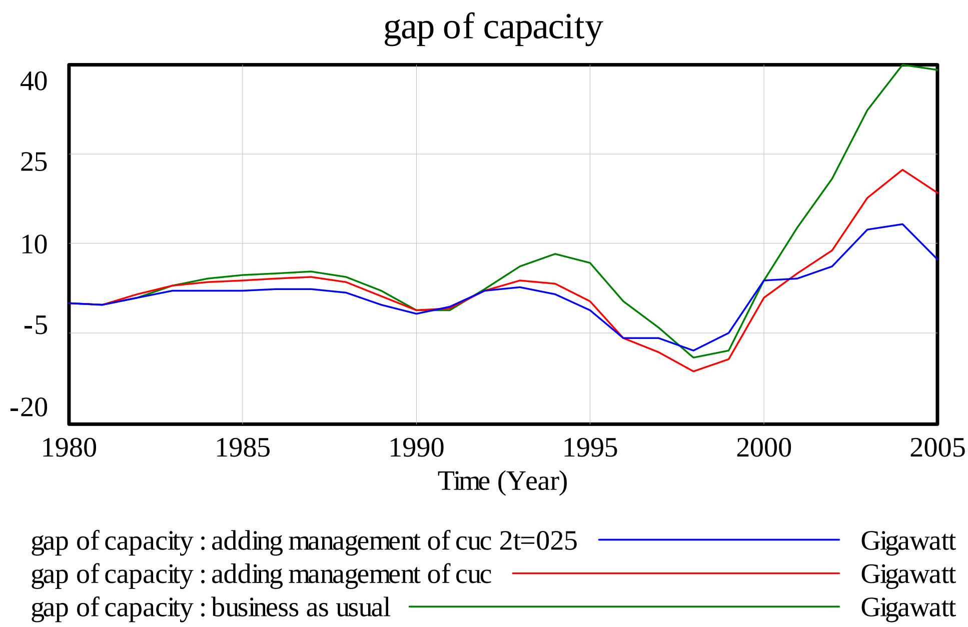


Figure 54 Policy Test: Gap of Capacity, Adding Management of CUC with Time to Estimate GDP Growth Rate and Time to Estimate Electricity Intensity Growth Rate both equal to 0.25 year, Adding Management of CUC and Business As Usual

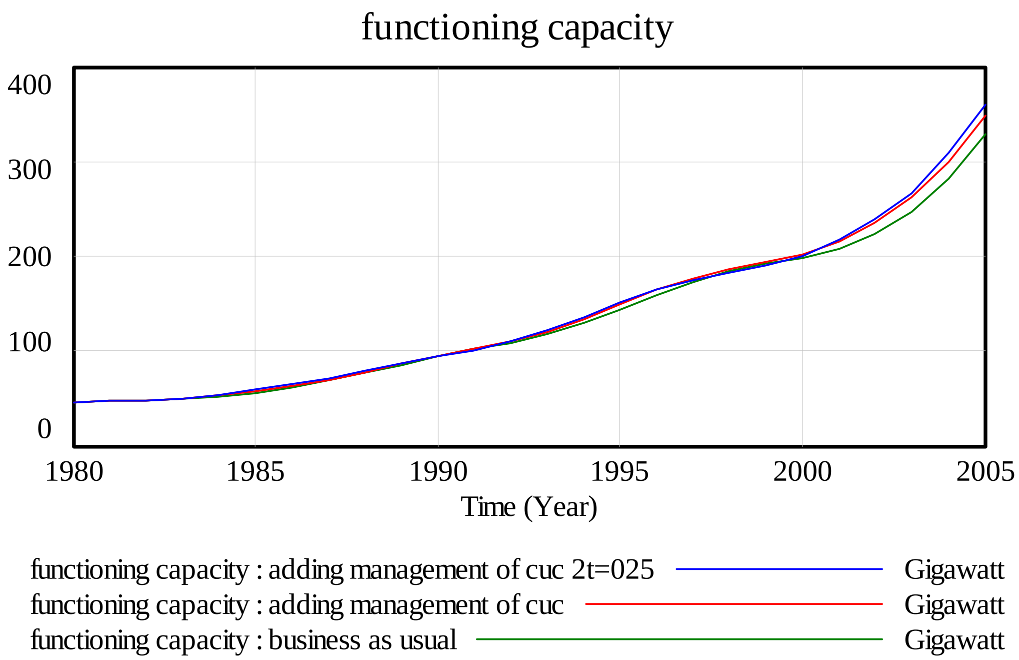


Figure 55 Policy Test: Functioning Capacity, Adding Management of CUC with Time to Estimate GDP Growth Rate and Time to Estimate Electricity Intensity Growth Rate both equal to 0.25 year, Adding Management of CUC and Business As Usual

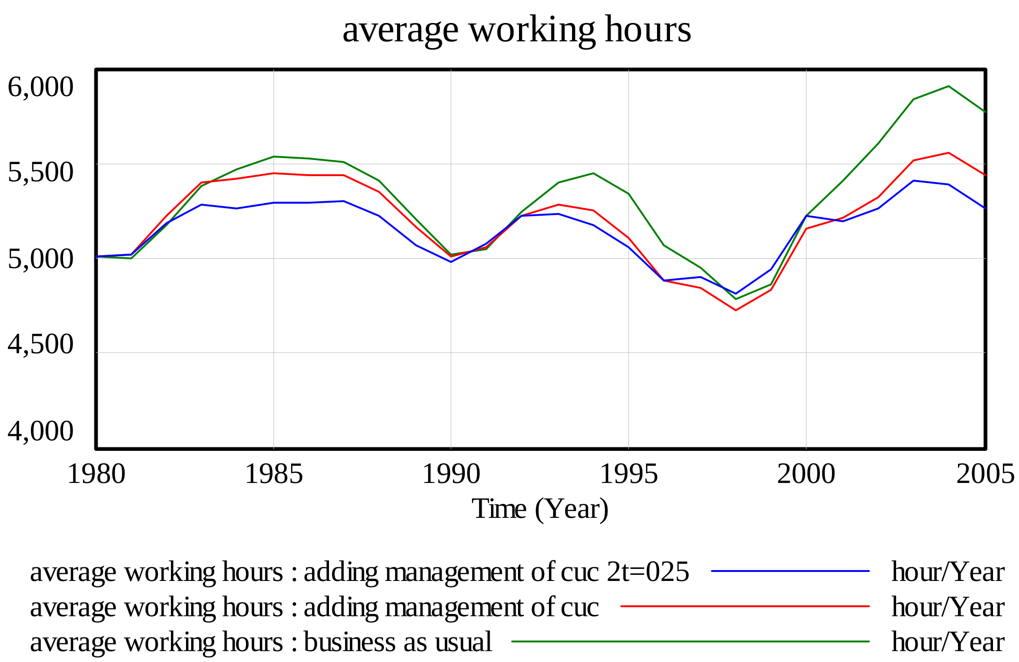


Figure 56 Policy Test: Average Working Hours, Adding Management of CUC with Time to Estimate GDP Growth Rate and Time to Estimate Electricity Intensity Growth Rate both equal to 0.25 year, Adding Management of CUC and Business As Usual

Now I will run policy robustness test to see whether the combination of policy options is robust subject to (bad) changes in the parameters that are out of NDRC's hand. There are 2 variables that are not controlled by policy makers: construction time and GDP growth rate. Let us run policy test when construction time ranges from 3 to 5 years on average (becomes longer). Look at the tests in Figure 57.

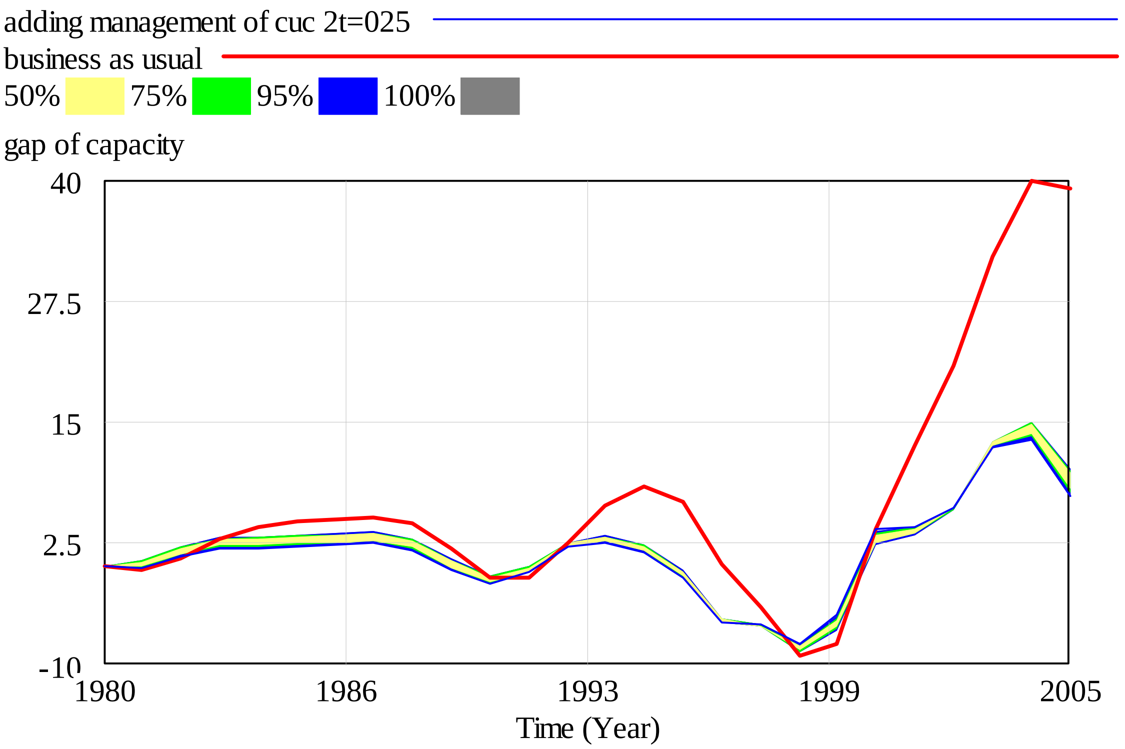


Figure 57 Policy Robustness Test: Combination of Adding Management of CUC and Updating the Estimates of GDP Growth Rate and Electricity Intensity Growth Rate on a Quarterly Basis, when Construction Time ranges from 3 to 5 years

As shown in Figure 57, when the combination of the 2 policy options is adopted, gap of capacity is not sensitive to construction time. This is mainly due to the fact that we take into consideration of construction time when deciding construction start by managing capacity under construction. I also run the policy robustness test of adding managing capacity under construction alone and the model is also not sensitive to construction time. Now let us change the growth rate of GDP to see whether the combination of policy options is also robust to fast GDP growth rate.

Let us assume the fractional GDP growth rate ranges from 3% to 15% after 2005, while electricity intensity is assumed to stay unchanged after 2005 so that growth rate of GDP is equivalent to growth rate of demand. We extend the time scale under study to 2030. (After 2005, GDP fractional growth rate is a constant and electricity intensity also stays unchanged, so time to estimate the growth rate of GDP and growth rate of electricity intensity does not have effect on model behaviors). Before the policy sensitivity test, let us compare the 2 model runs: cuc and no cuc (cuc means managing capacity under construction), assuming GDP fractional growth rate =10% (years before 2005, there is no management of capacity under construction as in history.). See the behaviors of gap of capacity and average working hours in Figure 58 and Figure 59.

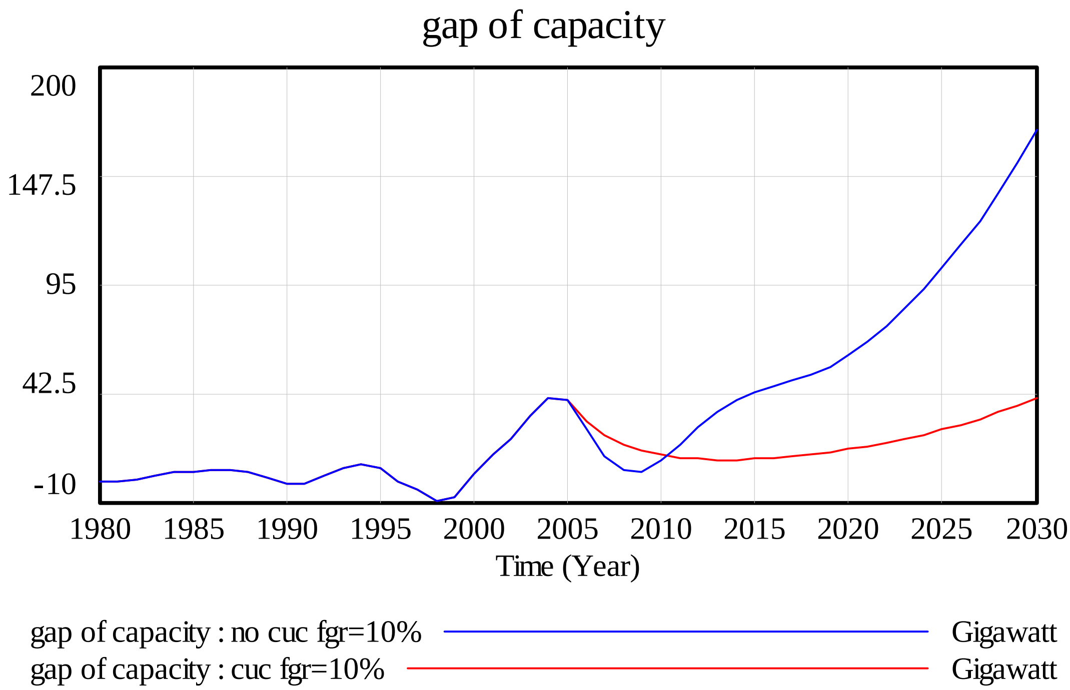


Figure 58 Policy Test: Gap of Capacity, Managing Capacity Under Construction and No Managing, when GDP Fractional Growth Rate=10%

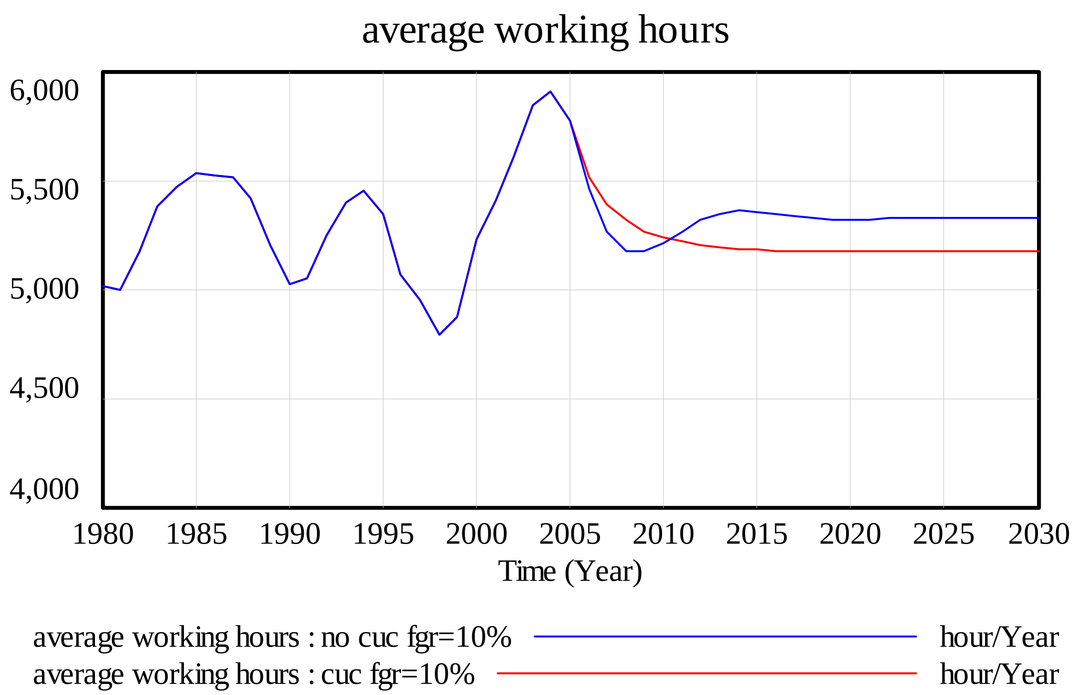


Figure 59 Policy Test: Average Working Hours, Managing Capacity under Construction and No Managing, when GDP Fractional Growth Rate=10%

As shown in Figure 58 and Figure 59, the behavior of gap of capacity and average working hours greatly improved after managing the stock of capacity under construction: both gap of capacity and average working hours greatly reduced and the oscillations in them were removed.

Now let us run the sensitivity test about GDP fractional growth rate ranging from 3% to 15%, when the policy of managing capacity under construction is carried out.

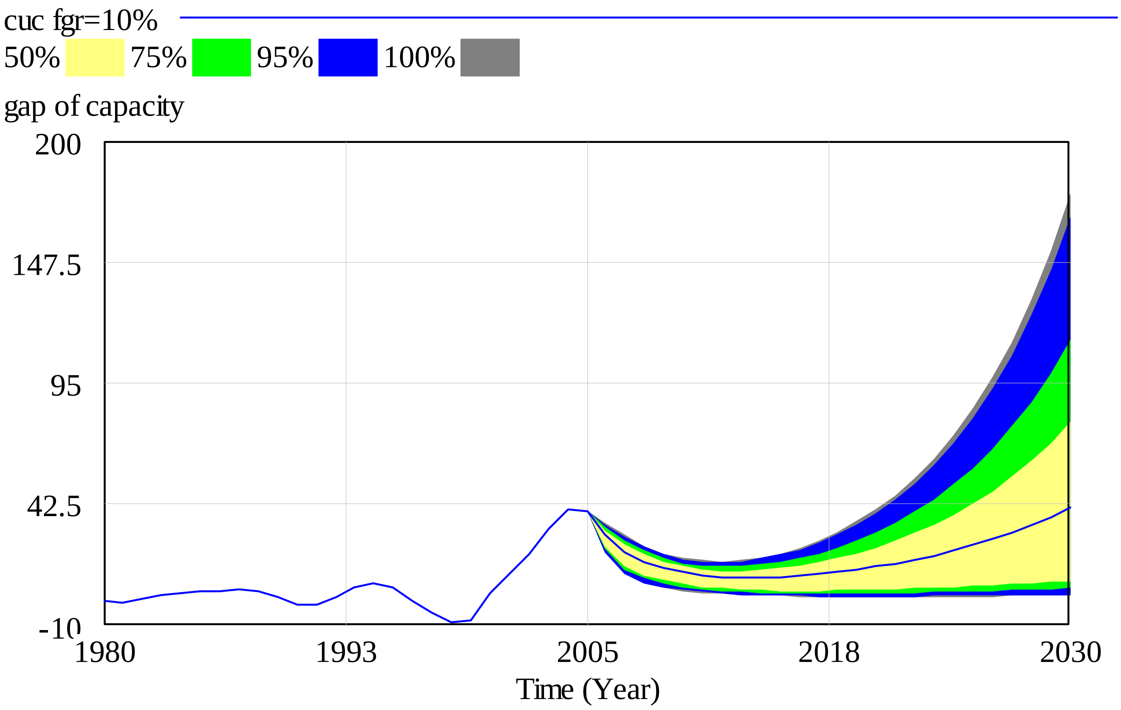


Figure 60 Policy Robustness Test: Managing Capacity under Construction, GDP Fractional Growth Rate 3%~15%

As shown in Figure 60, the policy of managing capacity under construction is not robust when GDP fractional growth rate is too high. However, this is not caused by the principle of managing capacity under construction itself. Instead, it is caused by the goal of capacity under construction we set in this case. When GDP fractional growth rate is too high, underestimates about desired capacity and capacity depreciation also increase rapidly. And estimate about capacity depreciation is a part of desired capacity under construction (the goal of capacity under construction) because only estimated capacity depreciation is available to decision makers, rather than the real-time capacity depreciation. Let us test this hypothesis by setting time to estimate capacity depreciation =0.25 year (0.25 year is the minimum realistic time for time to estimate capacity depreciation. Because in reality, it does not make any difference if NDRC update their estimates of capacity depreciation more often than they do to their estimates of total demand.). Then run the policy sensitivity test again. See Figure 61.

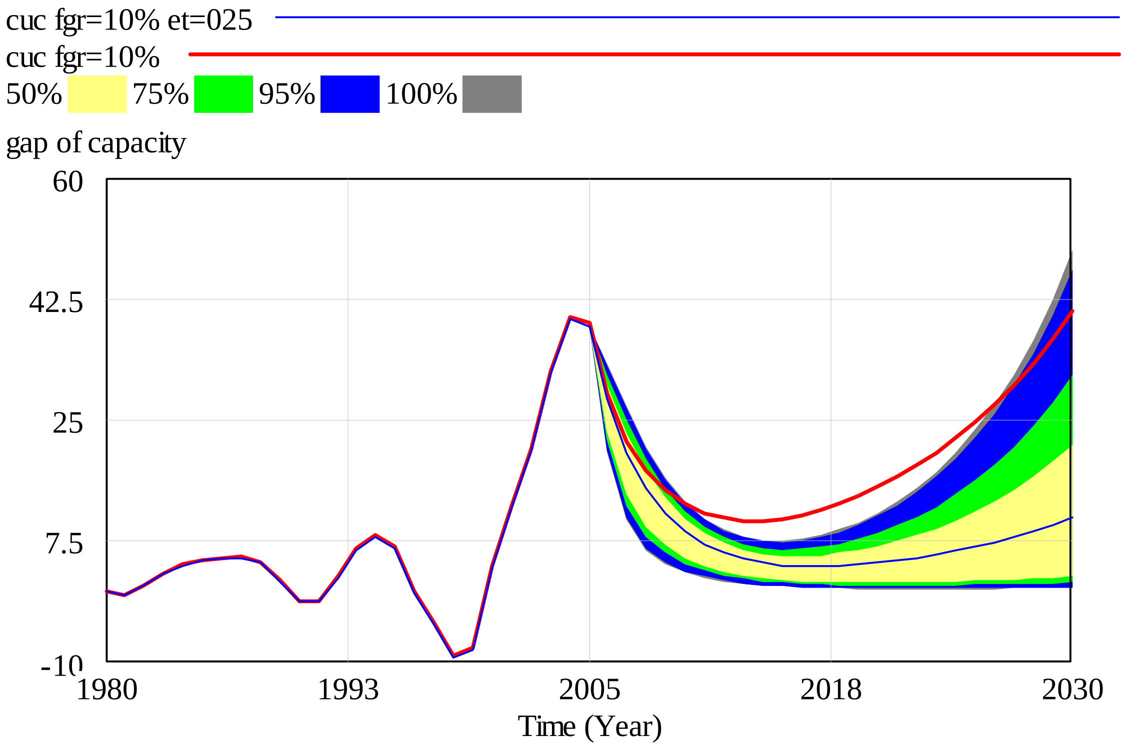


Figure 61 Policy Robustness Test: Managing Capacity under Construction while Time to Estimate Capacity Depreciation= 0.25, GDP Fractional Growth Rate 3%~15%

As shown in Figure 61, after setting time to estimate = 0.25 year (a quarter), gap of capacity is still sensitive to GDP growth rate, but much less. And the upper bound (GDP fractional growth rate = 15%) of the sensitivity run is only about a third of that in Figure 60 and is close to the run when time to estimate capacity depreciation is 1 year and GDP fractional growth rate is 10%. This indicates that updating the estimates about depreciated capacity more often, say on a quarterly basis could be a effective policy option.

In reality, it will increase much work for the decision makers to update their estimates about capacity depreciation every quarter, rather than every year. However, it is not as difficult as reducing the capacity adjustment time because reducing capacity adjustment time means investing more every time, which needs more effort and actually systematic effort. Updating estimates more often, however, only requires more effort on data collecting and data examining. Therefore, to update estimates about capacity depreciation more often is a comparatively feasible policy option. (I also tried changing perception time of demand but it does not change the model behavior much.)

However, the policy of updating estimates about capacity depreciation has to work together with the policy of managing capacity under construction. See Figure 62, without managing capacity under construction, time to estimate capacity depreciation hardly helps reduce capacity shortage.

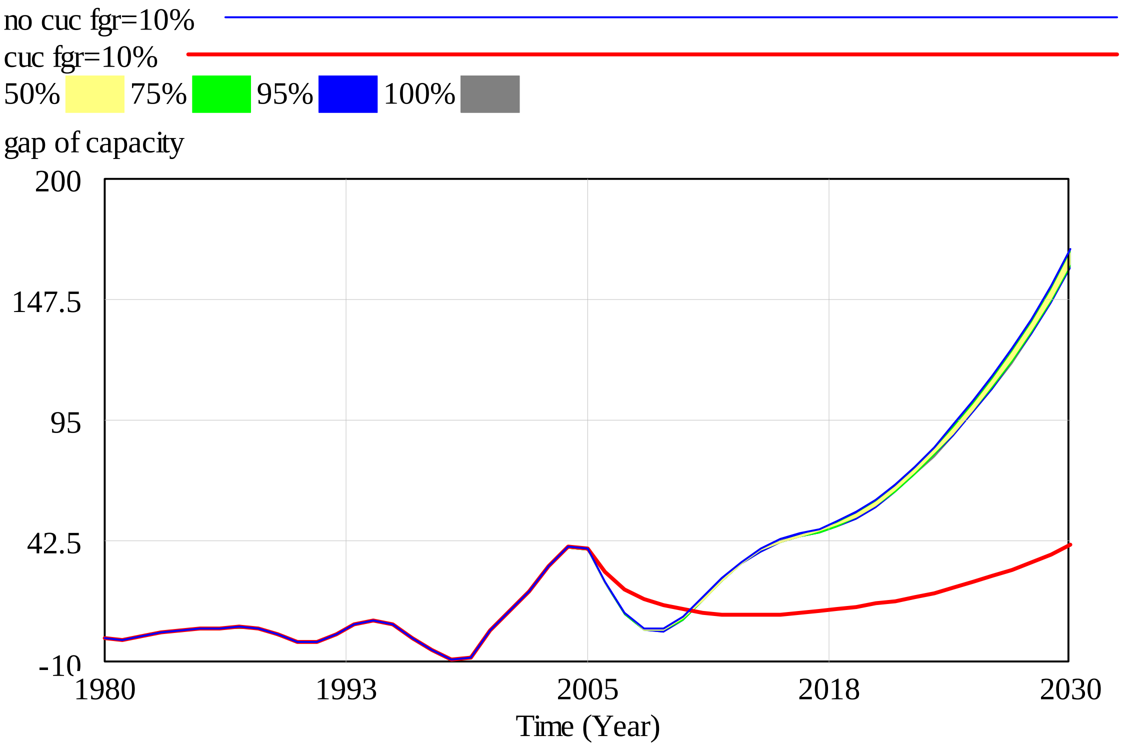


Figure 62 Policy Sensitivity Test: With and Without Managing Capacity under Construction when GDP Fractional Growth Rate =10%, Time to Estimate Capacity Depreciation = 0.25~1

Any way, as shown in Figure 61, it is impossible to eliminate capacity shortage when the underestimates of desired capacity and capacity deprecation is inevitable. And the capacity shortage is very sensitive to GDP fractional growth rate (demand growth rate), especially when GDP growth rate exceeds 10% per year, capacity shortage increases rapidly.

In the Outline of the 11th Five-Year Plan by the CPC Central Committee (2005), it is expected that China's GDP grows 7.5% annually. However, the GDP in 2006 is 10.24% bigger than that in 2005, which surpassed the expectation of 11th five-year plan. We do not know for the time being what the growth rate in the following 4 years will also surpass 7.5%, but in any case, we have to reduce electricity intensity in order to offset the fast growth rate of GDP, so as to constrain electricity demand growth from growing too fast.

By studying the electricity intensity in the past 25 years, it is found that there is a trend of decline in electricity intensity, i.e. improvement in electricity efficiency, even without effect from price, administrative measures and so on. See Figure 63 and Figure 64 below.

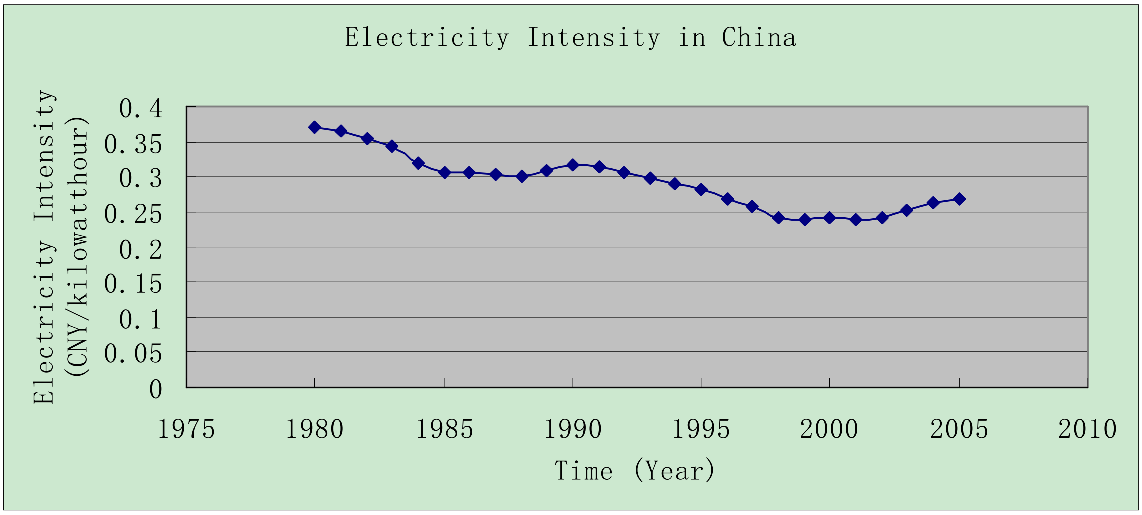


Figure 63 Electricity Intensity in China from 1980 to 2005

Source: Energy Information Administration, United States
World Net Conventional Thermal Electricity Generation, Most Recent Annual Estimates, 1980-2006
http://www.eia.doe.gov/emeu/international/electricitygeneration.html
National Bureau of Statistics of China (2007)
Gross Domestic Product
http://www.stats.gov.cn/tjsj/ndsj/2007/indexch.htm
Global Econ Data
China, GDP deflator, 1980~2006
http://www.econstats.com/weo/C035V021.htm

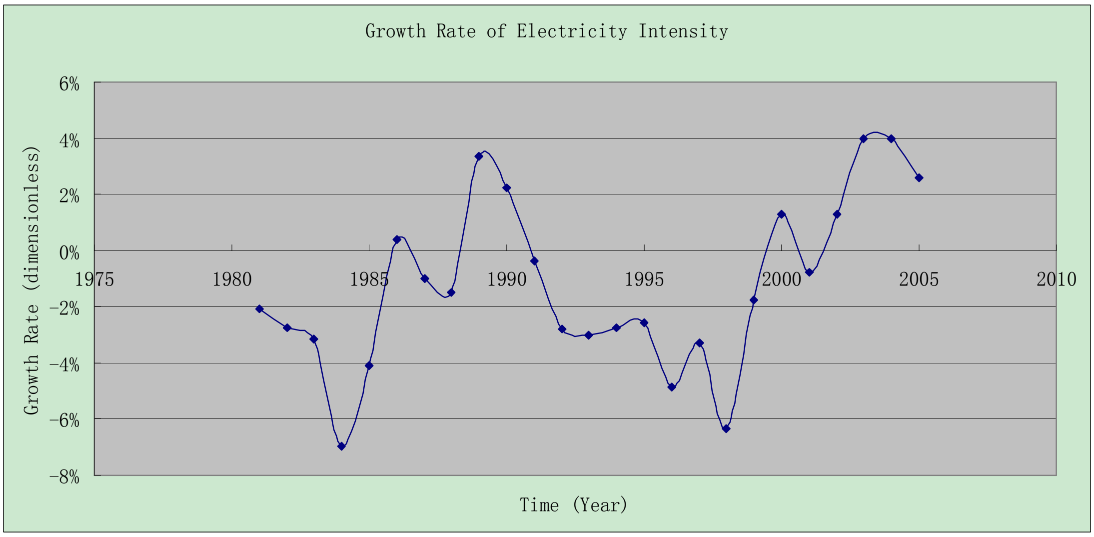


Figure 64 Growth Rate of Electricity Intensity in China from 1980 to 2005

In the past decades, electricity price in China has been very stable. However, we can see an average growth rate of -3% in electricity intensity, with only a few exceptions. However, electricity intensity has been increasing since 2001, although the growth rate of electricity intensity is on its decline. This calls for an effective pricing mechanism even more so as to lower electricity intensity.

In the paper named Testimony on The Effect of Restructuring on Price Elasticities of Demand and Supply, Stevens and Lerner (1996) summarized several studies of price elasticity in regulated electricity market in California. They found that short-run elasticity of residential, commercial and industrial demand is respectively -0.06 to -0.49**,** -0.17 to -0.25, -0.04 to -0.22 and long-run elasticity is respectively -0.45 to -1.89, -1.00 to -1.60 and -0.51 to -1.82.

In China, industrial consumption of electricity accounts for more than 70% of the total consumption, therefore, we can refer to short-run elasticity of industrial demand in California as a point of start, which is -0.04 to -0.22. (Why short-run rather than long-run is because I am going to analyze the yearly growth rate in electricity intensity and a year is a short term.) However, the electricity intensity in China has been much bigger than in the US. (The electricity intensity in 2005 in China is 0.269 Kilowatt/CNY, according to Figure 63, while electricity intensity in 1997 in the US is 0.402 Kilowatt/Dollar, according to EIA. The exchange rate between Dollars to CNY is around 8.) Therefore, the electricity intensity in China is almost 5 times as big as that in the US. In this sense, it is reasonable to assume the price elasticity in China is bigger than that in the US, because there is much more room for electricity efficiency to improve. Suppose the price elasticity in China is 2 times that in the US, which is -0.08 to -0.44 approximately.

1) Scenario I: price elasticity is -0.08

In this case, electricity intensity is very insensitive to electricity price. Suppose electricity price grows at 4% a year, then electricity intensity only declines at 0.32% per year, which hardly has any effect on electricity intensity. In this sense, pricing mechanism can not really help to reduce the growth rate of electricity demand, much less balance functioning capacity with desired capacity.

2) Scenario II: price elasticity is -0.44

In this case, electricity intensity is sensitive to electricity price. Suppose electricity price grows at 4% (around 0.024 CNY/Kilowatt) a year, then electricity intensity declines at 1.76% per year, which can offset almost 2% growth in China's GDP. As shown in Figure 61, when GDP growth rate is below 10% (GDP growth rate is equal to demand growth rate by then), gap of capacity is stable and comparatively small. Given the 10.24% GDP growth rate in 2006 and expected 7.5% annual growth rate in the 11^{th} five year plan, proper pricing mechanism does help to balance functioning capacity with desired capacity by making the growth rate of electricity demand less than 10%. Because China has been in electricity shortage for long, in which case price is supposed to rise if it is market determined. However, due to the improper pricing mechanism so far in China, the government takes a dominating role in determining electricity price, which makes electricity price fail to represent the relationship between electricity demand and supply and thus not increase as it should have.

6 Contributions and Limitations of this Study

6.1 Major findings

Managing the stock of capacity under construction can not only reduce or eliminate the oscillations in these two variables, but also greatly reduce capacity shortage. Without the policy of managing capacity under construction, no feasible policy is available to effectively reduce oscillations and capacity shortage. Managing the stock of capacity under construction is an indispensable solution to the dynamic problem addressed in the paper. In the meanwhile, the policy of managing the stock of capacity under construction is robust even if construction time becomes longer, say up to 5 years. However, this policy can not stop big capacity shortage from happening when GDP grows too fast and pricing mechanism is not working properly so as to reduce electricity intensity, i.e. improve electricity efficiency.

Other policy options to reduce capacity shortage could be eliminating the underestimates of electricity demand and capacity depreciation, introducing more market effect into electricity pricing and lowering the growth rate of GDP. Eliminating the underestimates turns out to be effective in terms of reducing capacity shortage after adopting the policy of managing capacity under construction. Therefore, it is recommended that NDRC update their estimates of GDP growth rate, electricity intensity growth rate and capacity depreciation more often, say on a quarterly basis. And of course, they also need to act on those updated estimates. Whether price is effective in affecting electricity intensity in China still needs more research. If the price elasticity is big enough, then improving the improper pricing mechanism now in China by introducing more market effect into pricing could be an effective solution as to reduce electricity intensity, thus offsetting the fast growth rate in GDP and reducing capacity shortage. China also needs to think about lowering the growth rate of GDP, called soft landing. Otherwise, the government needs to take measures in addition to pricing, such as administrative, financial and tax measures to reduce electricity intensity, so as to offset the effect of fast growing GDP and reduce capacity shortage.

6.2 Limitations and further research

First of all, the boundary of the research does not include other important elements in electricity industry, such as coal and grid. In my further research, I would like to include coal into the boundary. Because coal is also the main primary source of energy for electricity, so decreasing coal reserves could become a barrier for capacity growth. Plus, coal reserves determines coal price, which is the main cost for unit electricity produced, thus it is very important in determining electricity price.

Second, in the paper, electricity price is taken as exogenous because it is not affected by the feedback from the model in the time period under study. However, looking into the future, it is necessary to model electricity price as endogenous variable, which will be affected by the relationship between electricity demand and supply. I would like to do that in my further research. At the same time, I will model the structure from electricity price to capacity investment and structure from electricity price to electricity intensity.

Finally, the relationship between real-time electricity demand (load) and functioning capacity is not studied in the paper. In reality, we have to shift some load from peak hours to valley hours, in order to meet the load from consumers all the time. Electricity price proves to be a very effective measure in terms of load shifting according to relating literature, and there have been many researchers addressing different price mechanisms so as to shift real-time load from electricity consumers. For example, peak-valley electricity price has been used in industry-use electricity as a way of shifting load since late 1990s and is on trial for life-use electricity recently. Two parts electricity pricing mechanism came into use in 2005 and still needs much more research into it. I would like to extend the boundary of my research so as to study this aspect of electricity demand and pricing policy as well.

6.3 Final word

This University of Bergen master thesis provides a basic understanding of electricity shortage in China in the past few decades. It will be a point of departure for my second master thesis at Fudan University, China and a foundation for my further study into the electricity industry in China. What I will do in the next phase is examine electricity price and see how it interacts with electricity supply and demand. The objective of next phase will remain the same: to identify policies for reducing shortage of electricity in China.

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(Italic in brackets is the Chinese spelling of references in Chinese)

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Appendix A Terminology

Electricity is a secondary form of energy, converted from variety of primary energy sources, such as fossil fuels, hydro, uranium, wind, solar, tidal and so on.

According to these different primary energy sources, electricity plants are classified into thermal plant, hydro power plant, nuclear power plant. All conventional, large-scale electricity production uses the same fundamental technology in which a turbine, propelled by steam, water or gas, is used to drive a generator (Figure A. a). For smaller scale facilities, internal combustion engines or wind-driven blades may be coupled directly to a generator. Figure A. b gave a depiction of electricity supply chains, including thermal power, hydro power and alternative electric supply systems based upon wind and solar.

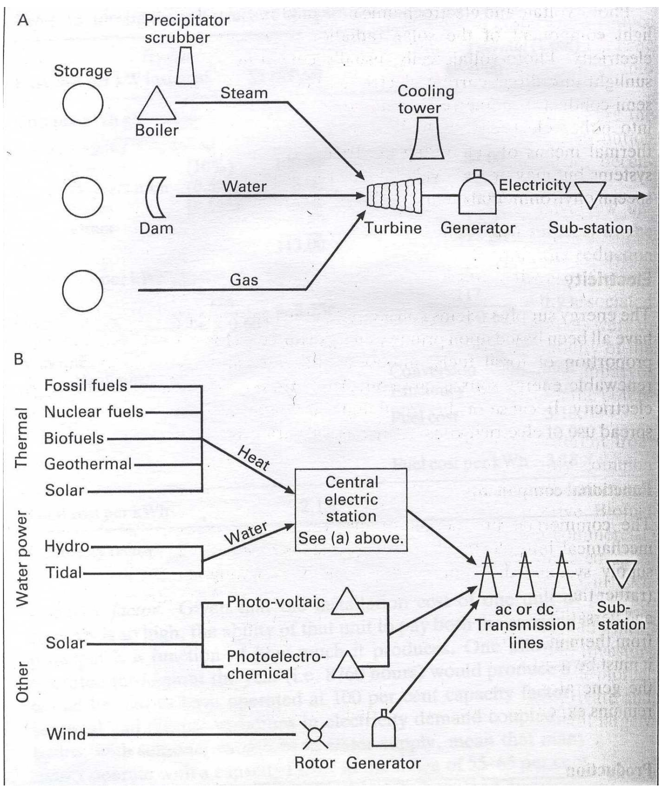

Figure A Functional Components of the Electricity Industry: (a) Central Electric Station Configuration, (b) Electricity Supply Chains

Source: Geography of supply, Figure 4.7

Generator converts one form of energy into the energy of electricity at a certain rate (joules per second, calories per day, or barrels of oil equivalent per year). This rate is the power of generator, single dynamo capacity. Watt is the international system of unit (SI) for power.

$$1 \text{ Watt} = \frac{1\,\text{Joule}}{1\,\text{Second}} \tag{1}$$

$$\text{Or, } 1 \text{ Joule} = 1 \text{ Watt-Second} \tag{2}$$

After a certain period of time, generators produces a certain amount of electricity, which is power (Watt) * time (Second), the unit of which is Joule. The same applies to electricity consumption. Electricity end-users consume electricity also at a certain rate, in form of bulbs, televisions, and fans and so on. The unit of consumption capacity is also Watt. After running for a certain time period, electrical equipment consumes a certain amount of electricity, which is measured in Joule.

Some units that are derived from Watt are also used in practice, such as Gigawatt, which is 1 billion Watt, equal to 10^9 Watt, and Terawatt, which is 1 trillion Watt, equal to 10^{12} Watt. In reality, hour is used more often to measure how long generators or electrical equipment have been running, rather than second. Accordingly, Gigawatt hour and Terawatt hour are often used as the unit of the amount of electricity produced by generators. For example, a generator of 1 Gigawatt capacity running for 1 hour generates 1 Gigawatt hour of electricity, while a bulb of 60 Watt capacity lighting for 1 hour consumes 60 Watt hour of electricity. In the following, the paper uses Gigawatt as the unit of electricity production rate (generating capacity) and consumption rate (consuming capacity), Gigawatt hour as the unit of generated electricity (electricity generation) and consumed electricity (electricity consumption).

Electricity must be used the instant it is produced. There is a connection from generator to end-users, called grid. Only the electricity generated by those generators that are connected to the grid can be consumed by electrical equipment at the end-users. The whole system from electricity production to consumption can be simplified as two machines connected by wire; one produces electricity, while the other consumes. Therefore, electricity production equals electricity consumption all the time. The power (capacity) of electrical equipment in use by end-users is regarded as instant electricity demand, or load from the customers, the unit of which is Gigawatt. Within a day, instant demand from end-users exists throughout and usually changes from time to time, and is difficult to meet at any instant. Electricity demand is always bigger and reaches its peak during office hours in a day, which is called peak load.

However, decisions about power plant construction are not made based on the electricity demand in every second. Instead, annual total electricity demand, which is the aggregated demand over a year, is usually taken as the basis to make a decision, the unit of which is Gigawatt hour. However, in reality, data about annual total electricity demand is usually unavailable. What is available is annual total electricity consumption, which is the satisfied annual total electricity demand, the unit of which is also Gigawatt hour. Every year, there is a projected annual total electricity demand, but how to make the projection is undisclosed to the public. That is also why there have been so many methods used to project annual total electricity demand, such as Grey System Theory, Time Series Model and Econometrics.

Installed generating capacity, is sum of the capacity of all the generators ready to run, the unit of which is Gigawatt. When there is electricity shortage, it can be either a power (capacity) shortage or electricity generation shortage. The former is the shortage of installed generating capacity (Gigawatt), which is the focus of this paper, while the latter is the shortage of generated electricity (Gigawatt hour).

Appendix B System dynamics

System dynamics is a feedback theory about policy making. Feedback is one of the core concepts of system dynamics. Stocks and flows, along with feedback, are the two central concepts of dynamics systems theory.

Stocks are accumulations. They characterize the state of the system and generate the information upon which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. By decoupling rates of flow, stocks are the source of disequilibrium dynamics in system.

In a system dynamics point of view, the behavior of a system arises from its structure. That structure consists of feedback loops, stocks and flows, and nonlinearities created by the interaction of the physical and institutional structure of the system with the decision-making processes of the agents acting within it. The basic modes of behavior in dynamic systems are identified along with the feedback structures generating them. These modes include growth, created by positive feedback; goal seeking, created by negative feedback; and oscillations (including damped oscillations, limit cycles, and chaos), and created by negative feedback with time delays.

Oscillation is the third fundamental mode of behavior observed in dynamic systems. Like goal-seeking behavior, oscillations are caused by negative feedback loops. The state of the system is compared to its goal, and corrective actions are taken to eliminate any discrepancies. In an oscillatory system, the state of the system constantly overshoots its goal or equilibrium state, reserves, then undershoots, and so on. The overshooting arises from the presence of significant time delays in the negative loops. The time delays cause corrective actions to continue even after the state of the system reaches its goal, forcing the system to adjust too much, and triggering a new correction in the opposite direction.

Oscillations can arise if there is a significant delay in any part of the negative loop. There may be delays in any of the information links making up the loop. There may be delays in perceiving the state of the system caused by the measurement and reporting system. There may be delays in initiating corrective actions after the discrepancy is perceived due to the time required to reach a decision. And there may be delays between the initiation of a corrective action and its effect on the state of the system. It takes time for a company to measure and report inventory levels, time for management to meet and decide how much to produce, and more time while raw materials procurement, the labor force, and other needed resources respond to the new production schedule. Sufficiently long delays at any one of these points could cause inventory to oscillate.