

# **A System Dynamics Based Study of Policies on Reducing Energy Use and Energy Expense for Chinese Steel Industry**

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# *Abstract*

Chinese steel industry is one of the energy intensive industries in China. Coal and electricity are the two main energy sources for steel making. Steel industry in China is experiencing its transition period because of economy transition during the industrialization period. Steel demand has increased significantly in recent years, which correspondingly enlarges the energy demand. On the other hand, energy prices of coal and electricity have been increasing dramatically since 1980 because of the macro-control from the government. Large energy demand leads to high energy consumption and high energy price raises the energy expense of steel making.

Motivated by the need to reduce energy use and energy expense, a System Dynamics based model is built to investigate policies in order to help Chinese steel industry ease energy problems during its transition period. The model helps to foster learning about a dynamically complex system, and thus contributes to a better understanding on the effectiveness, validity of energy policies. Results show that most of the investigated policy options are cost-effective. However, implementation remains a critical issue, the viability of energy tax and R&D subsidy is still questionable in the real world. Developing the technology of recycling scrapped steel is found to be useful in limiting carbon emission with comparatively easy implementation.

**Key Words:** Chinese steel industry, System Dynamics, energy price, energy demand, transition

*To My Dear Parents,*

*Mr. Zheng ZhenYan*

*Mrs. Tang Lianyin.*

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# *Chapter 1*

## **Introduction**

The industrial sector is the largest of the energy end-use sectors in China. It was responsible for the country's 70% of primary energy use and 53% of associated carbon dioxide emissions in 2004. The industrial sector is extremely diverse, encompassing the extraction of natural resources, conversion into raw materials, and manufacture of finished products. Five energy-intensive industrial sub sectors account for the bulk of industrial energy consumption and related carbon dioxide emissions (iron and steel, chemicals, petroleum refining, pulp and paper, and cement). China is facing increasing energy price, resource shortage and environmental destruction, such condition is worsening over time. For that reason, relevant measures have been carried out. The technology to improve energy efficiency in those energy-intensive industries may be the most effective and economical way for energy conservation and environment protection.

Challenges exist in adapting technologies, removing old and outdated equipments, improving technical production process in those energy-intensive industries. Such measures usually take one or even two decades to realize, which has a large discrepancy from what people expect to see. Thus long delay implies early reactions. Interrelationships and feedbacks among the above issues require us to think the problem in a dynamic way. Chinese steel industry which involves the above features will be studied in this research as a case analysis.

Steel industry is one of the energy intensive industries in China, and is responsible for the country's 15% of the total energy consumption and corresponding carbon dioxide emissions. Iron and steel production consumes a large quantity of coal, especially in China at its early stage of industrialization where outdated, inefficient technologies are extensively used to produce iron and steel. High energy demand during industrialization transition period and rapidly rising energy price due to resource scarcity and potential government policy

adjustment are two challenges for steel industry. The dynamic condition allows us to use some tool which can capture the above features and the interrelationships among them.

In this research, a System Dynamics based model is built. Its purpose is to explore the internal mechanism of the Chinese steel industry and to see how energy conservation policies help to reduce the high energy demand and energy expenditure during the economy transition period. The model is aimed to help the readers foster a way of understanding dynamic and complex feedback energy system; it is also the output of this study. Model results and relevant policies can be considered as examples of possible applications of the model. Two major problems will be studied in the model: energy efficiency technology development and substitution among steelmaking ways.

The rest of the paper is organized as follows. Major problems regarding energy in steel industry are elaborated in the following chapter. Then dynamic hypothesis including research methodology, assumptions and causal loop diagrams are illustrated in Chapter 3. Chapter 4 reviews relevant researches on the similar problems. We proceed by introduction and describing the detailed System Dynamics model in Chapter 5. Simulation results and model testing are then exhibited in Chapter 6. Chapter 7 discusses policy implementation and optimization. The paper concludes with a summary and future work in Chapter 8. Equation and documentation of each variable in the model can be found in the appendix in the end of the paper.

# ***Chapter 2***

## **Problem Articulation**

The most important step in modeling is problem articulation. This system dynamics based model is designed for a particular purpose and address a specific problem.

### **2.1 PROBLEM BACKGROUND**

The Chinese steel industry is one of the high energy-intensive industries; the energy problems in steel industry became serious in recent years. Two major issues are of special concern.

#### **2.1.1 Rapid Development of Steel Industry and Correspondingly High Energy Demand**

The steel demand in China has increased significantly since 1980 due to economic growth and increasing demand from other industries such as buildings, automobiles and other steel appliances. We are in the early stage of industrialization. The development of world economy and global capital accumulation keep simultaneous growth with the growth of steel cumulative consumption. From the experience of other developed counties, industrialization is a process of large natural resources consumption with rapid social capital accumulation. The U.S., Japan and some western European countries have all experienced an important developing section which based on iron and steel industry as their mainstay industry. Those countries' industrialization processes imply that such process necessitates large amounts of steel.

From 1901 to 2000, the accumulated steel consumptions in main developed countries are listed below:

U.S.: 7.1 billion tons

Japan: 3.8 billion tons

Former Soviet Union: 5.6 billion tons

Source: (Zhou, 2006)

China only consumed 1.9 billion tons in the corresponding time period, which indicates there is still a large discrepancy between the current level of Chinese industry and that of industrialized countries, but it also implies a big potential in Chinese steel industry.

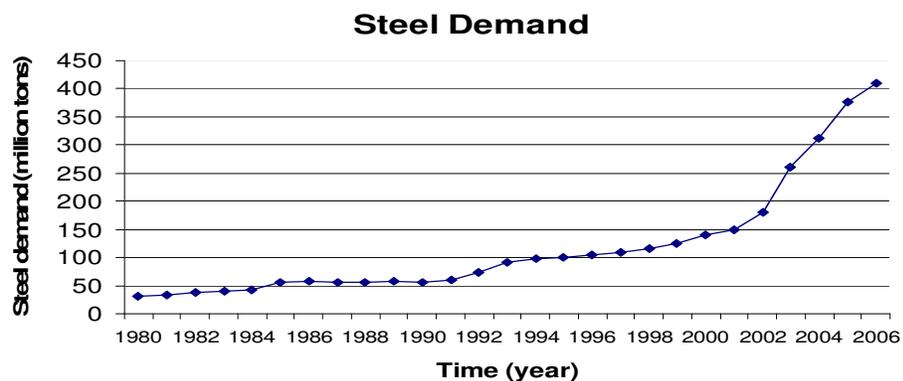
The experience of world developed countries indicates steel demand intensity is obviously different due to different developing stages and industrial structures. In general, the steel demand intensity appears as following changes:

Stages	GDP per capita (YUAN)	Steel demand intensity
Underdevelopment	Lower than 8000	Very low
Initial and intermediate	8000-16000	Rapidly increasing
Later	16000-32000	Remains at high level
Maturity	Higher than 32000	Slowly decreasing

Source: (Zhou, 2006)

**Table 2.1 Relationship between GDP per capita and steel demand intensity in different industrialization stages**

The data from IMF shows that the GDP per capita of China in 2006 is more than 10000Yuan, which means China has entered into initial stage of industrialization. Hence from the experience of other developed countries, the steel demand will keep the trend of continuous increasing for a long time.



Source: Chinese Iron & Steel Association

### **Fig.2.1 Steel demand in China**

From the figure above, it is obvious to find that the demand grows significantly, the growth remained strong during the market reforms in 1990s. In 1996 China became the world's largest producer of steel (IISI, 1999). Correspondingly, large steel demand necessitates large energy demand, steel industry in China has consumed large amount of coal and electricity.

Since reform and opening policies implemented around 1980, there is a dramatic reduction in energy consumption per ton of steel produced. The unit energy consumption has been reduced from 2.04 tce<sup>1</sup> in 1980 to 0.74 tce in 2005, which remarkably ease the pressure of steel production cost caused by the increase of energy price. Even we have achieved great improvement on reduction of energy consumption; there is still discrepancy from the level of developed countries, such as Japan, which has already reduced to 0.65 tce in 1990. The comparatively low energy efficiency for steel making in China is due to outdated, inefficient technologies and unreasonable production structure. Rapid increasing steel demand directly leads to high energy demand every year. The energy demand from steel industry has increased from 10% of total energy consumption in China in 1995 to 15% in 2004.

Large energy demand caused by rapid increasing steel demand has put a heavy weight on steel industry; it becomes both meaningful and practical to study how steel industry responds to save energy.

### **2.1.2 Dependence on Coal and Electricity and Problematic Price Increase**

Coal is the main energy resource used in China, which is true as well in steel industry. Coal and electricity together amount to more than 95% of the total energy consumption for steel industry. So what about the price condition for coal and electricity? Among all sectors in China, steel industry consumes more than 10% of the total coal consumption in China, while coal-fired power plants burn about half of China's coal and produce about half of the country's power. China's coal pricing system is divided into two parts. To ensure the electricity generation use, a certain amount of coal is ordered nationally. To meet the price of

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<sup>1</sup> Tce refers to ton of coal equivalent or standard coal, which is a generally used energy unit in China. Different kinds of energy have their own calorific value. In order to unify the standard, we transfer the measure of coal and electricity in terms of its weight for steel production into Tce. 1 ton of crude coal= 0.714 Tce= 7560kwh= 29270 MJ.

electricity set by the country at an artificially low level, the price of coal used in this sector is kept low too.

The other parts including the coal price for steel industry see their prices rise or fall in accordance with market forces.

Energy Price (YUAN/Tce)										
1990	1991	1992	1993	1994	1995	1996	1997	1998	.....	2006
240	250	290	350	410	470	567	587	549	.....	600

Source: (Wang, 1999), China Iron & Steel Association

**Table 2.2 Combined Energy Price of Coal and Electricity in China**

The price for both electricity and coal has been increasing since 1990. Table 2.2 shows an increasing trend of energy price. From the data series, even though the price keeps increasing rather slowly in recent years, possibilities of costly increases in energy price in the future are still big. Coal price of international market begins to respond to the rise of oil price of international market in recent years. Besides the rise from international market, some other policies which may be implemented in the near future will further raise the energy cost of the steel industry.

### **-Continuous Adjustment of Energy Resource Tax**

Continuous adjustment on energy resource tax has been made by the state administration of taxation during recent years. The resource tax rate of coal has been raised to 3 Yuan/ ton for the time being, such adjustments have been made several times since the initialization of resource tax in 1993. China is facing resource scarcity, huge waste of natural resource and serious environmental destruction and so on; one of the reasons for all these results is lack of relevant financial policies. The recent adjustments from state administration of taxation indicate that the reform of resource tax system tends to be intensified. Such upward adjustment will influence the production cost of steel industry. The tax rate is still comparatively low and will not give much effect on energy use and environmental protection. In the near future, the resource tax rate may continuously increase at a bigger magnitude. The proportion of energy cost in the production cost has large possibility to increase correspondingly, which may affect the profits of steel industries gradually.

### **-Indirect Price Increase by Coal Pollution Tax**

The carbon intensity of coal is much higher than that of other kinds of energy, CO<sub>2</sub> emission from unit coal combustion is two times the level from natural gas (CO<sub>2</sub> emission from unit oil combustion is between coal and natural gas). As described above, coal consumption takes up more than 70% of the total energy consumption for steel industry. CO<sub>2</sub> emission is proportional to energy consumption; high energy consumption from steel industry will directly lead to high CO<sub>2</sub> emission. The experts from state administration of taxation think that current coal price can not reflect its economic cost and scarcity of natural resources. (Huang, 2004) In this sense, coal pollution tax might be introduced in terms of the carbon contents from the use of coal. Consequently, coal price will increase indirectly.

### **2.1.3 Transition Problem**

As illustrated in 2.1.1 and 2.1.2, rapidly increasing steel demand leads to high energy demand while continuous increasing energy price will lead to high energy expense. The system has already entered into a so-called “transition period” as a result of industrialization transition and price increase since 1980. The transition period will terminate when China has entered the maturity period of industrialization. During this transition period, which probably will last for several decades, the steel industry may have to invest more on energy efficiency technology, adjust the steelmaking process structure in order to reduce energy use and expense.

Two main solutions are studied in this research to ease the transition problem: developing energy efficiency technology and steelmaking process improvement.

#### **1. Developing Energy Efficiency Technology**

“Energy efficiency technology” here refers to efficient utilization of natural resource, waste water, heat and gas recycling, continuous casting, reducing ore to steel ratio and hot metal to steel ratio and any measure that can reduce energy consumption for steel making.

There are currently 33 key iron and steel enterprises in China operated by the Ministry of Metallurgical Industry (MMI). These plants are generally old, ranging in age from 17 to 89 years old and averaging 48 years old (although the age of the plant does not give adequate information regarding later equipment upgrades). (MMI, 2005) Compared to the world

advanced level of energy efficiency, only a few steel plants have reached the level of advanced countries. Most of the steel plants still have a long way to go, equipments in those factories are usually outdated with inefficient technology. There is large potential to improve the energy efficiency in those factories as well as in non-MMI enterprises, i.e., iron and steel plants outside of MMI's supervision. By attaching more importance to the measures described above, significant energy savings are technically possible in China. However, the largest opportunities most likely exist in the construction of new plants, where state-of-the-art technologies are significantly more energy-efficient than existing plants. In this research, the dynamic process of technological development is investigated.

## **2. Improving Steelmaking Process**

There are mainly three ways of steelmaking: open hearth furnace (OHF), basic oxygen furnace (BOF) and electric arc furnace (EAF) using scrap. Steelmaking using a basic oxygen furnace (BOF) has a relatively low energy intensity compared to the energy intensity of open hearth furnaces (OHF). The BOF process is rapidly replacing the OHF worldwide, because of its greater productivity and lower capital costs, but the scrap input is rather small for the BOF-route, typically about 10-25%. The OHF is completely phased out in the end of 2000 in China.

Both BOF and OHF include the iron making process. During iron making process, sintered or palletized iron ore is reduced using coke (produced in coke ovens) in combination with injected coal or oil to produce pig iron in a blast furnace. Lime stone is added as a fluxing agent. Reduction of the iron ore is the largest energy-consuming process in the production of primary steel and also accounts for a high CO<sub>2</sub> emission.

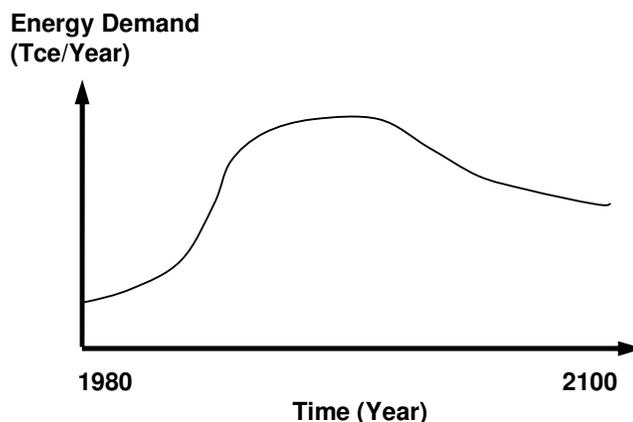
Electric arc furnace (EAF) using scrap is a process in which, the coke production and pig iron production are omitted, resulting in much lower energy consumption. By avoiding iron making process, EAF can save about 350 tce/ ton of steel produced. Thus, the EAF process only emits ¼ CO<sub>2</sub> of the amount that emitted in other traditional processes. EAF develops quickly with the development of steel industry, but the share of EAF increases slowly, it keeps lower than 20% after 1995. Only sufficient scrapped steel resource can ensure the possibility of developing EAF, because the increase of EAF production capacity is always limited by scrapped steel resource in China. Cumulative steel decides the source of the scrapped. Steel production exceeded 0.27 billion tons in 2004, accounting for 26% of the

world steel production, while the country's cumulative steel is only 7%. Thus, the obstacle for developing EAF is lack of scrapped steel resource. EAF in this research is regarded as an energy efficient way of steelmaking. The substitution among different steelmaking ways is another focus of the research, the adjustment dynamics is investigated.

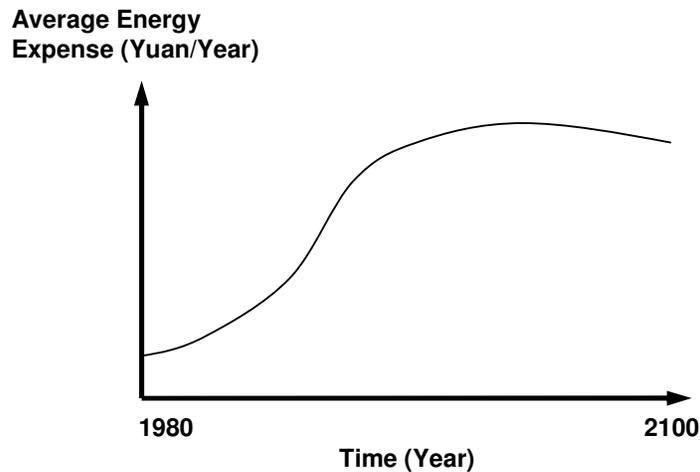
## 2.2 REFERENCE MODE

A reference model is a pattern of behavior, which can characterize the problem dynamically, unfolding over time, showing how the problem arose and how it might evolve in the future. It describes the problem through a set of graphs showing how it develops over time. To do so, some key variables and a time horizon that we consider to be important for understanding the problem are defined.

The time horizon for the model is set at 120 years (from 1980 to 2100). Such a long time period could reflect the predicted whole industrialization period which is one driving force behind energy demand for steel industry, showing how steel industry responds and acts during this transition period. In addition, tracing back to 1980 can show how the problem emerges and what its symptoms are. The key variables that can reflect the problem in this model are "Energy Demand" and "Average Energy Expense". Although "CO<sub>2</sub> Emission" is another focus that we concern about, it is directly related to "Energy Demand", so their reference modes will be quite similar. The behavior of "Energy Demand" can reflect how serious CO<sub>2</sub> emission is, thus there is no need to show both of them.



**Fig 2.2 Energy Demand Reference Mode**



**Fig 2.3 Average Energy Expense Reference Mode**

Steel demand increases significantly with the rapid economic development in China during recent years. It is a driving force behind energy demand. Although the energy price increases as well, the energy cost is somehow offset by the improvement of energy efficiency technology. As a result, the cost increases slowly, which can not prevent the rising trend of energy demand. Secondly, energy demand influences the energy consumption directly, which is closely related to the country's energy conservation. (See Fig 2.2)

The energy expense is directly influenced by the energy price variation and energy consumption (In this particular model, to simplify the model structure, we assume that energy consumption is a delay of energy demand.). The energy demand will eventually decrease responding to the decreasing steel demand after the transition period. However, if the energy price continues to increase and due to low potential for the improvement of energy efficiency in a long run, the expense may not decrease as fast as energy demand. (See Fig 2.3) Increase of energy expense does create a financial problem for steel industry, exerting pressure on the production cost of steelmaking. If we could ease the transition problem, it could largely benefit the steel industry in financial sense. In addition, policies are made to reduce the energy consumption for steel industry. If the economic value of saving from energy conservation is lower than increasing energy expense raised by certain policy such as energy tax, then such policies are not necessary to be implemented. In this case, energy expense acts as a cost-effective indicator for policies aiming at easing the transition problem. From these points of view, our key variables for this particular model are "Energy Demand" and "Average Energy Expense".

# *Chapter 3*

## **Dynamic Hypothesis**

### **3.1 RESEARCH METHODOLOGY**

The research is about an energy intensive industry. Such an industry in China is complicated by interrelated nature of the elements. Technological advances are stimulated from rising CO<sub>2</sub> emissions, and these advances affect costs and usage which in turn will influence the energy demand, the demand eventually affect the CO<sub>2</sub> emissions. There is no way to determine the ultimate effect of each above element on the industry's energy sustainable development unless one knows the behavior of the other elements and the inherent delays in the system. The complex interdependence of all these factors are dynamic themselves (changing overtime), so that no unique relationship exists between the static and dynamic behaviors of a given energy intensive industry.

Thus we need a dynamic framework within which these elements are allowed to operate on each other through time as they do in the real world. It is also allowed to examine the interrelationships and foresee the effects of different policies through the dynamic based model. System Dynamics is such a modeling methodology.

System Dynamics is a computer-aided approach for analyzing and solving complex problems with a focus on policy analysis and design. It is a methodology for studying and managing complex feedback systems. The elements described in the above paragraph have feedbacks among each other; one can not study the link between one factor to the other or in the opposite way independently and predict how the system will behave. Only the study of the whole system as a feedback system will lead to correct results.

The above way of studying a complex feedback system requires us to think the problem systematically. System thinking enables us to evaluate the transition problem more

comprehensively by taking dynamic feedbacks into consideration. It helps to make everything in the system connect to everything else. In this case, we combine all the factors such as energy demand, steel demand, technology development and CO<sub>2</sub> emission with dynamic interrelationships which were once neglected or even invisible, and make them easier for us to make policy regarding the transition problem.

### **3.2 MAJOR MODEL ASSUMPTIONS**

All models are wrong. Models are only valid under certain assumptions. For the sake of simplicity and tractability, several assumptions are adopted for this particular model.

1. Only focus on steelmaking, the ultimate product is just steel.
2. Steel production cost equals to the steel price.
3. Other production costs such as labor, capital and raw material costs grow at a constant rate. (It could be different between the historical period and future)
4. Energy structure share ratio (coal and electricity in this case) is constant during the whole time horizon.
5. Steel demand in reality is closely related to the progress of industrialization. We use GDP per capita to measure the progress of industrialization. And it is estimated that when GDP per capita reaches 4000\$, the steel demand will saturate. We use this estimation as our assumption as well.
6. Scrapped steel recycling only comes from the social capital depreciation; scrapped steel recycling in the model only serves the use for steelmaking.
7. EAF (electric arc furnace) as a more energy efficient steelmaking way has the same other production costs as BOF (basic oxygen furnace) and OHF (open hearth furnace).

The above assumptions we made may somehow limit the research scale, but they will not influence the validity of this research. Besides, such assumptions and exclusions can radically reduce the size of the model and help to achieve simplicity and clarity.



The above figure shows a general causal loop diagram (CLD) of the model. Important model variables and the causal relationships among these variables are linked by arrows with delays marking (two lines) and polarities. Note that the above CLD is a highly aggregated one; it just captures the major causal loops of the model. A much more detailed one would be difficult for the readers to identify which are more important or understand how they generate the dynamics.

All dynamics arise from the interactions of two types of feedback loops: reinforcing loop that amplifies whatever is happening in the system and balancing loop that counteract or oppose changes. Here in our CLD, reinforcing loops are labeled as R and balancing loops are labeled as B. There are two reinforcing loops and three balancing loops as it shows in the above figure.

## 1. Reinforcing Loops

### **R1: Improving Average Unit Energy Consumption through Increasing EAF Proportion**

Average unit energy consumption is an indication of energy efficiency. When the efficiency is improving (meaning that the average unit energy consumption is decreasing), the whole production cost is decreasing, which leads to an increasing steel demand. High demand needs an increasing production rate, which eventually adds up to the cumulative steel. The development of EAF requires sufficient scrapped steel resource, more scrapped steels from the depreciation of social capital (Here refers to the cumulative steel) will raise the proportion of EAF among steelmaking processes. Since the proportion of more energy efficient way is increasing, as a result, the energy efficiency will be further raised.

### **R2: High Steel Demand leads to High CO<sub>2</sub> Emission**

When there is a very high steel demand, we need more energy for steel making, which leads to higher CO<sub>2</sub> emission. High CO<sub>2</sub> emission as an environmental incentive to develop energy efficiency technology promotes the energy efficiency. When the average unit energy consumption is reduced through the above incentive, it directly lowers the production cost of steelmaking, which causes the steel demand to increase, and then repeatedly emit more CO<sub>2</sub>.

## 2. Balancing Loops

**B1: R&D Investment Results in the Improvement of Energy Efficiency Technology**

Only incentives can not lead to the improvement of technology, in order to achieve so, the industry has to invest on research and development (R&D). The higher ratio of sales revenue the industry sets aside on R&D, the lower the average unit consumption will be reduced. When the energy efficiency is improved, the production cost of steelmaking is reduced. Based on the assumptions we made above, the cost is just equal to the price of steel, lower price will lead to low sales revenue. Hence the R&D investment will be lower than before, which means no bigger improvement will be produced with low R&D investment.

**B2: High CO<sub>2</sub> Emission reduction through increasing proportion of EAF**

Since EAF is a more energy efficient way of steelmaking, it not only promotes the energy conservation but also reduces the CO<sub>2</sub> emission through saving energy.

**B3: High CO<sub>2</sub> Emission eventually will lead to a reduction on energy demand**

Based on the assumption we made above, all the energy demand will become actual consumption through a certain time period. High energy demand for steel industry in China means high CO<sub>2</sub> emission because of its high carbon emission from high proportional use of coal. High CO<sub>2</sub> emission stimulates the development of energy efficiency technology, which eventually leads to a reduction on average unit energy consumption. Eventually, the energy demand will be reduced.

In reality, all the above processes include delays; some of them are as long as more than 20 years, such as technology development and application. In the more detailed model structure, we include such delays as well in order to show people may not well-prepared to face the transition problem when there exists long time delays.

The variables linked from gray arrows are exogenous inputs or policy variables. They are modeled exogenously: some of them are introduced directly from data series of reality; others are modeled using some reasonable assumptions. All these exogenous variables are not in the main causal loops, while they may influence the model behavior substantially under some scenarios. Details about their influence are described in the sensitivity tests and policy design chapters.

# **Chapter 4**

## **Literature Review**

Energy issues are usually complex and dynamic, they have many properties such as non-linearity, stock and flows, feedback loops, delays and so on and so force, all of which indicates it is a suitable field to apply System Dynamics methodology. The industry sector is the largest of the end-use sectors, consuming 50 percent of delivered energy worldwide in 2003, and industrial energy use is projected to grow more rapidly than that in the other end-use sectors. (IEO 2006) However System Dynamics studies on a certain energy intensive industry are few. Energy efficiency and related policy design are the main focus regarding energy issues in energy intensive industries. In this chapter, researches concerning the above two respects carried by System Dynamics are reviewed and commented. The chapter concludes that a System Dynamics based model with endogenous energy efficiency technology and energy policy design in a regional or sectoral background can contribute to this field.

### **4.1 SYSTEM DYNAMICS MODELING IN TECHNOLOGICAL DEVELOPMENT**

This research focuses on the energy efficiency technology's development in an energy intensive industry. The behavior of the energy system is shaped by the evolution of technology. However, nearly all models treat technology in the energy system as an exogenous factor. Endogenous technology creates path-dependence and the opportunity for lock-in of dominant carbon-based energy sources (Moxnes 1992).

System Dynamics research regarding technology development can be traced back to William (1972). He described the technology as '*not easily quantified and the process of implementing*

is a long undertaking'. It is many years before a technological breakthrough results in a significant market impact, the long undertaking may take about twenty years. (Peter 1968).

Meadows (2005) mentions that

*'...the most common criticisms of the original World3 model (Meadows 1972) were that it underestimated the power of technology and that it did not represent adequately the adaptive resilience of the free market'.*

Since technology operates only on imperfect information and with delay, they can enhance the economy's tendency to overshoot. William's or Meadow's model all show that technological development is usually undertaken with response to economic or environmental pressures. These pressures maybe rising costs, the potential for profit, pollution, or tax incentives from government.

This paper deals with developing energy efficiency technology in steel industry in China. The incentives are from CO<sub>2</sub> emissions and rising energy price and also the R&D investment from the industry or the subsidy from government. The whole technological development includes long time delay to develop and implement. Besides simply doing research on how to reduce energy consumption, the improvement of technical process is included as well.

## **4.2 SYSTEM DYNAMICS MODELING IN ENERGY POLICY**

Simply developing energy efficiency technology is not enough. The improvement from technological development on energy efficiency is limited, especially with rising cost of technology advancement. In recent years, there is a shift of focus in technological development regarding energy to energy policy design and implementation. In China, policies such as energy tax, standards have not been implemented yet due to high cost and difficulty to implement in a large scale.

Naill (1992) did a cost effectiveness analysis of U.S. energy policies to mitigate global warming. He described such policies as following:

*'Relating these costs to their effects on the energy system and carbon emissions provides measures of the relative cost effectiveness of alternative policy options'.*

Naill's research suggests that energy policies should be evaluated through comparing their relative expenditure with relevant measures of their effects.

Wirl (1991) focused on energy tax that is presumably introduced because of its favorable environmental side effects. He concludes that this tax instrument performs poorly from a public finance point of view.

*'Such a tax requires substantial flexibility, either with respect to the revenues or with respect to the tax rate itself'.*

Fiddaman (2002) tested a family of emissions permits and tax policies like the Kyoto Protocol under a range of assumptions. He concludes that nearly all policies proposed by modelers do no more than stabilize emissions at historically high levels. Permits and energy tax as two policy options appear impractical for reaching ambitious targets like zero emissions. He also mentioned that *'the search for optimal policies needs to be expanded to other kinds of instruments—technological and social for example.'*

Both Wirl's and Fiddaman's study suggest the implementation of energy policy needs to be taken into consideration as another indicator for policy analysis, and policies regarding energy could be extended to alternatives with low cost and easy implementation.

Endogenous technological development and policy design are two important factors for energy issues. However, we would like to see a model involving these two points in a more specific background. A comprehensive and detailed modeling needs to take account of a wide variety of possible situations such as interrelationships between diverse economic sectors, energy sub sectors, energy demand and alternative energy resources substitution. Because of its complexities, it may be better to model the national energy sector by sub sector (e.g. industry, residential and transportation). In the case of significant regional differences, such as climate, infrastructures, energy source availability and political factors, it may be appropriate to develop a sub sector regional model. The comprehensive national energy model can then be assembled by coupling several sub sector regional models. Similar work along these lines has already been done by Dyner *et al* (1990). By doing so, we can help the users to digest the whole energy system bit by bit and come to a better understanding.

# Chapter 5

## Model Description

### 5.1 INTRODUCTION

In this chapter, main features and structures of the System Dynamics model are presented. Model boundary with assumptions are presented using model boundary chart. Detailed System Dynamics model is described in sectors by defining key variables and illustrating important relationships connecting the relevant stock and flow. The complete equation list of all the model variables can be found in the appendix.

### 5.2 MAPPING SYSTEM STRUCTURE

A model boundary chart is used to help us communicate the boundary of the model and represent its causal structure. It summarizes the scope of the model by listing and classifying key variables into three categories. See the following chart for details:

<b>Endogenous</b>	<b>Exogenous</b>	<b>Excluded</b>
<ul style="list-style-type: none"> <li>- Indicated steel demand</li> <li>- Average unit energy consumption</li> <li>- Indicated unit energy cost</li> <li>- Average energy demand</li> <li>- CO2 generation rate</li> <li>- Average energy expense</li> <li>- Actual proportion of EAF</li> <li>- R&amp;D investment</li> </ul>	<ul style="list-style-type: none"> <li>- GDP growth rate</li> <li>- Population</li> <li>- Unit other production costs</li> <li>- OHF proportion</li> <li>- Reference energy price</li> <li>- Reference percentage investment in R&amp;D by steel industry</li> </ul>	<ul style="list-style-type: none"> <li>- Inflation</li> <li>- Inventories</li> <li>- Markup</li> <li>- Other factors influencing technology development</li> <li>- Other factors influencing EAF proportion</li> <li>- Types of Steel products</li> <li>- Other toxic gases</li> <li>- Energy Substitution</li> </ul>

### **Fig 5.1 Model Boundary Chart**

The purpose of the model decides what factor should be included. In this case, GDP growth and energy price increase are assumed to be exogenous; they are the root of the problem that we want to find out and to see what impact they will have on the endogenous structure. “Reference percentage investment in R&D by steel industry” is introduced directly from data series; the feedback from that is small. The process of technological development (Average unit energy consumption is the outcome of technological development) and CO<sub>2</sub> emission are more problematic.

The list of excluded concepts further limits the model boundary and gives important warnings to the readers. In this particular model, the economic factors are assumed to be exogenous such as GDP growth rate, so there is no need to include inflation. Since it is a long-term based model, short-term business cycles such as markup on production costs and inventories of steels and iron ores as raw materials are omitted.

As for the factors influencing energy efficiency technological development, increasing energy price (economical factor) and CO<sub>2</sub> emission (environmental factor) and R&D investment as financial support are three main incentives, the impact from others compared to the above factors are small, so we exclude the others.

The other factors influencing EAF developments such as market impact or other new ways of steelmaking are excluded. The lack of scrapped steel is the main concern for the current period, but we do not deny the fact that the impact from scrapped resource will be mitigated in a long run. So in this case, it is just an optimistic assumption.

When we talk about energy efficiency in steel industry, it always refers to the energy consumption for producing steels which is the end use production in steel industry, other products like iron just serves for steelmaking.

The toxic gases emitted from steelmaking are quite a lot such as nitrogen oxide, sulfur dioxide and so on and so force. Among all the emitted toxic gases, carbon dioxide and sulfur dioxide are comparatively more important. In this case, we only choose carbon dioxide so as to compare the policies (carbon tax aiming at reducing CO<sub>2</sub> emission) implemented by other

countries. The model also treats the energy system in a fairly aggregated fashion, so interfuel substitution (coal vs. gas, for example), is not considered, another optimistic assumption.

### 5.3 SUBSYSTEM DIAGRAM

A subsystem diagram shows the overall architecture of a model. Each major subsystem is shown along with the flows of material, money, goods, information, and so on coupling the subsystems to one another. The subsystem diagram in figure 5.2 shows what is dealing with in each subsystem and their interactions between each other.

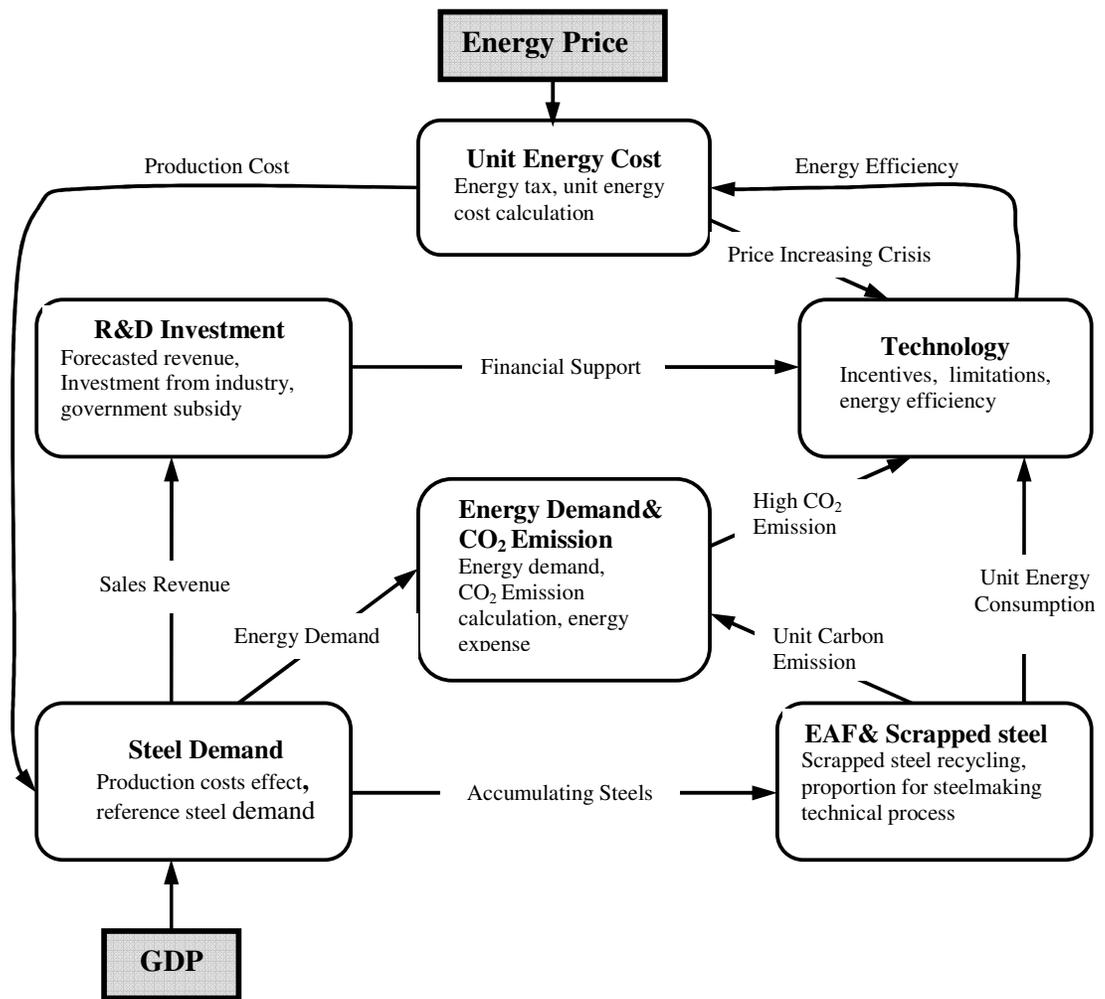


Fig 5.2 Subsystem Diagram

All the subsystems in the above diagram are bridged with arrows. The relationships between each two subsystems are expressed with the output variables from one subsystem to the other.

All together, the whole system consists of six subsystems. Energy price and GDP are taken exogenously and are thus out of the model boundary.

## 5.4 SECTOR DOCUMENTATION

The model is formulated in terms of the subsystem diagrams above. As illustrated in the subsystem diagram, the model consists of six sub sectors. Detailed descriptions of the formal stock and flow structures are presented below.

### 5.4.1 Steel Demand Sub Sector

This sub sector mainly deals with steel demand formulation. The *actual steel demand* is the output variable in this sub sector, it represents the actual steel demand needed yearly. We get this variable by modeling the reference steel demand after affected by the production cost effect. The reference steel demand depends on the GDP growth. The structure of modeling reference steel demand is shown below:

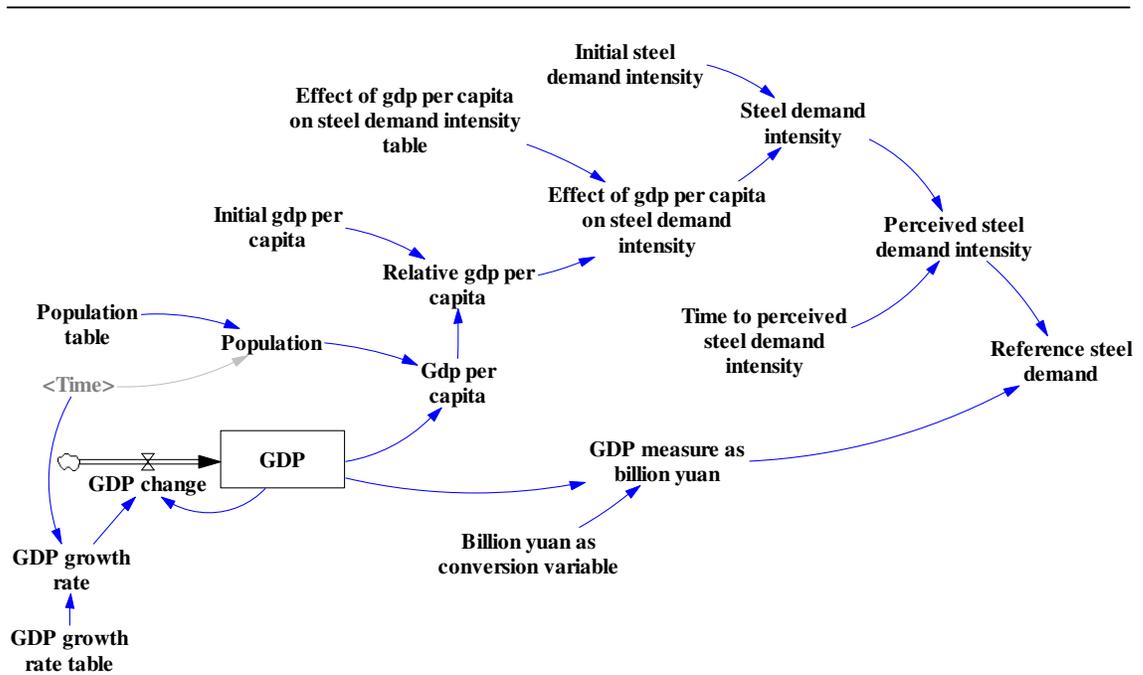


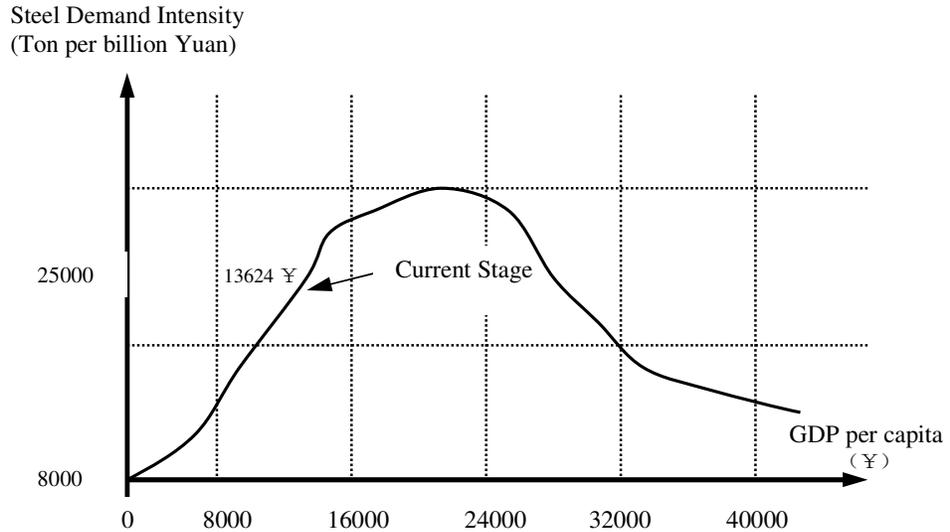
Fig 5.3 Structure of Reference Steel Demand

We can indirectly get reference steel demand by modeling the *steel demand intensity* which is the steel demand per billion Yuan of GDP. There is an important relationship here between GDP per capita and steel demand intensity. We introduce the GDP growth and population

directly from data series in order to get GDP per capita. Dividing GDP by the total population, we get the *GDP per capita*. We take the initial value of GDP per capita (in 1980) as a reference value and calculate the *Relative GDP per capita*.

$$\text{Relative GDP per capita} = \frac{\text{GDP per capita}}{\text{Initial GDP per capita}}$$

With the increasing of GDP per capita, the steel demand intensity will behave in the following way.



**Fig 5.4 Relationship between Steel Demand Intensity and GDP per capita (Zhou 2006)**

As we illustrated in the Introduction Chapter, the steel demand will saturate when the GDP per capita reaches around 32000¥. The United States has already passed the maturity period of industrialization; the steel demand intensity in 2004 of US is around 7700 ton per billion Yuan. From the experience of developed countries, we roughly estimated the maximum steel demand intensity is around 25000 Yuan and will drop to around 8000 Yuan when the steel demand reaches its peak. We represent the relationship in the above graph with a variable called *Effect of GDP per Capita on Steel Demand Intensity*. The Relative GDP per capita acts as the input of the table function, the output will be the effect on steel demand intensity. Thus we can get the steel demand intensity in the following way:

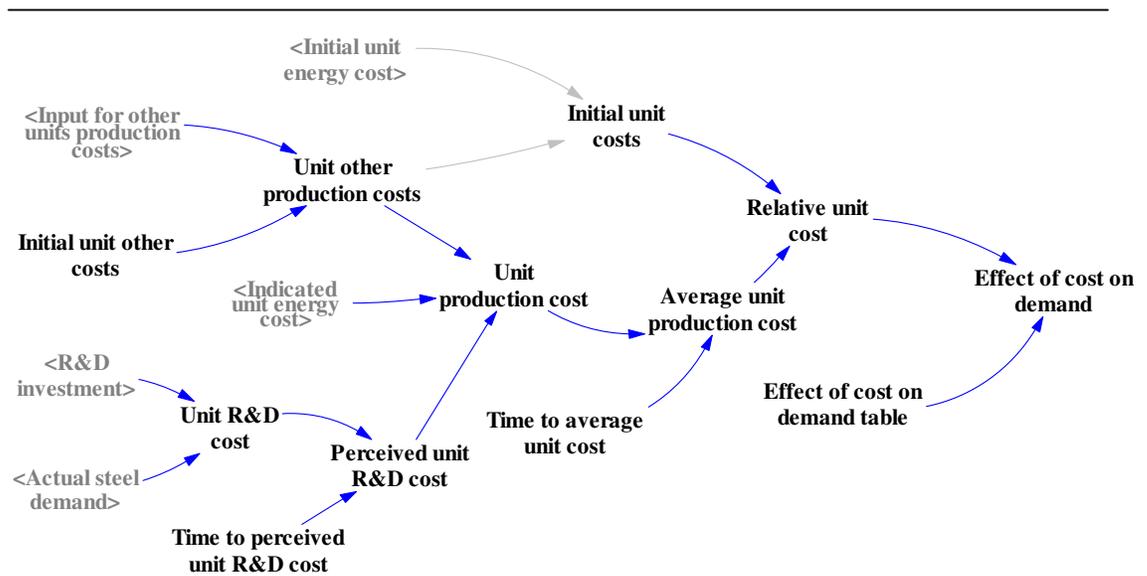
$$\text{Steel Demand Intensity} = \text{Initial steel demand intensity} * \text{Effect of gdp per capita on steel demand intensity}$$

Note the **Initial Steel Demand Intensity** in the equation is the value in 1980. Then, peoples' perception of the steel demand intensity is formulated using a smooth function<sup>2</sup>.

*Perceived Steel Demand Intensity*=smooth (*Steel demand intensity*, *Time to perceived steel demand intensity*)

Eventually we can get the **Reference Steel Demand Intensity** by multiplying the steel demand intensity with GDP measured as billion Yuan (using billion Yuan to measure GDP instead of Yuan to match with steel demand intensity's unit).

In this sub sector, another important structure we need to know is the cost effect on the reference steel demand. The structure of modeling the cost effect is shown below:



**Fig 5.5 Structure of Cost Effect on Steel Demand**

The light color variables are shadow variables which are imported from other sub sectors, they will be described later. In order to get the cost effect, we have to model the production cost first. The production cost in this particular model consists of unit other production costs, unit energy cost and unit R&D cost. Unit R&D cost and unit other production cost are formulated in this sub sector.

<sup>2</sup> The SMOOTH function is commonly used to take time averages and represent expectations. It is written as  $y = \text{SMOOTH}(x, t)$ , the equation is exactly the same as  $(y-x)/t$ .

*Unit production cost*=*Indicated unit energy cost*+ *Indicated unit other costs*+ *Indicated unit R&D cost*

**Unit Other Production Cost** means all the other production costs except the energy and R&D cost to produce one ton of steel. It is formulated by adding exogenous inputs on the initial unit other production cost in 1980.

*Unit Other production cost*= *Initial unit other costs*\**Input for other units production costs*

Those inputs include ramp function with different ramp slopes and thus lead to different cost variation patterns. They will be raised later.

**Unit R&D Cost** means the total R&D investment shared on each unit production cost. Since we assume the steel demand equals the production, so the formulation will be as follows:

$$\text{Unit R\&D Cost} = \frac{\text{R \& D investment}}{\text{Actual steel demand}}$$

R&D investment each year could be quite different, and usually it takes a long time to implement the new technology, so the peoples' perception of R&D investment is formulated as a smooth function:

*Perceived unit R&D cost*= *Smooth (Unit R&D cost, Time to perceived unit R&D cost)*

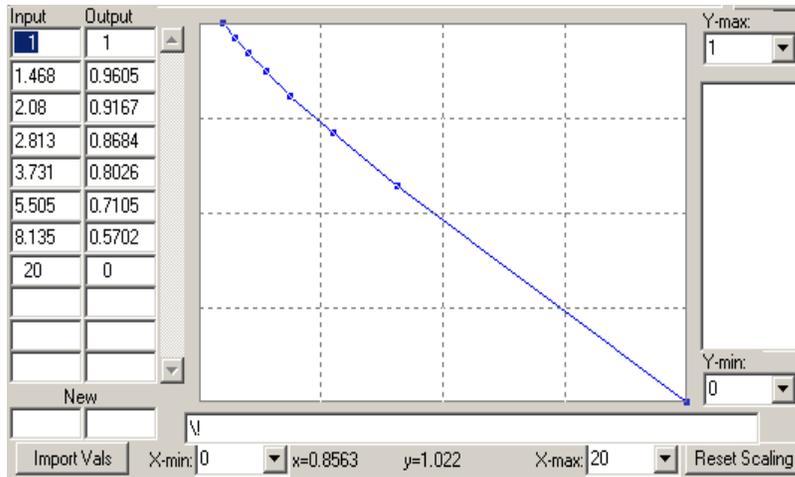
Unit production cost is averaged within average time, which becomes the **Average Unit Cost**; it is formulated using a simple smooth function.

*Average unit cost*= *smooth (Unit production cost, Time to average unit cost)*

In order to model the cost effect, we need to know the relative cost to its initial cost in 1980. In this case, the **Initial Unit Cost** consists just unit other production costs and energy costs because of no R&D expenditure before 1980. We calculate the **Relative Unit Cost** as follows:

$$\text{Relative unit cost} = \frac{\text{Average unit cost}}{\text{Initial unit cost}}$$

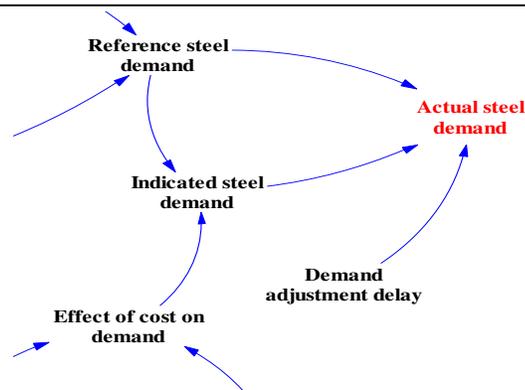
Now we can model the cost effect, it is obvious that higher cost leads to lower demand; we use a very simple linearly effect of cost on demand table function, the graph below illustrated the table function.



**Fig 5.6 Graph of “Effect of Cost on Steel Demand” as a table function**

The input (X axis) refers to the Relative unit cost while the output (Y axis) is the effect. As we see the figures on the left side of the table, there is no effect if cost remains at its initial level. With the increasing of the unit cost, the price of the steel increases correspondingly (As it is assumed the price equals to the cost in the first chapter), eventually the demand begins to fall. If the cost is high enough to suppress the demand, then no body can afford to buy any steel, in this particular model, we assume when the cost is twenty times the initial cost, and then there is no demand for steel.

Based on the reference steel demand and cost effect on steel demand, the **Actual Steel Demand** can be formulated like the structure below:



**Fig 5.7 Structure of Modeling the Actual Steel Demand**

*Indicated Steel Demand* is reference steel demand with the cost effect, it is simply the multiplication of these two. The *Actual Steel Demand* is the stabilized demand after the effect; the actual value still needs time to adjust. We pick up the reference steel demand as its initial value. See the equation below:

*Actual Steel Demand* = *SMOOTH*(*Indicated steel demand*, *Demand adjustment delay*, *Reference steel demand*)

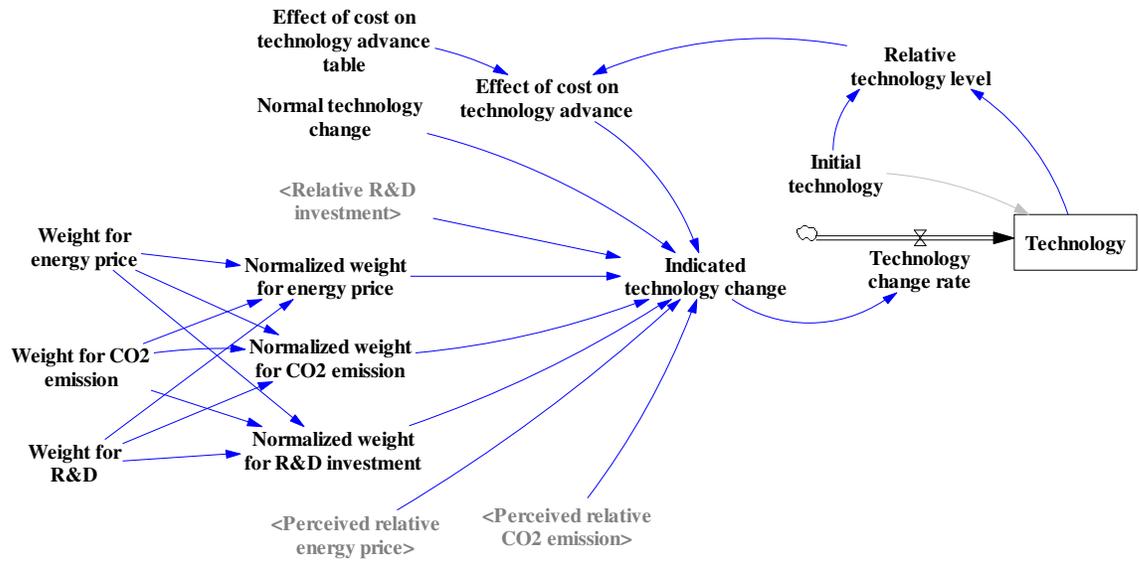
### 5.4.2 Technology Sub Sector

The technology here refers to the energy efficiency technology; it includes all the technical improvement to save energy such as recycling wasting gas, heat, continuous casting, reducing ore to steel ratio and hot metal to steel ratio. This sub sector deals with several important factors:

1. Technology change from all the incentives such as CO<sub>2</sub> emission, energy price increasing and its financial support, namely the R&D investment.
2. The effect of energy efficiency technology on unit energy consumption for steelmaking.

We begin from the first factor to formulate the technology. The *technology* is modeled as a stock with its virtual unit: technology. The flow of technology is technology change rate, here

we assume the technology level will never fall once it has been improved, thus the flow will only be the inflow.



**Fig 5.8 Structure of Technology development**

The key variable in the above structure is obviously indicated technology change, which includes all the factors that influence the technological development.

### 1. Factors that promote the development of technology

The incentives to improve the technology include the CO2 emission and energy price increase, R&D investment is another important factor as the financial support to development technology. All the above three factors promote the advancement of technology; they are imported from other sub sectors.

Note since we do not know which of the above incentives or the financial support is more important, thus weights are set for each of them. The weights here refer to the importance that steel industry attaches to. We assume that effect of both incentives and financial support is 100% on the technological change. Thus, the effect of one certain incentive will be the incentive times its weight. So the total effect of all the incentives will be the sum of each effect.

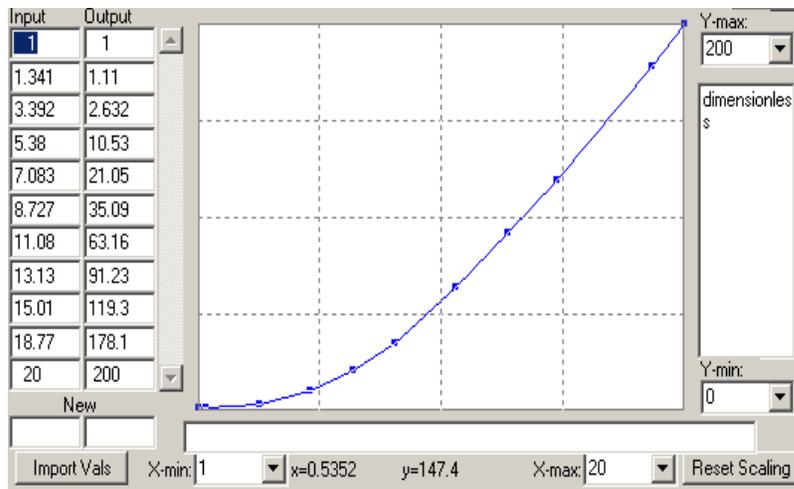
In order to make the calculation easier, we use normalized weight here. The sum of the normalized weights will be 100%. Thus the user can set any value for each weight, which will be normalized by the following way (take energy price as an example):

$$\text{Normalized weight for energy price} = \frac{\text{Weight for energy price}}{\text{Weight for CO}_2\text{ emission} + \text{Weight for energy price} + \text{Weight for R \& D}}$$

The other two normalized weights are formulated in the similar way. For the details of weight setting, we will discuss more in the policy analysis chapter.

## 2. Factors that limit the development of technology

With the advancement of technology, more investment is required. The variable *effect of cost on technology advance* refers to the cost of affecting an incremental advance in technology, the cost is assumed to gradually increase as more investment is required for each marginal increase in technology. It is formulated using a table function as below:



**Fig 5.9 Graph of “effect of cost on technology advance” as a table function**

The input of the above table(X axis) refers to the relative technology level, which is simply the current technology level relative to the initial level in 1980. The output (Y axis) refers to the effect which limits the technology advancement. When technology level remains at its initial level, there is no cost effect to limit technology improvement. With the advancement of technology, more and higher human capital is required, older and outdated machines are

substituted by higher efficient ones, all of which add cost to further technological development. In the early stage of technology development, the cost is low and increases slowly with technology improve because of large potential and low requirement for human capital and cheaper capital substitution. When the energy efficiency is fairly high, there is little potential to get it improved, thus the cost will increase dramatically in order to further improve the energy efficiency.

Thus we can calculate the technology change by involving all the above factors. The related variable is variable called **Indicated Technology Change**, which includes all the influential factors on technological development

*Indicated technology change* =

$$\begin{aligned}
 & ((\text{"Relative R \& D investment"} * \text{"Normalized weight for R \& D investment"}) + \\
 & (\text{Normalized weight for energy price} * \text{Perceived relative energy price}) + \\
 \text{Normal technology change} * & \frac{(\text{Perceived relative CO}_2 \text{ emission} * \text{Normalized weight for CO}_2 \text{ emission})}{\text{Effect of cost on technology advance}}
 \end{aligned}$$

The **Normal Technology change** in the above equation is a constant variable and is set to be the technology change rate without any other external factors.

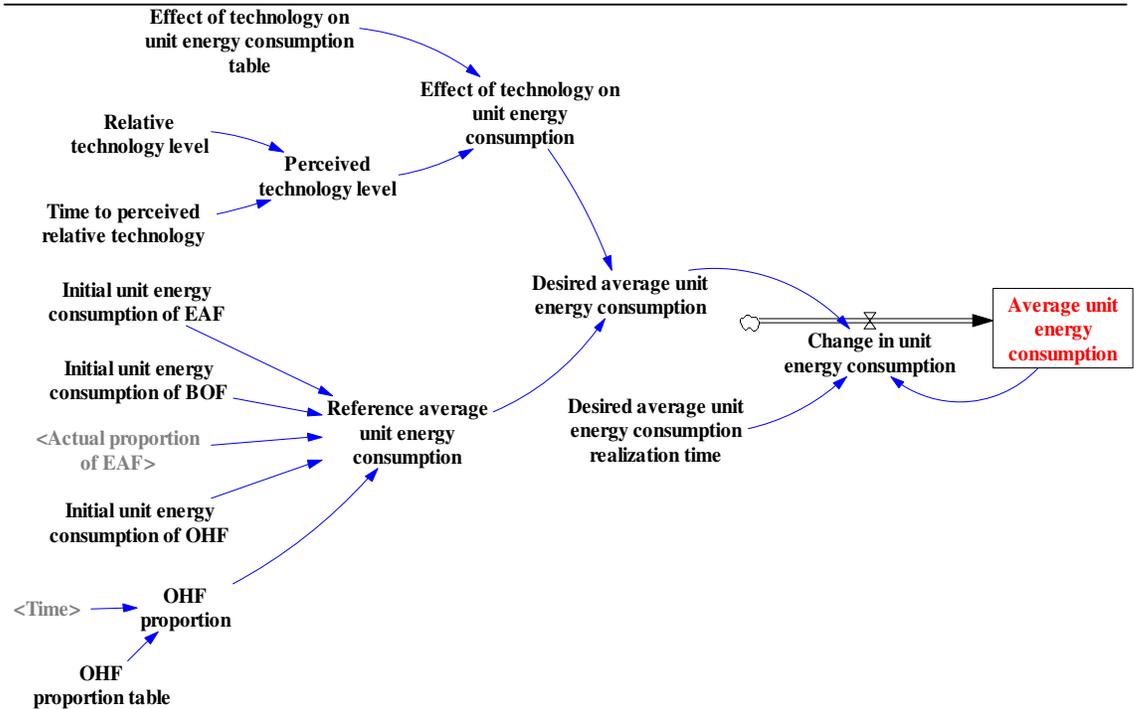
The Technology is a stock variable, its flow, namely technology change rate equals to the indicated technology change.

**Stock:** *Technology*

**Init:** *Technology = Initial technology*

**Flow:** *Technology change rate = Indicated technology change.*

After the formulation of technology, we want to know how it influences the energy efficiency. The energy efficiency is expressed as **Average unit energy consumption**; it is the energy consumption for making one ton of steel. The structure to model the technological effect and the formulation of average unit energy consumption is shown below:



**Fig 5.10 Structure of technological effect on energy efficiency**

Since there are three ways to make steel, energy consumption for each of them is different. The aggregated energy consumption for unit steel making is the sum of the energy consumption of each way times its proportion in steelmaking. Those steelmaking processes consist of EAF (Electric Arc Furnace), BOF (Basic Oxygen Furnace) and OHF (Open Hearth Furnace).

Among them, the OHF way of steelmaking has died out, while it did exist in the previous two decades. From the data serious of Chinese steel industry, the proportion of OHF decreases quite linearly, and it almost died out in 2000. In this case, we assume it decreased linearly from its initial proportion in 1980 to 0 in 2000.

The proportion of EAF is modeled endogenously in the “EAF & Scrapped Steel” sub sector. When we know two proportions of steelmaking way, the proportion of BOF will be the residual of 1 minus the other two proportions. Thus we can calculate the Reference Average Unit Energy consumption by aggregating each proportion times its initial unit energy consumption.

*Reference average unit energy consumption=*

Initial unit energy consumption of BOF\*(1-Actual proportion of EAF-OHF proportion)  
 +Initial unit energy consumption of EAF\*Actual proportion of EAF  
 +Initial unit energy consumption of OHF\*OHF proportion

All the above steelmaking processes are technically improving, since it is hard to see which one of them has been improved the most, we assume the energy efficiency technology has the same effect on all of them.

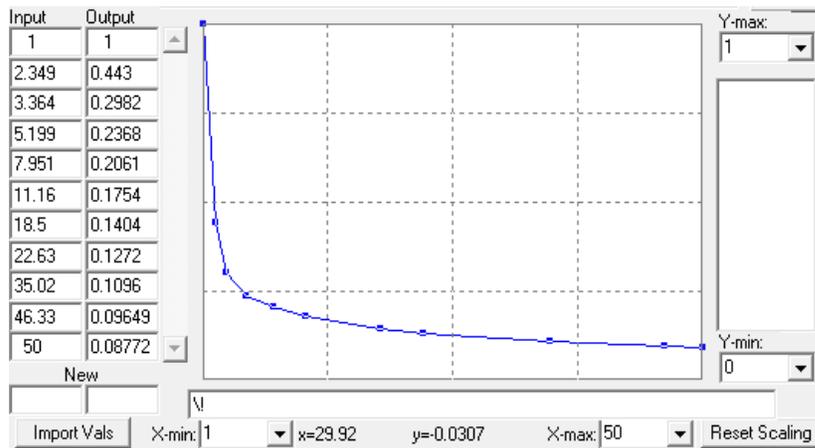
The **Relative Technology Level** is the technology level relative to its initial level. We calculate this variable as follows:

$$\text{Relative technology level} = \frac{\text{Techno log } y}{\text{Initial techno log } y}$$

It is an indication of the changes in technology level. Then, peoples' perception of the relative technology level is formulated using a 3<sup>rd</sup> order delay function<sup>3</sup>, because it takes time for people to estimate and perceive the actual change of technology.

*Perceived technology level* = DELAY3 (*Relative technology level*, *Time to perceived relative technology*)

The effect of technology on energy efficiency is formulated using a table function.



**Fig 5.11**Graph of “effect of technology on energy efficiency” as a table function

<sup>3</sup> Returns a 3rd order exponential delay of the input, conserving the input if the delay time changes. The reason we use a 3<sup>rd</sup> order delay is that people do not perceive the technological change immediately to an improvement in technology; people may perceive the actual change after some time has passed.

The input (X axis) refers to the perceived technology level, while the output(Y axis) refers to the effect. When the technology remains at its initial level, no effect happens on the energy efficiency (unit energy consumption of steelmaking). In the early stage of technological development, people do not attach much importance on energy conservation, and that is just the early stage of industrialization in China, so all the machines are old and outdated with low energy efficiency. With the time going on, we know the importance of technology, thus China imported technology from other developed countries in the beginning. On the other hand, the Chinese industry began to invest on R&D. It is easier to improve technology from a comparatively low level with low expenditure. With the time going on, even the technology level is high, the potential to improve energy efficiency becomes smaller because we can not expect to produce something without any energy consumption.

Thus we can get the ***Desired Average Unit Energy Consumption*** by multiplying *effect of technology on energy efficiency* with *Reference average unit energy consumption*. It is the unit energy consumption that people hope to achieve.

The ultimate goal of this sub sector is to formulate the ***Average Unit Energy Consumption*** as a stock variable, which refers to the average unit energy consumption for the current year after new technology has been implemented.

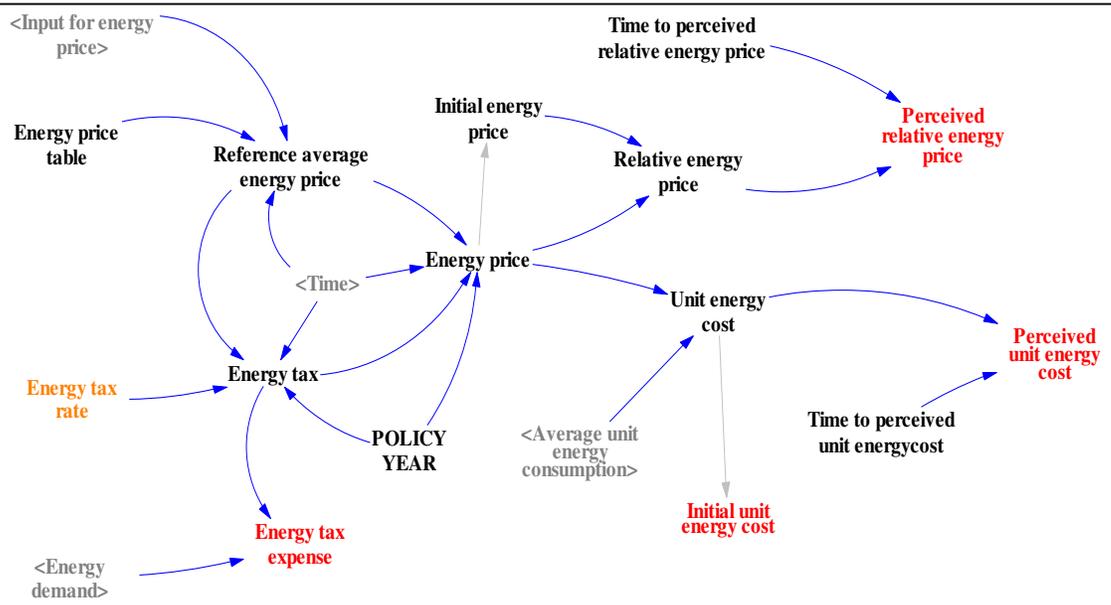
Its initial value is the initial unit energy consumption for steelmaking in 1980; the equation of its flow is formulated as below:

*Change in unit energy consumption*

$$= \frac{\text{Desired average unit energy consumption} - \text{Average unit energy consumption}}{\text{Desired average unit energy consumption realization time}}$$

### 5.4.3 Unit Energy Cost Sub Sector

This sub sector deals with the formulation of energy price, it is one of the incentives that influences technological change; in addition, it directly influences part of the production cost, namely the unit energy cost. The structure of this sub sector is shown below:



**Fig 5.12 Structure of Energy Price Formulation and Its Influence on Other Sub sectors**

We begin from the formulation of energy price. Note the energy price here refers to a weighted average price, since the main energy source for steel industry is coal and electricity. The percentage for each of them is quite constant, to simplify the model, we combine these two prices into one. The price for the historical period (1980-2006) is introduced directly from Chinese Iron & Steel Association.

For the time after 2007, we use some exogenous input to predict the price increasing trend. So the reference average energy price will be calculated as follows:

$$\text{Reference average energy price} = \text{Energy price table (Time)} * \text{Input for energy price}$$

Note the *Energy price table (Time)* refers to a table function involving the historical data for energy price from 1980 to 2006. After 2007, it mainly depends on the input. Since it is rather impossible for the energy price (Both coal and electricity) to have a sharp increase in the future, we use a ramp function for this input. The slope (just like the magnitude of price increase) of the ramp function needs sensitivity tests; we will raise this point in the testing chapter.

The energy price may not only refer to the above reference energy price, but also be influenced by the government policy. For this particular model, **Energy Tax** is one of such policies, it is assumed to be the tax rate times the energy price, which means it is proportional to the energy price. The policy year decides the time to implement policy; we can even select a historical year to see whether the condition will be improved if we implemented the policy earlier. We calculate the energy tax as follows:

*Energy tax= IF THEN ELSE (Time>=Policy year, Energy tax rate\*Reference average energy price, 0)*

We use “If then else” function here to control the policy implementation time. Only if the time reaches the policy year can the policy be implemented.

**Energy Tax Expense** is the tax expense paid by the steel industry. It is an output to the R&D investment sub sector and a key variable for the “tax recycled as subsidy” policy. The formulation is simply the energy demand times the energy tax per unit; we will mention it in details in the policy analysis chapter.

The incentive from energy price increase is modeled in this sub sector. We have formulated the energy price, so the price change between the current year and the initial year is expressed by **Relative Energy Price**.

$$\text{Relative energy price} = \frac{\text{Energy Price}}{\text{Initial Energy Price}}$$

Then, peoples’ perception of the price change is formulated using a smooth function.

*Perceived relative energy price=smooth (Relative energy price, Time to perceived relative energy price)*

The above perception of the change in energy price will warn people to realize the price increasing crisis and take measures.

**Unit energy cost** is another output of this sub sector; it is the energy cost among the production cost. The formulation is simply the multiplication of energy price and the unit energy consumption. Due to the unstable energy price, unit energy cost varies each year; it

takes people to perceive the actual change in unit energy cost. So we calculate the perceived unit energy cost as follows:

$$\text{Perceived unit energy cost} = \text{smooth}(\text{Unit energy cost}, \text{Time to perceived unit energy cost})$$

### 5.4.4 Energy Demand & CO<sub>2</sub> Emission Sub Sector

This sub sector deals with the formulation of CO<sub>2</sub> Emission as an incentive for technological development and the formulation of two key variables for the model, namely Energy Demand and Average Energy Expense. The structure of this sub sector is shown below:

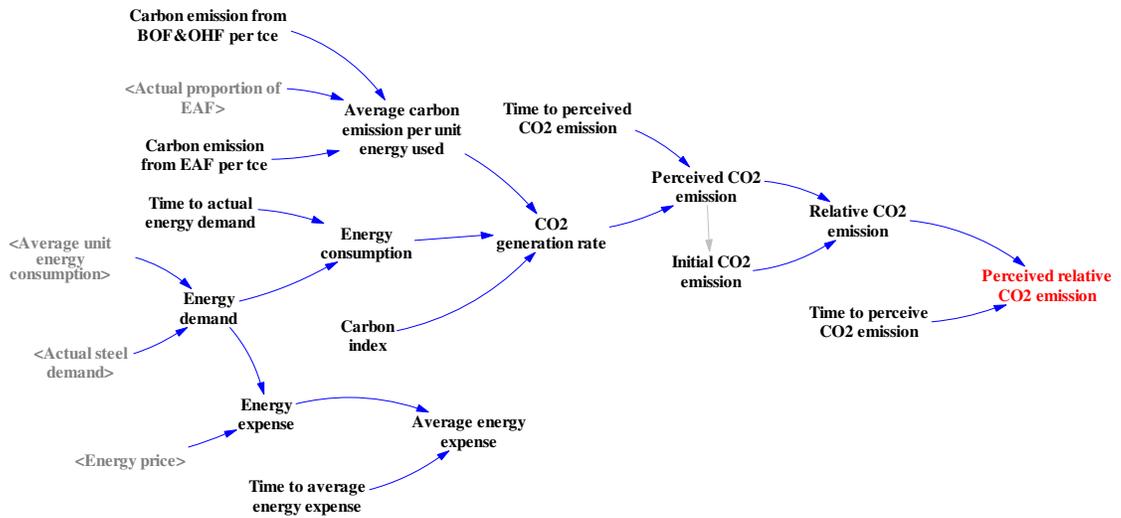


Fig 5.13 Structure of Energy Demand and CO<sub>2</sub> Emission

We start from the modeling *Energy Demand*, which is required by the whole steel industry. Since we know the steel demand (formulated in the steel demand sub sector) and how much energy is needed to produce one ton of steel (formulated in the technology sub sector), then the energy demand will simply be the multiplication of the steel demand and average unit energy consumption.

$$\text{Energy demand} = \text{Actual steel demand} * \text{Average unit energy consumption}$$

Then we can calculate the expenditure that steel industry spends on energy by multiplying the energy price with energy demand.

$$\text{Energy expense} = \text{Energy demand} * \text{Energy price}$$

The energy expense is averaged within time to get average energy expense based on recent years; it is modeled using a smooth function.

$$\text{Average energy expense} = \text{Smooth}(\text{Energy expense}, \text{Time to average energy expense})$$

The **Average Energy Expense** functions as an indicator in the model, it refers to the average expenditure that steel industry spends on the energy use. It is one of the key variables in the model, and can be tested to see whether the policy is cost-effective.

When the Energy Demand is known, based on the assumption we made in the former chapter, the consumption is equal to the energy demand. The **Energy Consumption** in the model is formed as a delay of the energy demand; it refers to the total amount of energy consumed by steel industry every year.

$$\text{Energy consumption} = \text{Smooth}(\text{Energy demand}, \text{Time to actual energy demand})$$

Now we can model CO<sub>2</sub> emission. CO<sub>2</sub> emission is closely related to fossil energy consumption, coal emits the most carbon among all kinds of energy resources and it is the mostly used energy for Chinese steel industry as well. In this case, we calculate carbon emission per unit energy used first. The carbon emission varies based on different technical process of steelmaking, which means the average carbon emission will depend on the unit carbon emission for each technical process times their respective proportion.

As for BOF and OHF, they all include iron making process, so they consume much more coal (acts as a reducer to extract iron from iron ore) than EAF. As the literature shows (Shan, 2001), carbon emission for the way of BOF and OHF are almost the same, so we consider their carbon emission per unit energy consumed are equivalent. Then we calculate the average carbon emission per unit energy used as follows:

$$\text{Average carbon emission per unit energy used} =$$

*Actual proportion of EAF\*Carbon emission from EAF per tce+ (1-Actual proportion of EAF)\*Carbon emission from BOF&OHF per tce*

Based on the carbon emission, we need some conversion variable to get the CO<sub>2</sub> emission. This conversion variable is called **Carbon Index**; this parameter refers to the ration between the molecular weight of carbon dioxide and the atomic weight of carbon.

So we formulate the CO<sub>2</sub> Generation Rate as follows:

*CO2 generation rate= Energy consumption\*Average carbon emission per unit energy used\*Carbon index*

The actual emitted CO<sub>2</sub> takes time for people to perceive. Then peoples' perception of CO<sub>2</sub> emission is formulated using a smooth function.

*Perceived CO2 emission= smooth (CO2 generation rate, Time to perceived CO2 emission)*

The actual change of CO<sub>2</sub> emission based on the initial emission is the relative emission.

*Relative CO2 emission=  $\frac{\text{Perceived CO2 emission}}{\text{Initial CO2 emission}}$*

Peoples' perception of the actual change of CO<sub>2</sub> emission is formulated as a smooth function.

*Perceived relative CO2 emission= Smooth (Relative CO2 emission, Time to perceive CO2 emission)*

The perceived relative CO<sub>2</sub> emission acts as another incentive warning the industry about its environmental damage and stimulates its technological development to reduce energy consumption.

### 5.4.5 EAF & Scrapped Steel Sub Sector

This sub sector deals with the steel scrapping and recycling process, and their influence on EAF proportion. The big picture is shown below:

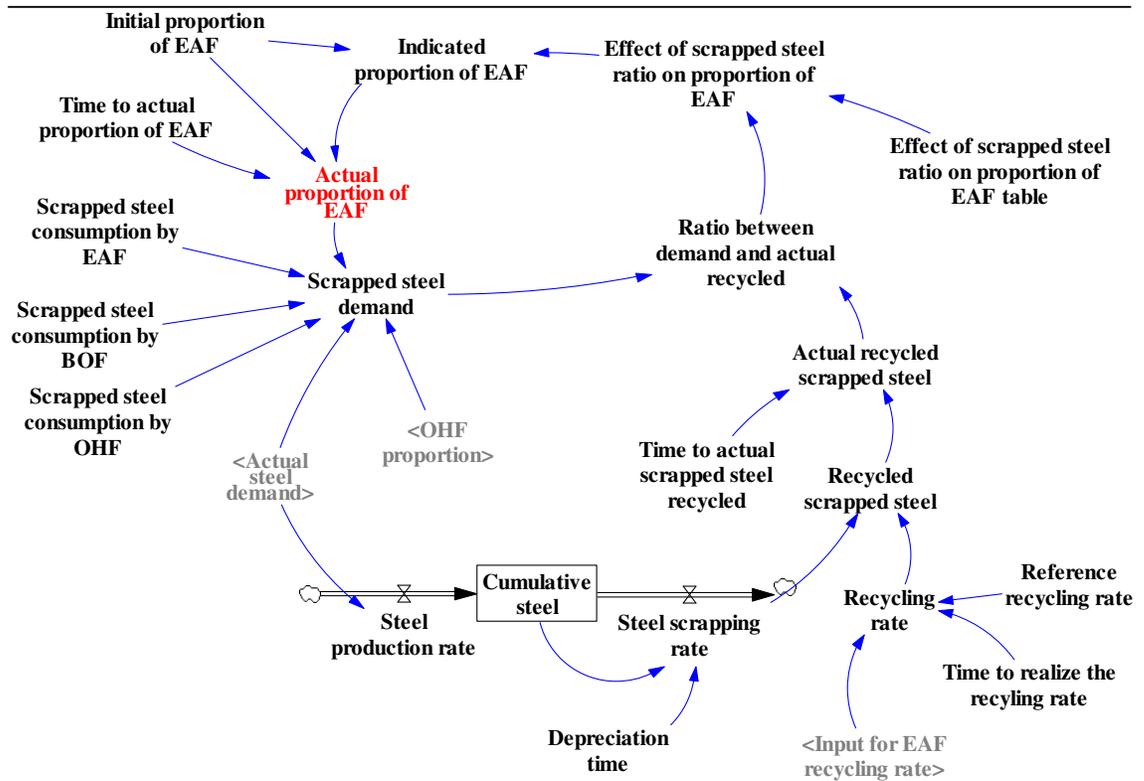


Fig 5.14 Structure of EAF proportion and scrapped steel recycling

We start from the formulation of *Scrapped Steel Demand*, which is the demand needed for all three steel production processes. It is the sum of each scrapped steel consumption times its respective proportion among the general steel production. We assume the scrapped steel consumption for each process remains constant overtime and we calculate the total scrapped steel demand as follows:

*Scrapped steel demand*=

$$Actual\ steel\ demand * Actual\ proportion\ of\ EAF * Scrapped\ steel\ consumption\ by\ EAF + Actual\ steel\ demand * (1 - Actual\ proportion\ of\ EAF - OHF\ proportion) * Scrapped\ steel\ consumption\ by\ BOF + Actual\ steel\ demand * Scrapped\ steel\ consumption\ by\ OHF * OHF\ proportion$$

The purpose of this sub sector is to formulate the EAF proportion among the steelmaking processes. It is closely related to the scrapped steel resource. Whether the actual recycling rate can meet the demand will decide EAF's development.

The next step is to formulate the recycled scrapped steels. The source of the recycling is from the scrapping steels. Among all ways of producing scrapped steels, the depreciation of social capital takes up the most, and scrapped steels are mostly used for steelmaking. (Zhang, 2003) The other ways of producing scrapping steels are assumed to be used for other kinds of use.

For the simplification of the modeling, we assume the scrapped steel resource for steelmaking all comes from the social capital depreciation. The social capital refers to the cumulative steel resource in this particular model, and it is expressed as a stock variable. Its inflow is steel production rate, which is assumed to be equal to the steel demand, while the outflow is the scrapping rate from social capital depreciation after a certain depreciation time.

**Stock:** *Cumulative Steel*

**Init:** *A constant number, the steel resource accumulated before 1980*

**Inflow:** *Steel production rate = Actual steel demand*

**Outflow:** *Steel scrapping rate =  $\frac{\text{Cumulative steel}}{\text{Depreciation time}}$*

After the steel is depreciated to scrapped steels, people try to recycle them for further use. The amount about how much they can be recycled depends on the recycling rate. In China, the recycling technology develops quite slowly, such technology has recently been attached more importance because of the price rise of iron ore. But how to develop recycling technology needs to be raised in the future study and is not our research focus. Instead, we use some exogenous inputs such as step function to test the influence of recycling rate. These inputs will be added based on the reference recycling rate that is used before. And since technology needs a long time to develop and implement, so time delay is taken into consideration as well. We calculate the recycling rate as follows:

*Recycling rate = Reference recycling rate \* Smooth (Input for EAF recycling rate, Time to realize the recycling rate)*

Then we can calculate the recycled steel by multiplying the scrapping rate with the recycling rate:

$$\text{Recycled scrapped steel} = \text{Steel scrapping rate} * \text{Recycling rate}$$

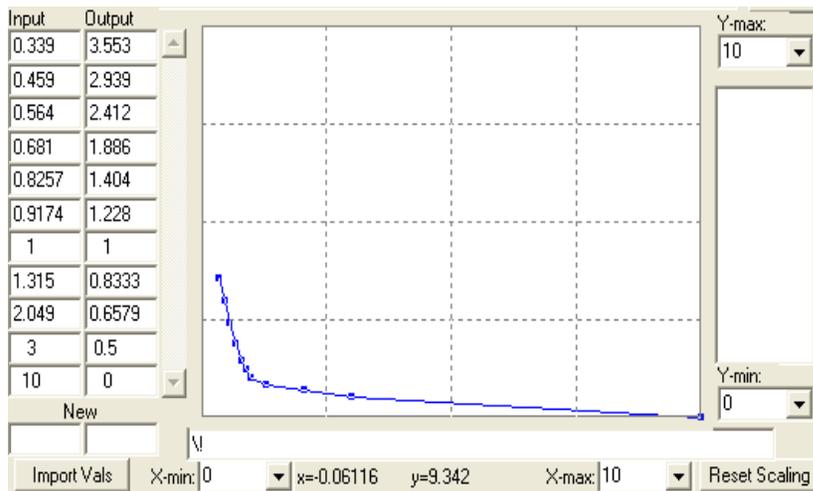
The actual number of recycled steels still needs time to be estimated, the equation of the actual recycled steels is shown below:

$$\text{Actual recycled scrapped steel} = \text{Smooth}(\text{Recycled scrapped steel}, \text{Time to actual scrapped steel recycled})$$

Divided by Scrapped Steel Demand, we can calculate the difference between the actual existing scrapped steel and the scrapped steel demand.

$$\text{Ratio between demand and actual recycled} = \frac{\text{Scrapped steel demand}}{\text{Actual recycled scrapped steel}}$$

The scrapped steel supply and demand is the only factor that influences the EAF development as we assumed, so here a table function is used to express this effect, which is called *Effect of Scrapped Steel Ratio on Proportion of EAF*, and the table is shown below:



**Fig 5.15 Graph of “Effect of Scrapped Steel Ratio on Proportion of EAF” as a Table Function**

The input (X axis) refers to the ratio between demands and actual recycled, while the output (Y axis) refers to the effect. When the demand equals the actual recycled steels, there is no effect produced on EAF proportion. When the recycling rate is higher than the demand which means it is enough to cover the demand, the price of scrapped steel declines causing people tend to use more scrapped steels instead of iron ore which means EAF is preferred to use more. Since more energy-efficient way is encouraged, once the demand is fulfilled, it is easier to raise the proportion due to the government's policy. When there is fewer scrapped steel resource, and it can not meet the demand, the proportion of EAF will slowly drop because of the above reason.

Thus the indicated proportion of EAF will be its initial proportion times the effect described above.

*Indicated proportion of EAF = Initial proportion of EAF \* Effect of scrapped steel ratio on proportion of EAF*

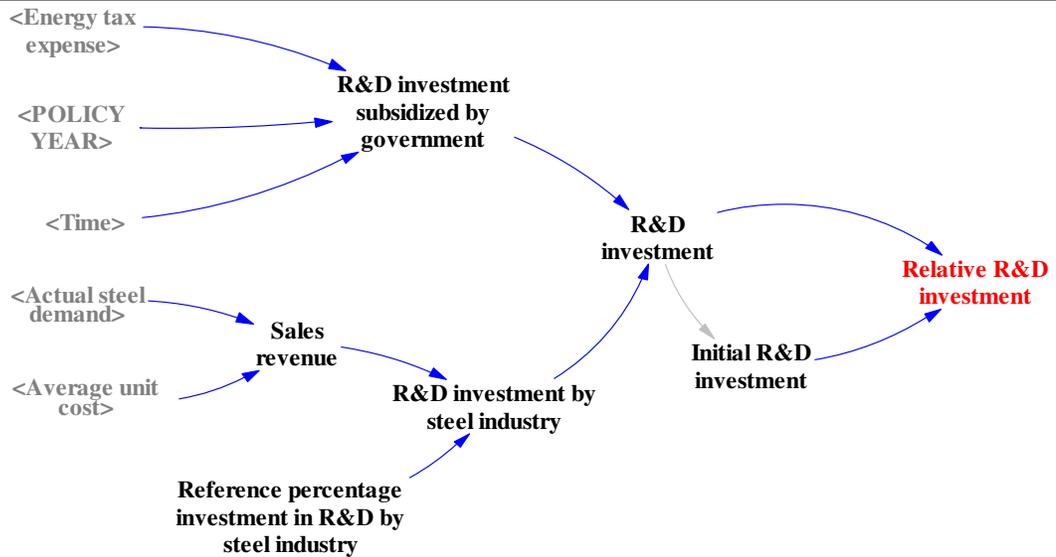
The actual proportion of EAF needs time for people to investigate, and that time delay also includes installing and the removing facilities.

*Actual proportion of EAF = DELAYII (Indicated proportion of EAF, Time to actual proportion of EAF, Initial proportion of EAF)*

The above **delayII function** is similar to delay functions, it means first order delay with initial value, and in this case, the initial proportion of EAF will be the initial value in 1980.

#### **5.4.6 R&D Investment Sub Sector**

This sub sector deals with the R&D investment by the steel industry and by the government in a form of subsidy as a policy structure. The R&D investment will be the output of this sub sector as a financial factor to develop technology. See the structure below for details:



**Fig 5.16 Structure of R&D investment**

In the past two decades, the expenditure of steel industry on R&D remains at around 1% of its sales revenue (China technology statistical yearbook 2005). Technological influence on energy efficiency has been improved a lot in the past, the potential to develop more advanced technology is not as large as before, so we assume the industry tends to keep its investment on R&D as usual.

The R&D investment is set aside from its sales revenue. As the assumption we made in the first chapter, cost equals to price and demand equals to the sales rate. So the multiplication of these two will be the sales revenue.

$$\text{Sales revenue} = \text{Average unit cost} * \text{Actual steel demand}$$

Then the R&D investment by the steel industry will be as follows:

$$\text{R\&D investment by steel industry} = \text{Reference percentage investment in R\&D by steel industry} * \text{Sales revenue}$$

Another part of R&D could be the government subsidy; it is formulated as a policy, so no subsidy exists before the policy year. With regarding to such government subsidy, we design

two ways of implementation: direct government subsidy with repayment by industry and tax revenue recycled as subsidy. The formulations for both cases are listed below:

*R&D investment subsidized by government= IF THEN ELSE (Time>=POLICY YEAR, Energy tax expense, 0)*

To compare the effectiveness of subsidy with tax, we assume this amount of subsidy equals to energy tax expenditure. Then the R&D investment is calculated as the sum of government subsidy on R&D and the investment by steel industry.

*R&D investment= R&D investment by steel industry+ R&D investment subsidized by government*

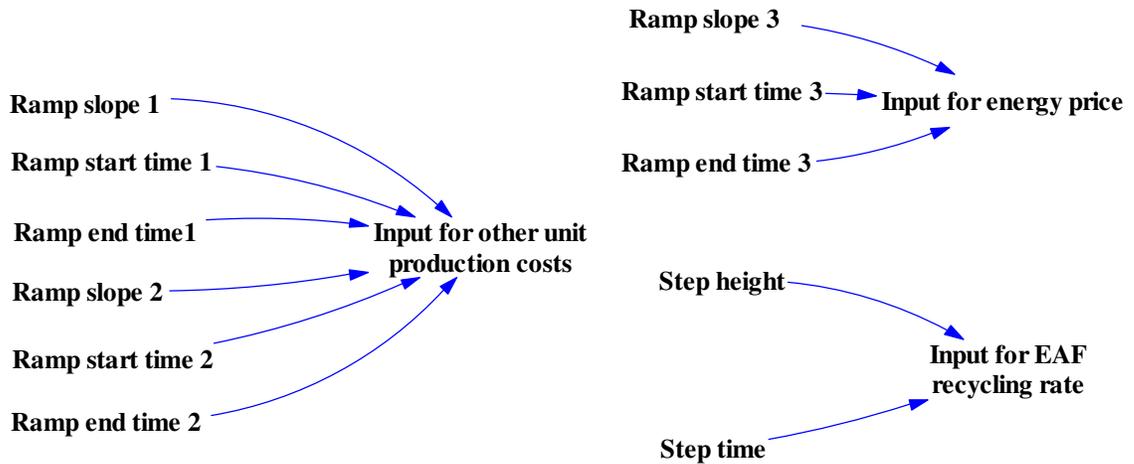
R&D investment is a financial support to technological development, and the improvement of which is assumed to be proportional to the amount that invested in R&D. So the actual change in R&D investment for current year relative to the investment in 1980 is expressed as **Relative R&D Investment** which is also the output of this sub sector, the equation is shown below:

*Relative R&D investment= R&D investment/ Initial R&D investment*

### 5.4.7 Exogenous Inputs

The exogenous inputs here refer to the variables that we create to predict the future behavior of some uncertain variables including energy price, EAF recycling rate and other unit production costs. The exogenous inputs have no realistic meaning in real life; they consist of some functions that are used to test model behavior such as ramp and step functions.

The structures of these exogenous inputs are shown below:



**Fig 5.17 Structure of Exogenous Inputs**

These inputs will take effect on their respective variables by means of the function they contain.

The formulation of *input of other unit production costs* is divided into two parts in terms of different time periods. We use different ramp slopes for the two time periods, so the first ramp slope functions between 1980 and 2006, and then the other ramp function gets started from 2007 and works until 2100. The equation is listed below:

$$\text{Input for other unit production costs} = 1 + \text{Ramp}(\text{Ramp slope 1}, \text{Ramp start time 1}, \text{Ramp end time 1}) + \text{Ramp}(\text{Ramp slope 2}, \text{Ramp start time 2}, \text{Ramp end time 2})$$

The above input will take effect on the Initial unit other costs

The same formulation way works with energy price as well, the equation is listed below:

$$\text{Input of energy price} = 1 + \text{ramp}(\text{Ramp slope 3}, \text{Ramp start time 3}, \text{Ramp end time 3})$$

The above input will multiply the energy price table to get the reference energy price.

As for *Input for EAF Recycling Rate*, it exists in a form of policy variable, so it does not function in normal scenarios. We use a step function for the input, while it does not mean the recycling rate will be raised immediately. On the contrary, based on the long delay added to

this exogenous input (see 5.4.5, EAF & Scrapped Steel Sub sector), the technology to raise recycling rate takes several decades to reach a high level. The equation is listed below:

*Input for EAF recycling rate = 1 + step (Step height, Step time)*

The policy is needed only if the step height is given a certain value except for zero. When they are set at zero, it means the policy does not work. This input will take effect on the reference recycling rate to get actual recycling rate.

## **5.5 SUMMARY**

The formulation of the above model structure focuses on representing the energy issues in steel industry of China. The model can not comprehensively capture all the features that contain in the real steel industry, but the defects can somehow be made up from certain relevant assumptions. The structure of the model captures the energy efficiency technology development process and the relationship of scrapped steels and EAF development process. Moreover, most structures of policy design and testing are included as well.

# **Chapter 6**

## **Model Testing**

### **6.1 INTRODUCTION**

After the model is formulated, we still can not say the results are valid or can be trusted. The model could produce errors or has limitations under certain circumstances. Model testing is thus designed to uncover errors so you and your clients can understand the model's defects, improve it, and ultimately use the best available model to assist in important decisions. This chapter describes several specific tests which are designed to verify whether the model works fine to match the research purpose of this work.

Tests in this chapter help to understand the suitability of the underlying structure, find out the robustness and sensitivity of the results according to the assumptions that we made regarding the model boundary, interactions among sub sectors. The tests we carry out here include boundary adequacy, structure assessment, dimensional consistency, parameter assessment, extreme conditions, behavior sensitivity and integration error tests.

### **6.2 BOUNDARY ADEQUACY TESTS**

Boundary adequacy tests assess the appropriateness of the model boundary for the purpose at hand. The boundary adequacy tests for this study include the determination of the model boundary and investigating whether all the important feedback loops are taken into consideration.

#### **1. Model Boundary Determination**

Helpful tools for determining what the boundary is include model boundary charts and subsystem diagrams, both of which are described in Chapter 5.

Important concepts for addressing the problem should be endogenous in the model. For this particular model, the evolution of technology is endogenous compared to other energy models. The problem is closely related to the energy efficiency technology which is the main way for the steel industry to save energy, and technology bridges key variables all together with feedback loops to construct the mechanism of the system. Several policies are aimed to ease the problem through influencing technological development.

All constants are exogenous but may in fact be variable over time in this model. For instance, reference recycling rate, it is changing over time in reality. At the early stage of the industrialization in China, cumulative steel resource which directly decides the amount of scrapped steels is small. During that period, the steel industry in China did not attach much importance to recycling scrapped metal products because the government has not realized the importance of sustainable development. Hence, the technology for recycling scrapped steel develops slowly. But the condition may be improved in the future, yet if so, policies and reasonable exogenous inputs can be carried out, since the technology for recycling has no relationship with the endogenous energy efficiency technology. Recycling technology is not our research focus, so we exclude it from the research scope. Hence, this constant assumption is adequate for the boundary of the model.

## **2. Important Feedback Loops**

For the second point, we need to consider whether any potentially important feedbacks omitted from the model, if included, might be important given the purpose of the model.

We do have some exogenous inputs for this particular model, such as GDP growth and other unit production cost. Both of them can to some extent be influenced by some of the endogenous structure such as steel demand, but there is no direct relationship. In addition, it does not make sense if we do include them as a part of the feedbacks. Steel production and demand is only a fairly small part that can influence the GDP growth, so the impact can be omitted. As for the other unit production costs, we need to add more economic related variables into the structure if we need to include it, yet the focus of the model might deviate. So in this case, we only focus on the energy costs, which is one of the most increasing costs among the total production cost. Modeling energy cost corresponds to the purpose of the model.

With respect to the purpose of this study, and in terms of the boundary chart and subsystem diagrams we use in the former chapter, the model boundary is appropriate for the purpose.

## **6.3 STRUCTURE ASSESSMENT TESTS**

Structure assessment tests ask whether the model is consistent with knowledge of the real system relevant to the purpose. The tests focus on the level of aggregation and the conformance of the model to basic physical realities. Structure assessment tests are carried using subsystem diagrams, stock and flow maps, causal loops diagrams and direct inspection of the equations. We test the model in the following ways:

### **1. Conformance of the Model to Basic Physical Realities**

Common violations of physical law involve stocks that can become negative. In our model, all the stocks have their real meaning in real world, and all their real quantities or the value of measuring its level cannot be negative. Most of the stocks are modeled with net inflow, their equations and structures of modeling show none of them would become negative in any case. Only cumulative steel has its outflow, namely steel scrapped rate, which is formulated using a first-order negative feedback loop. This loop restricts the scrapping rate from the cumulative steel so that the scrapping rate turns to zero when there is no steel resource.

### **2. No Free Lunch is provided**

Free lunches arise when activities that require important resources in the real system are assumed to occur without those resources in the model. Take scrapped steel recycling technology as an example; we only create exogenous inputs on the recycling rate. While recycling technology cannot be developed without any R&D investment, so to some extent, this exogenous input on the recycling rate is sort of free lunch. The reason we did so is just to take it as a policy variable, we want to see the effect of raising the recycling rate on improving energy conservation and CO<sub>2</sub> emission reduction. Including the structure of investment on recycling technology does not help a lot for the research purpose, and it just complicates the model structure. In this case, original and simpler model should be retained without involving the above extra details.

### 3. Level of Aggregation

The model is built based on related studies, technical literatures and online database. It maps the basic structure of the real Chinese steel industry energy system, which is divided into six subsystems: Steel Demand, Technology, Unit Energy Cost, Energy Demand& CO<sub>2</sub> Emission, EAF& Scrapped Steel and R&D Investment. All of the above subsystems are closely related with feedbacks. The variables in all the subsystems have their corresponding meanings in the real world. Therefore, the model constructed in this way can to some extent replicate the dynamic change in reality.

## 6.4 DIMENSIONAL CONSISTENCY

A System Dynamic model has dimension for each of its variable, even “dimensionless” can also be regarded as a dimension. The dimension for each variable is specified when the model is built, the consistency test for dimension may reflect nothing more than unit error or missing units. Such errors reveal important flaws in your understanding of the structure or decision process you are trying to model.

The criterion we use for the dimensional consistency test is *that each equation must be dimensionally consistent without the inclusion of arbitrary scaling factors that have no real world meaning*. We can only find out such fudge factors through direct inspection of the equations. All the equations for the model is available in the appendix, by inspecting the equations and automated dimensional analysis by the simulation software, we can say the model is dimensionally consistent, and all the parameters defined in meaningful names.

## 6.5 PARAMETER ASSESSMENT

This assessment can make sure the values of all the parameters are reasonable and every constant (and variable) has a clear, real- life meaning.

The basic way to estimate the values of each parameter are formal statistical estimation from numerical data, or judgmental estimation. In our study, both of the methods are used depending on the data availability. Historical data like GDP growth rate, energy price are

easily found in some online database or official published year books. Important social concerns are often evaluated and analyzed on their future growth trend by experts; our estimation is based on these evaluations. Only estimation without verification is unqualified. We estimate their future values by sensitivity tests in order to find out their robustness.

The second way is used when values of the parameters required by the model are not available or the data required by the model are at different aggregation levels from data available. The study focuses on the whole Chinese steel industry; the level of aggregation is high. Therefore, judgmental estimation based on experts' opinion, scientific literatures and our experience and knowledge is required.

Some technical parameters are created only for modeling purpose, while no real data is available. For instance, some technical parameters such as "Carbon Emission from a certain steelmaking process including EAF, BOF and OHF" are rather difficult to get their exact values. We get to know the value by summing up the carbon emission for each technical process of steelmaking such as casting, rolling, and iron making.

Another example is the cost and price of steel. The price of steel is changeable in the real world market depending on supply and demand or other factors which are beyond this research scope. In our research, the price and cost are assumed to be equivalent with each other due to the high aggregation level of the model.

By examining the values for all the parameters in the model, it helps us to get a more accurate and reliable understanding of the model and we find out the aggregated structure is acceptable for the research purpose.

## **6.6 EXTREME CONDITION TESTS**

The extreme test evaluates the robustness of the model to see whether the model works under extreme conditions. A model should behave in a realistic fashion no matter how extreme the inputs or policies imposed on it are. Extreme conditions refer to those that can never happen in the real world. The test is carried out by imposing extreme conditions as scenarios in simulations

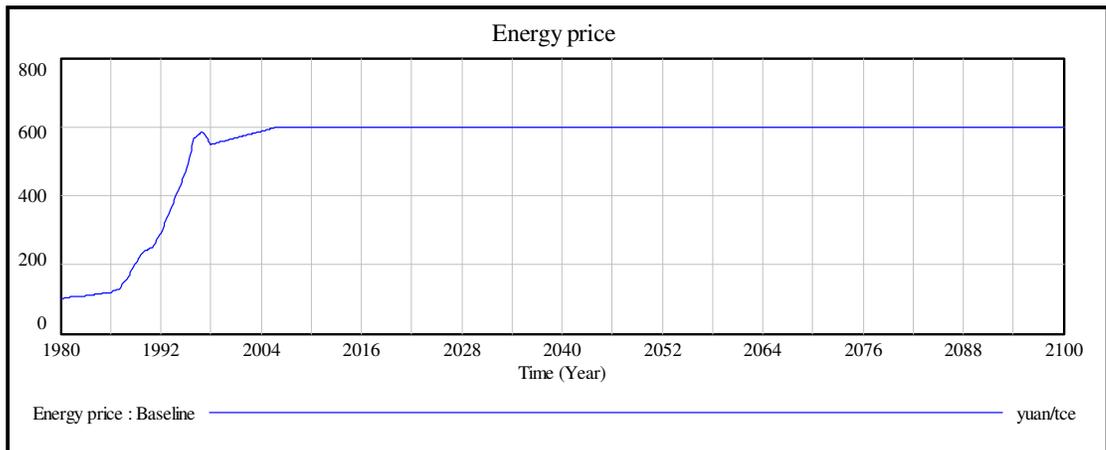
of the model. We set extreme values for variables or test inputs like step function to create extreme conditions.

Before all the tests are taken, a baseline scenario (without any exogenous inputs) is introduced for the testing purpose. The baseline scenario refers to the case that there is no significant driving force such as energy price, GDP growth to cause the problem, all such factors will remain constant or stop function. This is for the purpose of testing isolated effect of each factor. The detailed settings are listed below.

### 6.6.1 Baseline Scenario

#### Energy price setting:

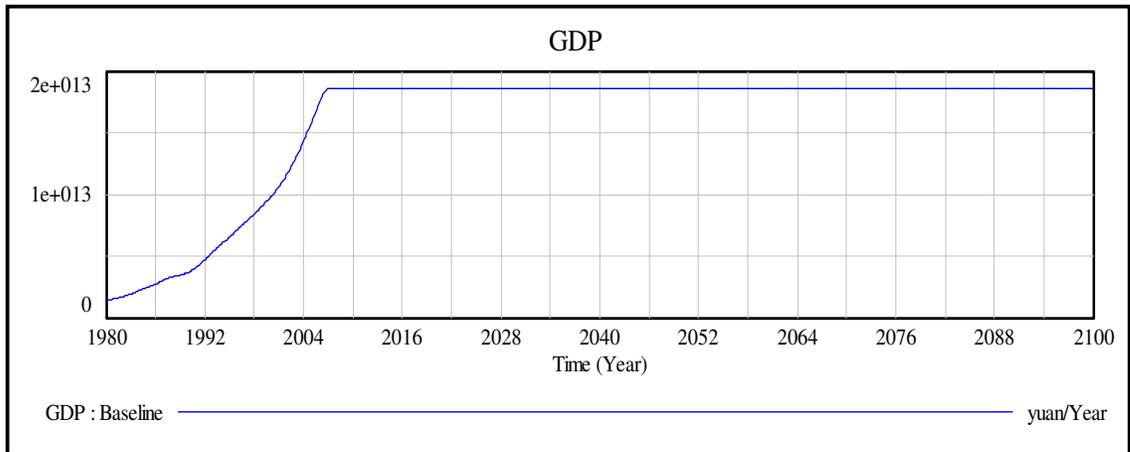
The baseline scenario is made under the assumption that the energy price is introduced directly from data series from 1980 to 2006 and will keep at the level of 2006's until 2100.



**Fig 6.1 Energy Price setting under the Baseline Scenario**

As we see in the graph, the energy price keeps at 600 Yuan/tce until 2100.

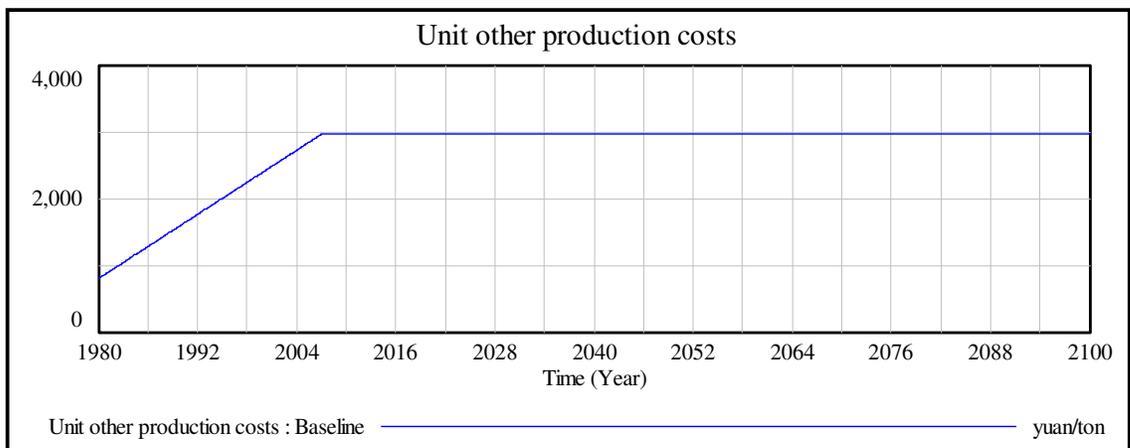
#### GDP growth rate setting:



**Fig 6.2 GDP Growth Rate Setting under the Baseline Scenario**

GDP growth is an important driving force behind the steel demand. When the GDP growth rate drops to zero, GDP will remain at its 2006's level, which means the reference steel demand should remain at 2006's level.

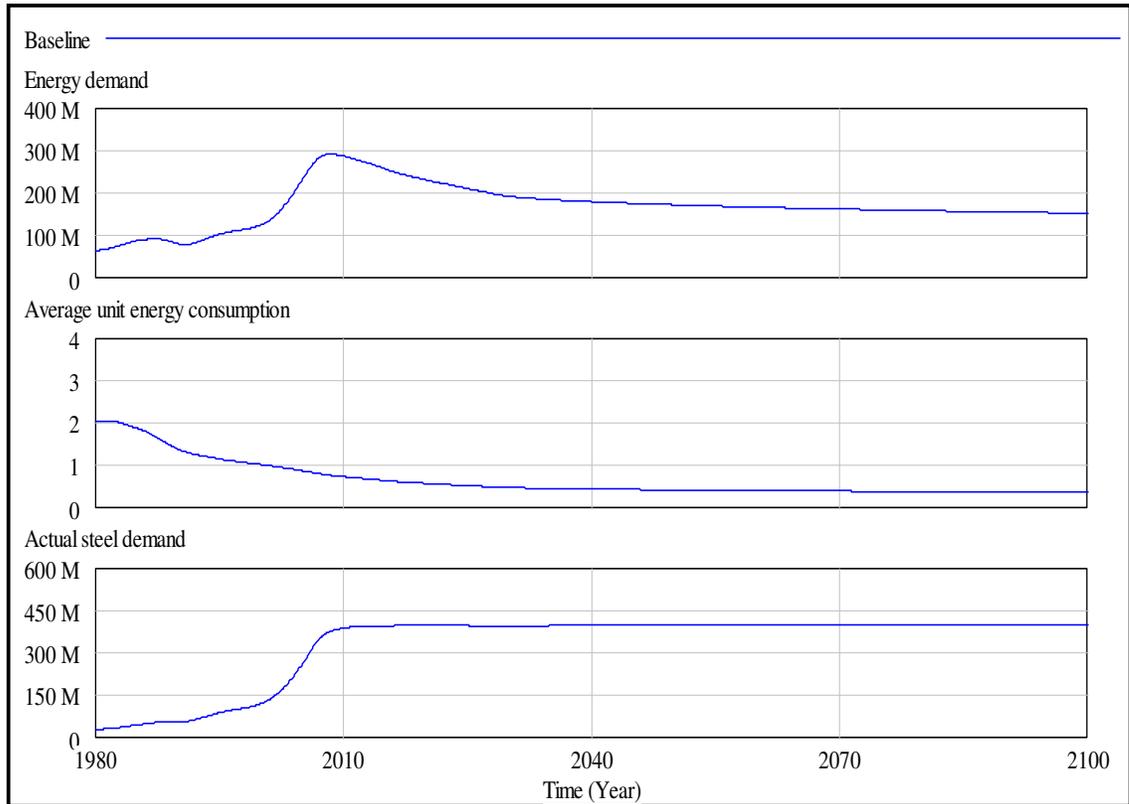
**Units other production costs setting:**



**Fig 6.3 Unit Other Production Costs under the Baseline Scenario**

The transition problem is caused by the rapidly increasing energy price and steel demand. The introduction of GDP and population is to model the reference steel demand. But only keeping these two variables constant after 2007 is not enough, the actual steel demand will still be influenced by the production costs. Unit other production costs is an important part of unit production cost, while from the historical data, we find that it grows at a steady and flat trend.

For the purpose of not affecting the steel demand, we keep it constant at the level of 2006 until 2100. The results of important model variables from these baseline settings are shown below:

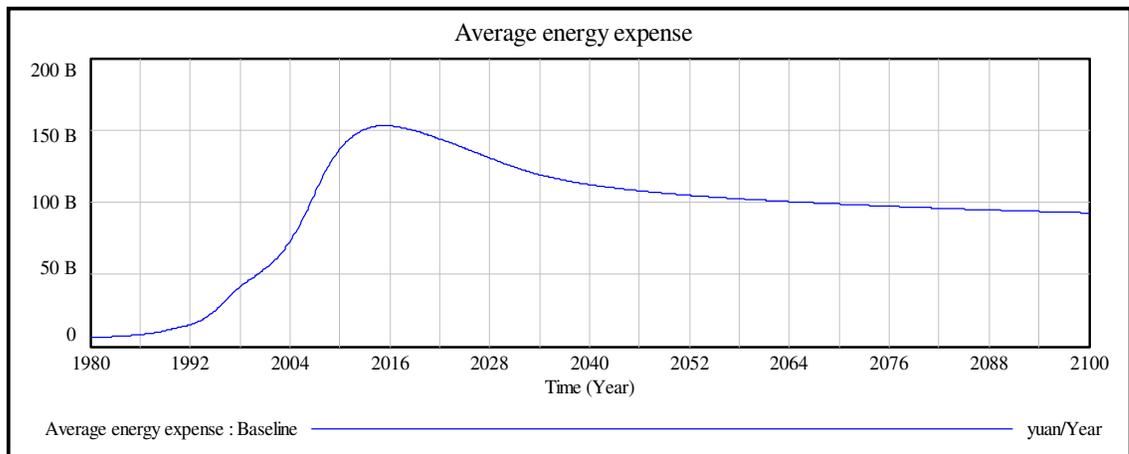


**Fig 6.4 Energy Demand under the Baseline Scenario**

The behavior of energy demand is decided by the steel demand and unit energy consumption. As the behavior of steel demand shows above, it is the result of keeping other exogenous inputs constant. There is almost no consequent change in steel demand, but the behavior keeps rising at a very low rate due to the cost effect. With almost constant steel demand and unit cost, the sales revenue remains unchanged. Since we assume a reference R&D investment percentage, steel industry keeps investing on energy efficiency technology at the same amount of investment expense every year. While the technology development also comes from two incentives: CO<sub>2</sub> emission and energy price rising. Due to the existing but unchanged steel demand and continuously advancement of energy efficiency, the energy demand drops. Hence CO<sub>2</sub> emission will decline correspondingly from 2007. As for the energy price, the price level in 2007 is still high compared to its initial level. So even it no longer increases, the high energy price still can become another incentive for the industry to invest in R&D.

Without strong incentives to develop energy efficiency technology, the energy efficiency improves slowly, which means the average unit energy consumption declines slowly after 2007.

The average energy expense comes from the result of energy price and energy demand. The expense declines due to the decreasing energy demand with constant energy price after 2007.

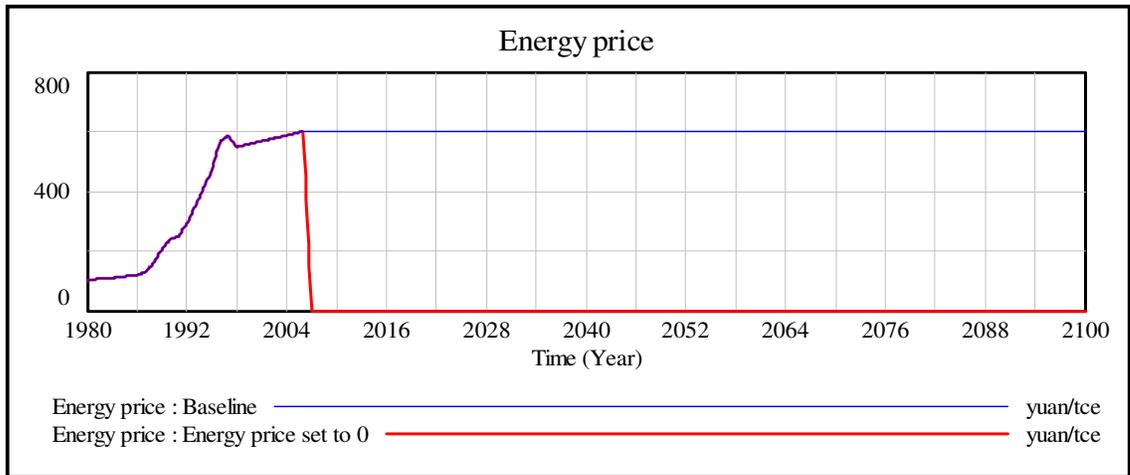


**Fig 6.5 Average Energy Expense under the Baseline Scenario**

Note we do not believe that this baseline condition ever exists. There are always variations in the real world. Yet when the model is set without change in exogenous inputs, it becomes a simplification of the reality. We can show all the tests and isolated effect of all kinds of exogenous inputs.

### 6.6.2 Extreme Test1: Energy Price Drops to 0

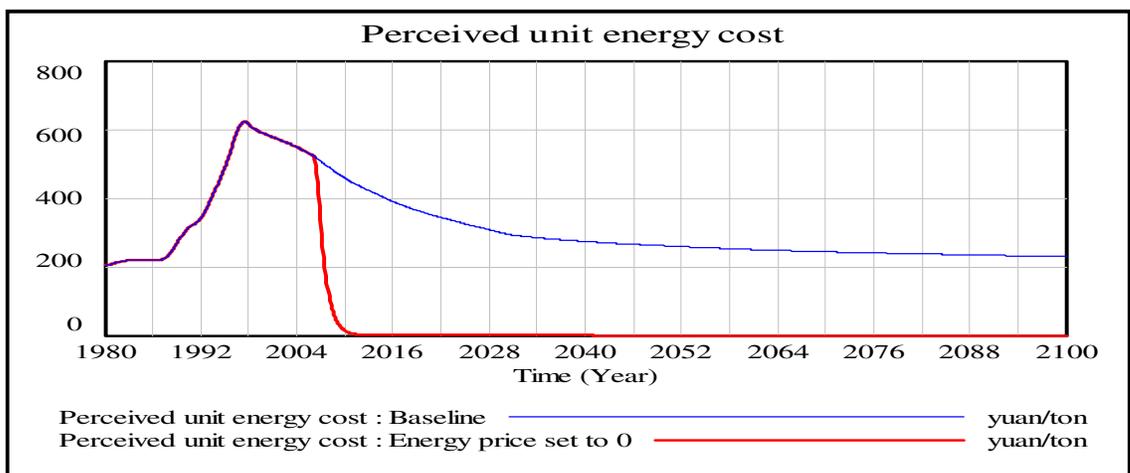
Based on the baseline scenario, firstly, we test the model under the extreme condition that the industry can get energy for free. The detailed operation is simply set energy price to 0 in 2007 and remains until 2100. For the purpose of comparison, we will show both the extreme condition and baseline condition in the same graph. Meanwhile, keep the other variables as what they set in the baseline case.



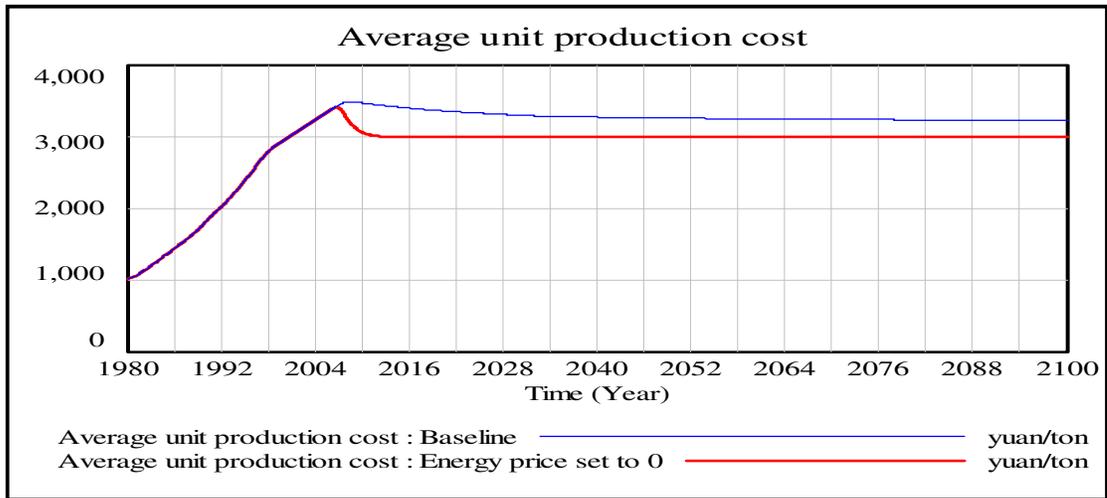
**Fig 6.6 Energy Price in Extreme Test 1**

The actual energy price is the reference average energy price plus the energy tax, since no policy implemented in the extreme tests, the actual energy price equals to the reference one. In this extreme test, no wonder that unit energy cost suddenly drops to zero in 2007, as it is the multiplication of the energy price and average unit energy consumption.

When the unit energy cost drops to zero, the total unit production cost goes down. Note that it decreases at a small extent, since we assume the other production costs keep constant, so the only variation comes from the decrease of unit energy costs. The behaviors of both cases turn to equilibrium eventually. In the extreme case, industry needs time to realize the new policy and adjust their production way. In the baseline case, since the energy price keeps constant from 2007, while unit energy consumption is decreasing, all of which leads to a reduction on unit energy cost over time.



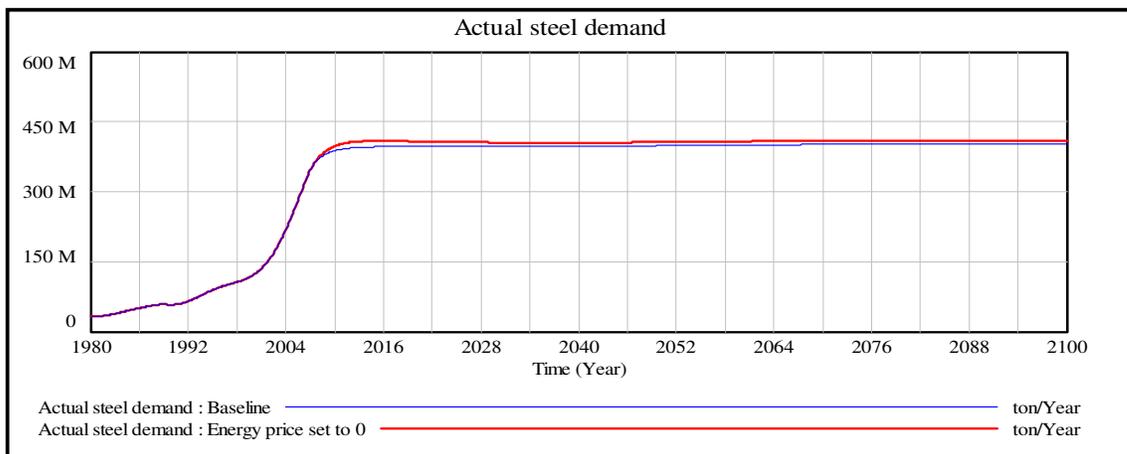
**Fig 6.7 Perceived Unit Energy Cost in Extreme Test 1**



**Fig 6.8 Average Unit Production Cost in Extreme Test 1**

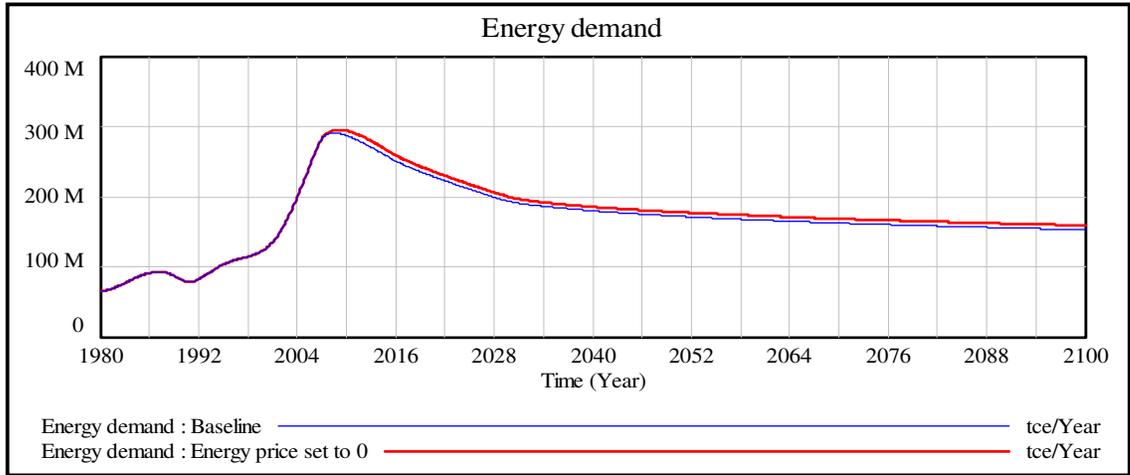
The unit energy cost is only one part of the total production cost. The extreme case actually eliminated the unit energy cost by purchasing energy for free, which leads to a step reduction on the production cost. Since there is no rising energy price crisis, the energy cost can not increase any more, on the contrary, it will decrease due to the improving energy efficiency. The above reason explains why there is no substantial reduction on the whole production cost even the energy cost turns to zero.

The production cost directly influence the steel demand. When cost increases, demand may decrease. As the graph is shown below, the demand seems to be influenced a little. This is due to lower and lower proportion of unit energy cost among the total cost with the time going on.



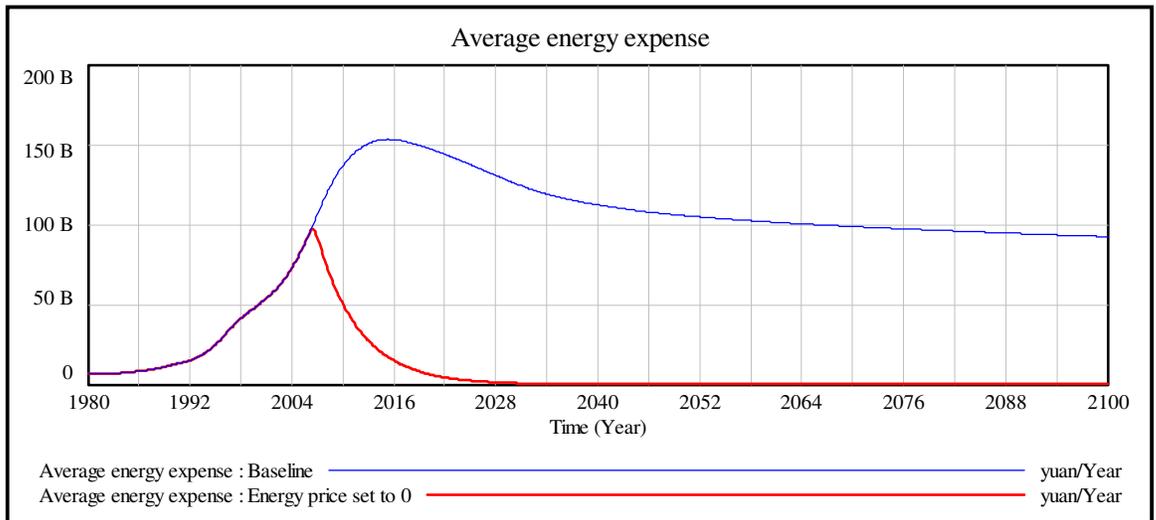
**Fig 6.9 Actual Steel Demand in Extreme Test 1**

“Energy demand” is the multiplication of steel demand and average unit energy consumption. Higher steel demand than the baseline case drives energy demand to increase correspondingly.

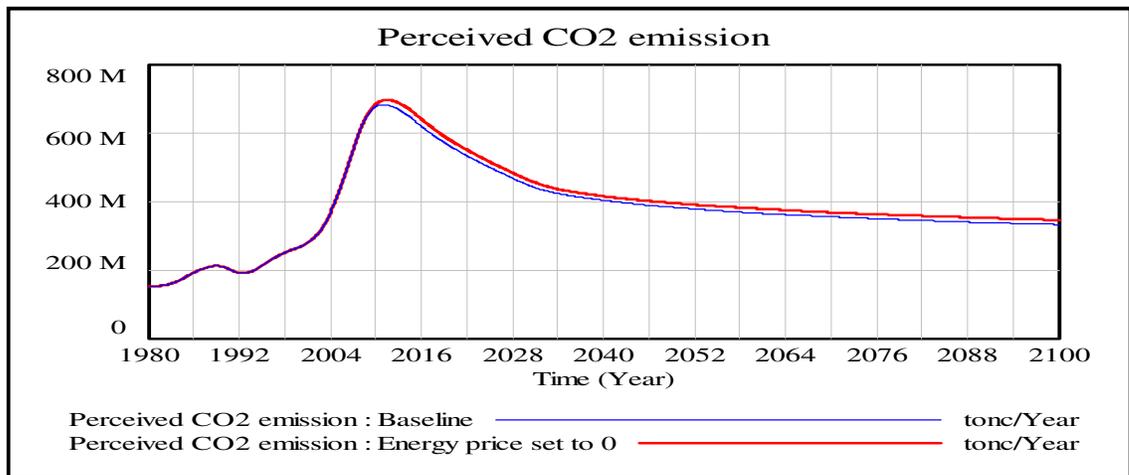


**Fig 6.10 Energy Demand in Extreme Test 1**

Responds to the price cut to zero, the industry no longer needs to spend on the energy expense. Note this is the average energy expense; we averaged the energy expense into 5 years. Thus from the behavior below, the expense will slowly turn to zero instead of a sharp reduction.



**Fig 6.11 Average Energy Expense in Extreme Test 1**



**Fig 6.12 Perceived CO<sub>2</sub> Emission in Extreme Test 1**

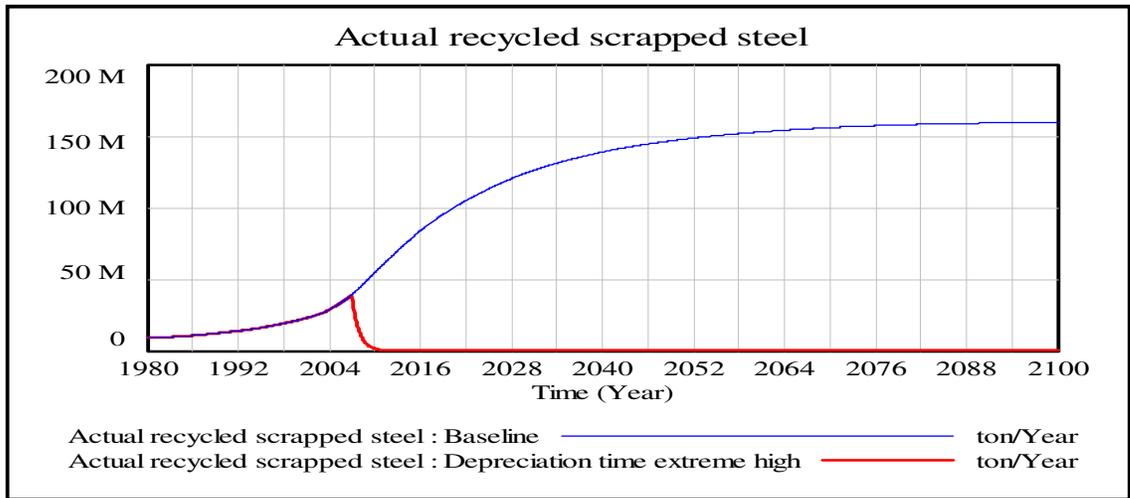
Responds to the change in energy demand, CO<sub>2</sub> emission increases correspondingly at a small rate.

### 6.6.3 Extreme Test 2: Depreciation time of cumulative steel is extremely high

In this extreme test, we raise the depreciation time of cumulative steel resource to an extremely high level. The cumulative steel actually refers to social capital in reality, such as buildings, machines of any products made of steel. The average depreciation time for these capitals in China is around 18 years for the baseline scenario. Based on the original depreciation time, we add a step function with an extremely high value to raise the time.

$$\text{Depreciation time} = 18 + \text{step}(1e+008, 2007)$$

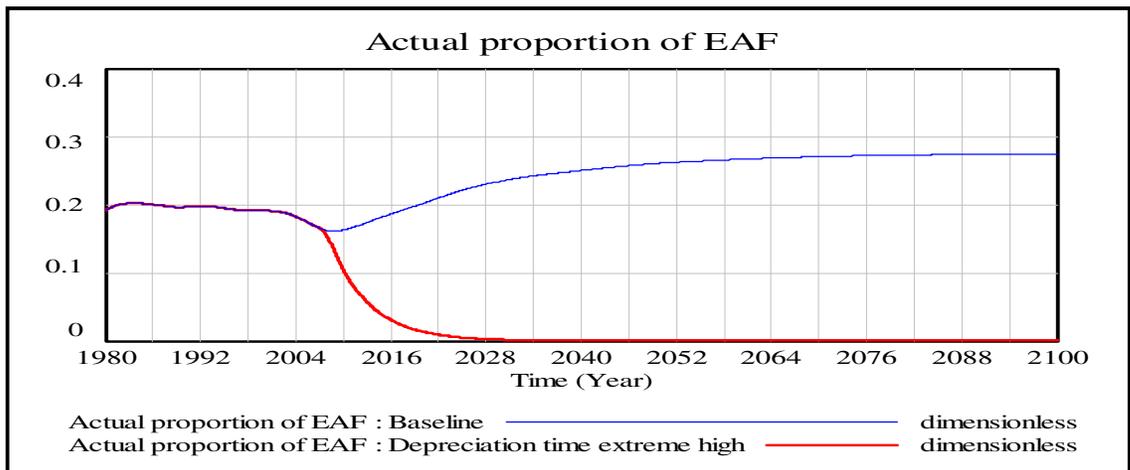
Equation above indicates it takes extremely long time for the social capital to depreciate. The scrapped steel comes from the recycling of the depreciation of social capitals. As a result, the behavior of actual recycled scrapped steels is shown in the graph below.



**Fig 6.13 Actual Recycled Scrapped Steel in Extreme Test 2**

As figure 6.13 shows, it is easy to understand that with extremely long depreciation time, scrapped steel will no longer exist in the market. Note that it will not suddenly respond to the change of rising depreciation time, because it takes time for people to recycle the old products or assets with shorter depreciation time during past years.

As a result, no scrapped steels are available, which makes it impossible to use EAF any more, thus the proportion of EAF goes towards zero.



**Fig 6.14 Actual Proportion of EAF in Extreme Test 2**

From the above results of extreme tests, we can say the model is able to capture underlying physical realities and constraints that affect behavior outside the conditions observed in the past.

## 6.7 Behavior Sensitivity Tests

Sensitivity tests allow you to test the robustness of the model to see whether the results change in ways important to your purpose when assumptions are varied over plausible range of uncertainty. Limited to time and resources, to do comprehensive sensitivity analysis is generally impossible since it requires testing all combinations of assumptions. In this sense, it would be wise to focus on the relationships and parameters that we suspect are both highly uncertain and likely to be influential.

For this research, behavior mode sensitivity tests are carried out; we introduce different scenarios to see the model behaviors responding to them. All the scenarios below are created based on the “Baseline Scenario” that we introduced in the extreme tests. The consequent results of these scenarios are compared with those in baseline scenario.

### 6.7.1 Sensitivity Test I: Pure Energy Price Increase

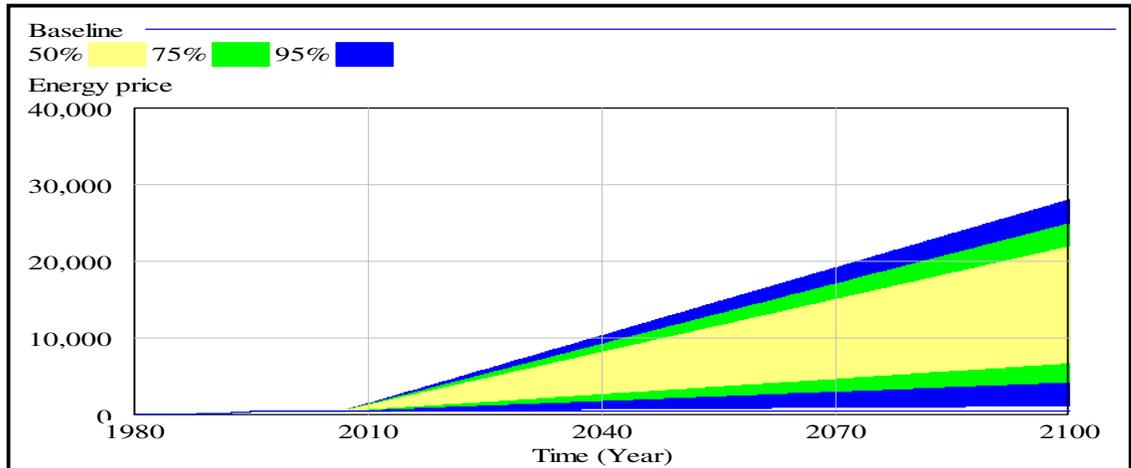
Based on the baseline scenario, we relax the constant energy price assumption and simulate the model with a ramp increase in energy price.

From the historical trend and literatures, we find a rapidly increasing rate on energy price before 2007, 6 times the price level in 1980. No body knows how it behaves in the future, but there are high possibilities that energy price will keep increasing after 2007. In terms of the current situation in China, the price of coal and electricity is made by Chinese National Development and Reform Commission. In order to meet the needs from the whole industry and social life, it is rather impossible that the energy price will suddenly be raised to a very high level, so we give up the thinking of using a step increase for the energy price. Instead, a ramp function input is used here.

The energy price expression is:

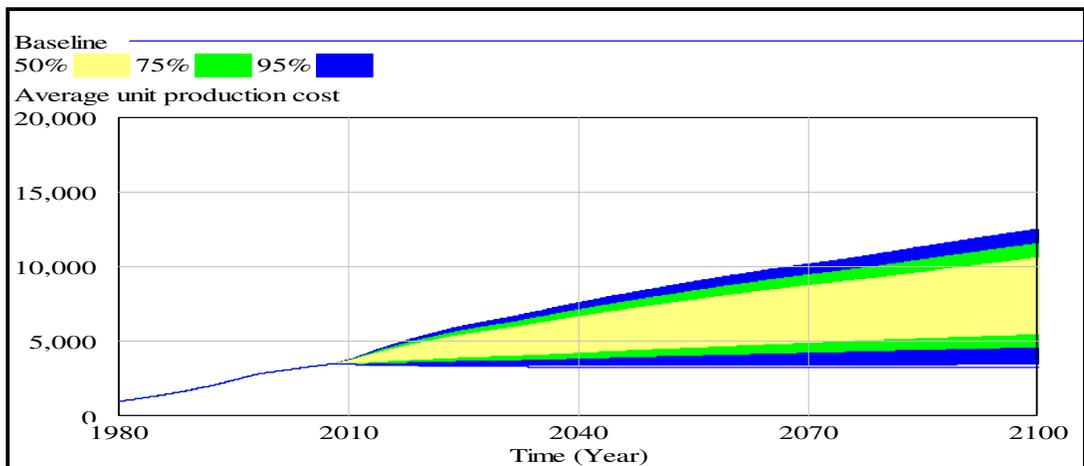
*Energy price table (Time)\* Input for energy price, in which Input for energy price = 1 + ramp (slope, 2007).*

The ramp function above means the price will increase at a certain slope. A sensitivity test on the slope of ramp function is carried out below. The results of other key variables caused by the change of the slope are depicted in the following graphs. The slope is varied between 0 and 0.5 and the model will be simulated for 200 times.

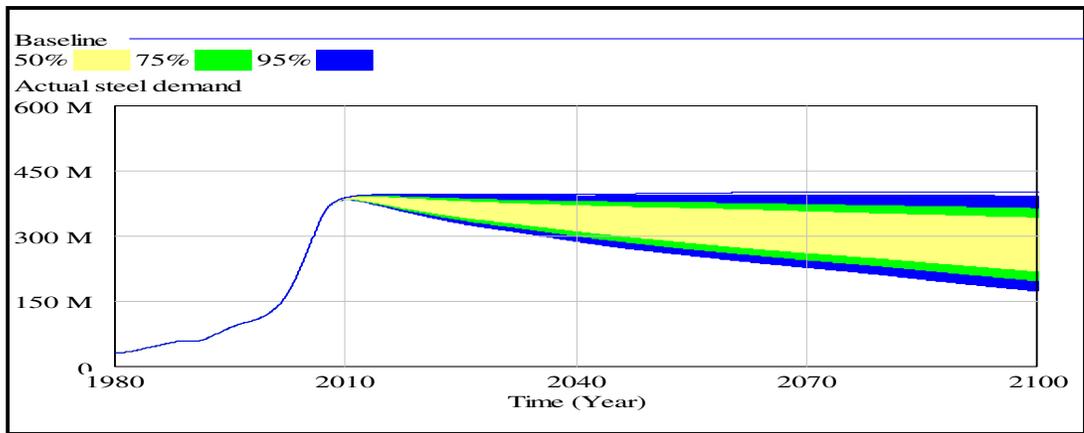


**Fig 6.15 Energy Price under Sensitivity Testing 1**

The line in bottom area is the behavior of baseline scenario. The simulation results in the graph are displayed as confidence bounds. These are computed at each point in time by ordering and sampling all the simulation runs. The whole behavioral areas ranges from the simulation run at slope 0 to slope 0.5. 50% means half of the 200 simulations will concentrate in this area with specified color. 75% means 25% of the 200 simulations will concentrate in the area with specified color. So do the other percentage.

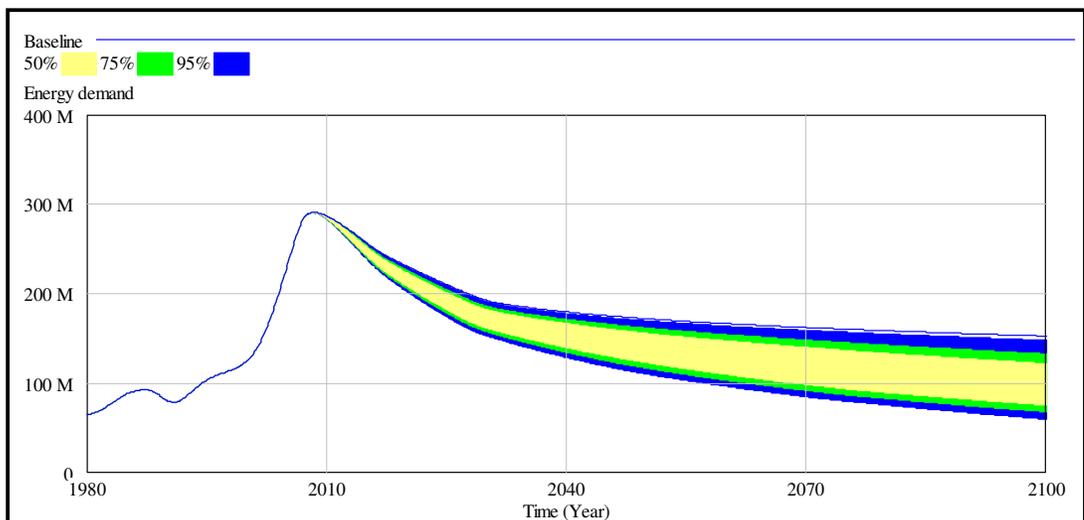


**Fig 6.16 Average Unit Production Cost under Sensitivity Testing 1**



**Fig 6.17 Actual Steel Demand under Sensitivity Testing 1**

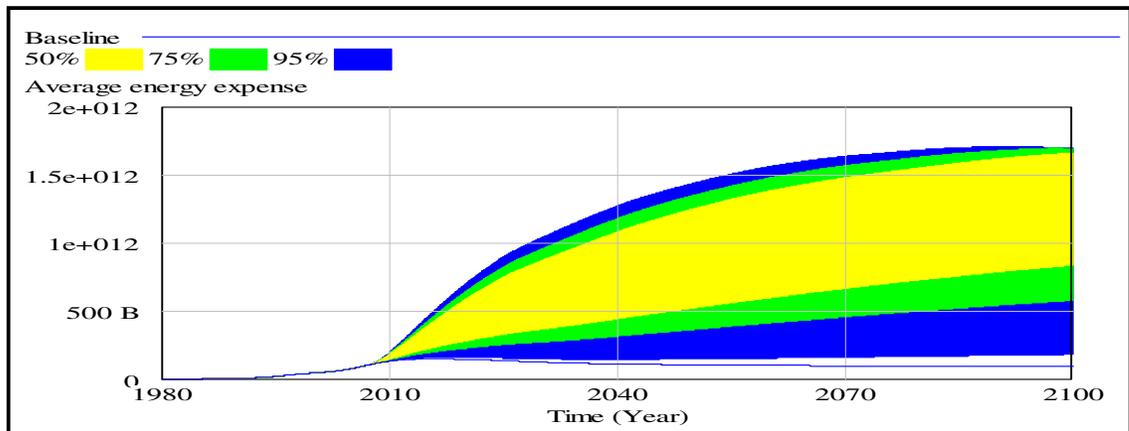
When the energy price varies like figure 6.15 shows, the unit production cost will increase correspondingly, which leads to a corresponding reduction on the steel demand. The behavior changes a little in the beginning, then changes substantially with the time going on as a result of ramp input, the bigger the ramp slope, the bigger the variation is.



**Fig 6.18 Energy Demand under Sensitivity Testing 1**

Figure 6.18 indicates the energy demand decreases correspondingly with steel demand decrease. Note that it does not decrease as much as steel demand because of even slower technological development than the baseline scenario. With decreasing steel demand, the sales revenue is decreasing, which makes industry invest less than before. Thus energy efficiency will not be improved as much as it does in the baseline scenario. The above graph indirectly tells us another incentive  $\text{CO}_2$  emission becomes weak, because  $\text{CO}_2$  emission is closely

related to energy demand. Thus this incentive to develop energy efficiency technology no longer becomes important to the industry.



**Fig 6.19 Average Energy Expense under Sensitivity Testing 1**

Figure 6.19 indicates the direct result of pure energy price increase is a significant increase in energy expense. From figure 6.18, we know there is a reduction on energy demand, but the increment of energy price is higher than the demand reduction. The reason is that the cost effect on the steel demand is not proportionally reinforced. Energy cost is just one part of the production cost; it is somehow offset by the improvement of energy efficiency. So there is no proportional increment on the production cost due to energy price increasing. In this sense, the steel demand will not decrease that much, thus there is no bigger reduction on energy demand. But the price increase will directly put weight on the industry's energy expense, that's why the average energy expense increases significantly.

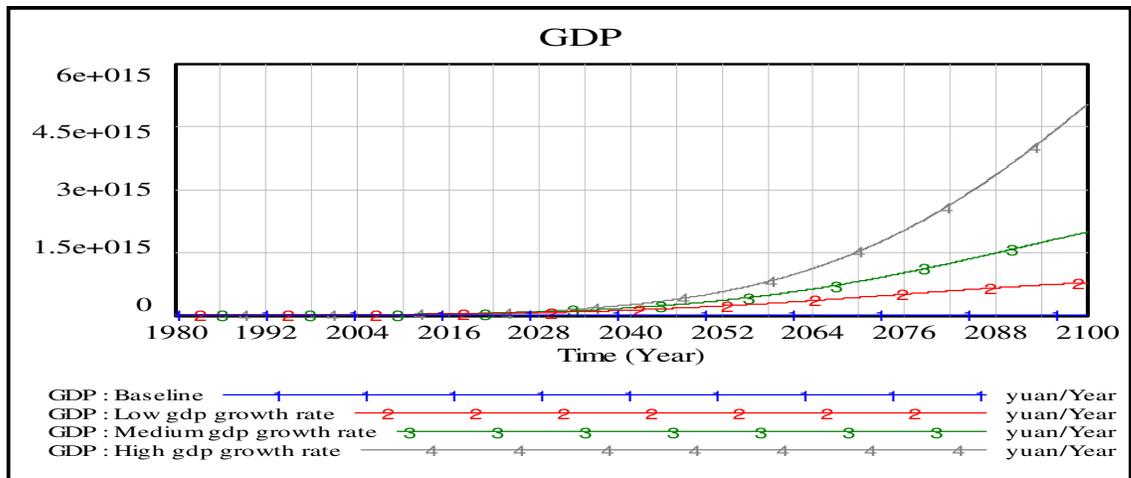
## 6.7.2 Sensitivity Testing II: Pure GDP Growth

In this test, we relax no GDP growth rate setting in the baseline scenario and keep the other exogenous input settings just as they behave in the baseline scenario

With respect to GDP, we use GDP growth rate to model it. GDP varies a lot in China's historical data, and it is hard to predict its future trend with a certain value. With regarding to its recent years' development trend, the GDP growth rate keeps at an average rate of 9%, such growth rate may last for one or two decades, then slowly drop to a low rate.

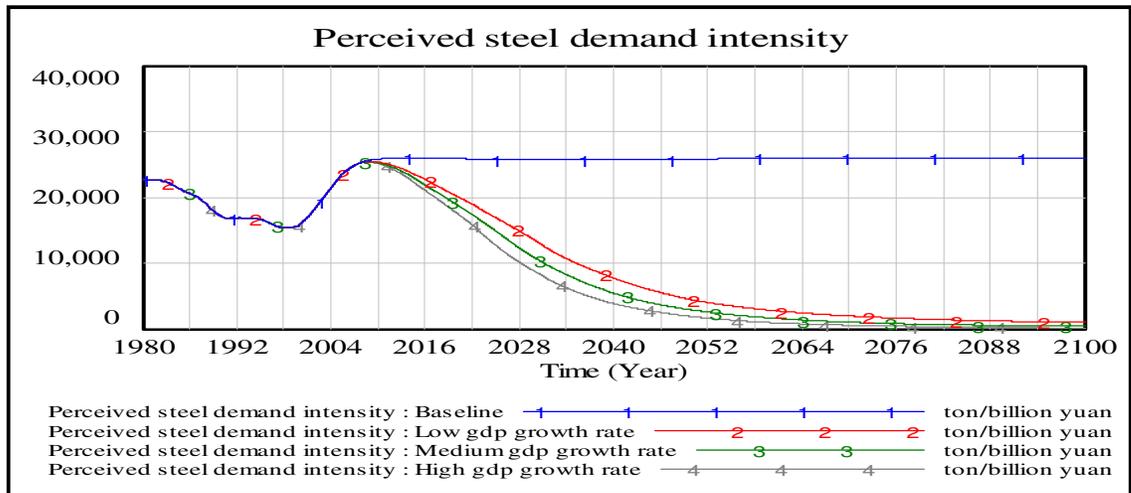
We want to test the most reasonable development trend of GDP growth rate to model GDP per capita. Three scenarios are provided here, each one has a certain high growth rate in 2007, and then we assume it will slowly and linearly drop to a low rate in 2100.

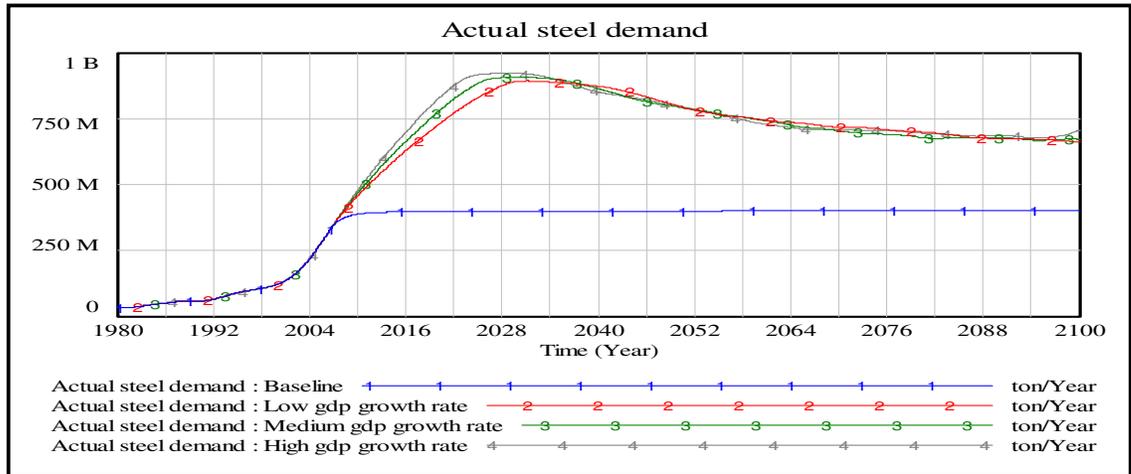
- High GDP growth trend: From 9% in 2007 to 3% in 2100.
- Medium GDP growth trend: From 8% in 2007 to 2% in 2100
- Low GDP growth trend: From 7% in 2007 to 1% in 2100



**Fig 6.20 GDP of three conditions under Sensitivity Testing 2**

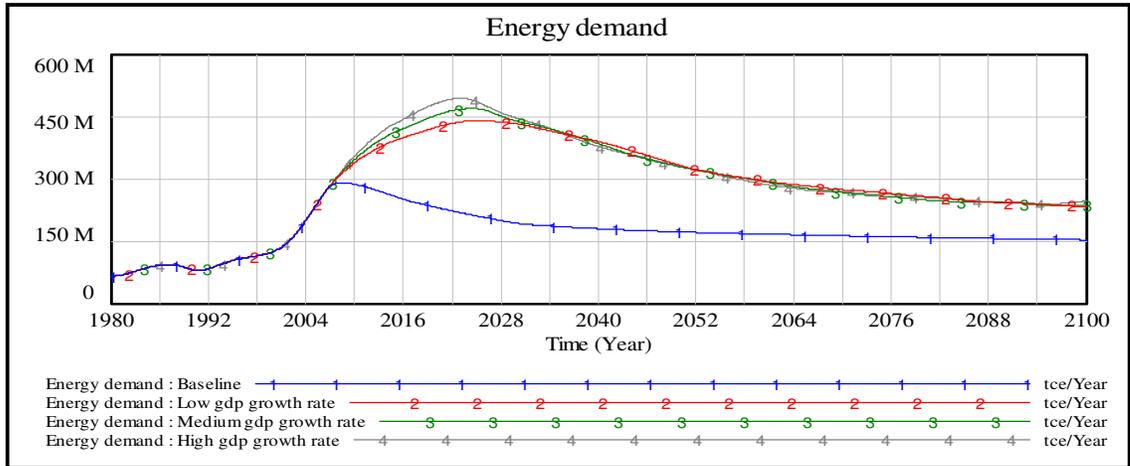
The behavior of GDP growth is shown in figure 6.20. With growth rate taken on, the GDP in three scenarios will grow exponentially. (Compared to the exponential growth condition, the behavior in the baseline looks like a line)



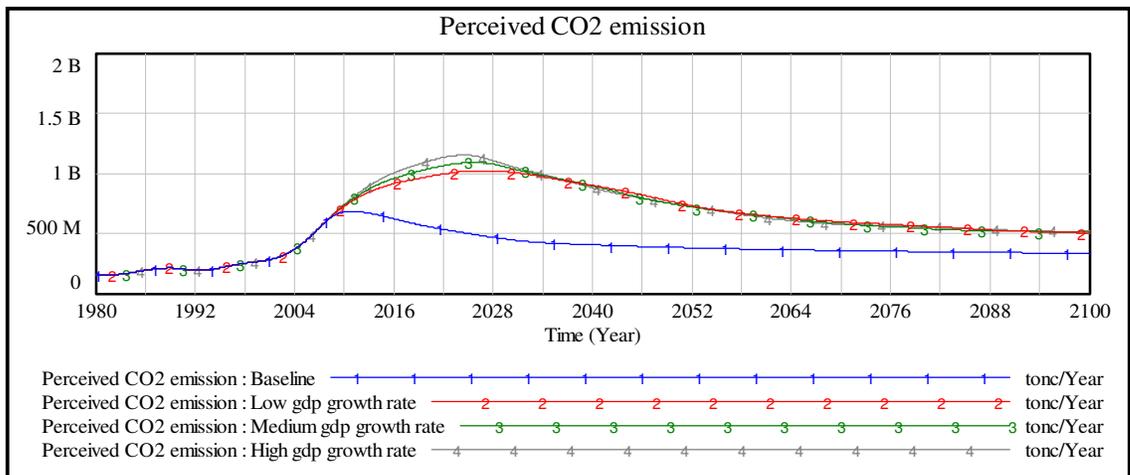
**Fig 6.21 Perceived Steel Demand Intensity under Sensitivity Testing 2****Fig 6.22 Actual Steel Demand under Sensitivity Testing 2**

When GDP grows, GDP per capita increases, it drives the steel intensity to decrease (Figure 6.21). As it is illustrated in the model description chapter, we set 4000\$, which is 320,000RMB as a milestone of GDP per capita. When it reaches that height, the steel demand will reach its peak, and then slowly decrease.

As three scenarios show in the graph 6.20, GDP grows in three different trends depending on their different growth rate. The high scenario behavior grows higher and faster than the other two, which means GDP per capita reaches 320,000RMB earlier than the other two, so the steel demand saturates earlier than the other two. When all three curves reach their peak, they all slowly decrease and look like to be coinciding with each other in the end. The reason for this moving-close trend behavior is that high scenario will produce high GDP per capita, which cause the steel demand intensity to decrease even faster than the other two do. At the same time, its GDP grows faster than the other two, the multiplication of these two constitute the steel demand.

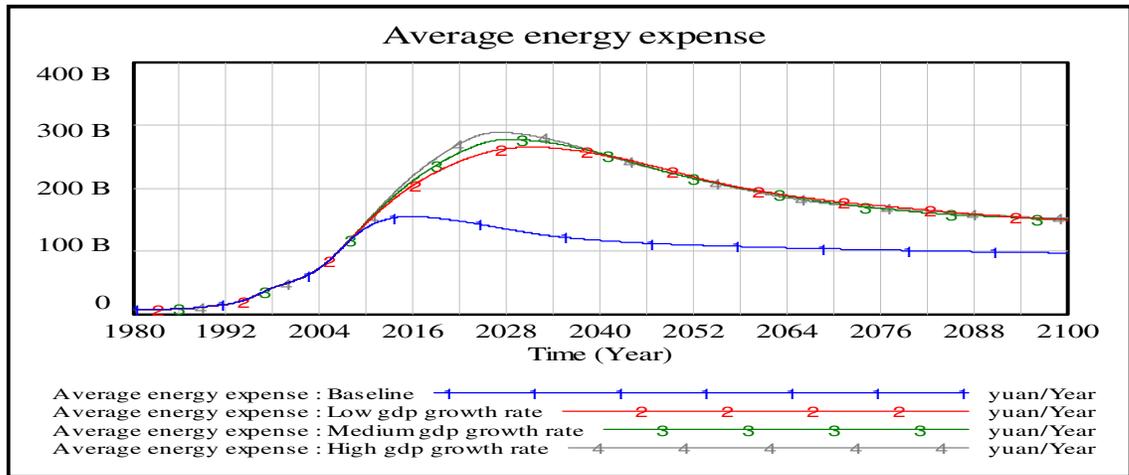


**Fig 6.23 Energy Demand under Sensitivity Testing 2**



**Fig 6.24 Perceived CO<sub>2</sub> emission under Sensitivity Testing 2**

Figure 6.23 indicates a similar behavior trend in energy demand to steel demand. Since energy demand is the multiplication of steel demand and unit energy consumption, there is little impact from different scenarios of GDP growth rate on unit energy consumption, so energy demand mainly depends on the steel demand. The difference of the behaviors of three scenarios comes from the difference in the steel demand. With regarding to CO<sub>2</sub> emission in figure 6.24, it is the direct cause of energy consumption; the difference in behaviors has the same reason as the energy demand.



**Fig 6.25 Average Energy Expense under Sensitivity Testing 2**

Energy expense in this case depends on the energy demand, since only the GDP growth assumption is relaxed, no energy price increase in this testing. So the average energy expense will follow the trend that energy demand does.

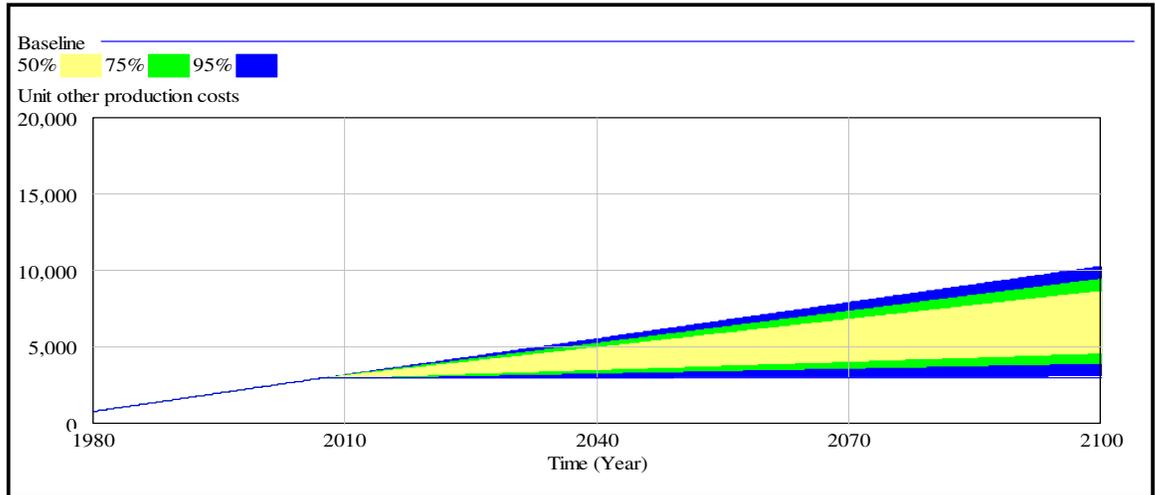
### 6.7.3 Sensitivity Testing III: Pure Unit Other Production Costs Increase

In this test, we relax unit other production costs setting and keep the other exogenous inputs settings just as they behave in the baseline scenario

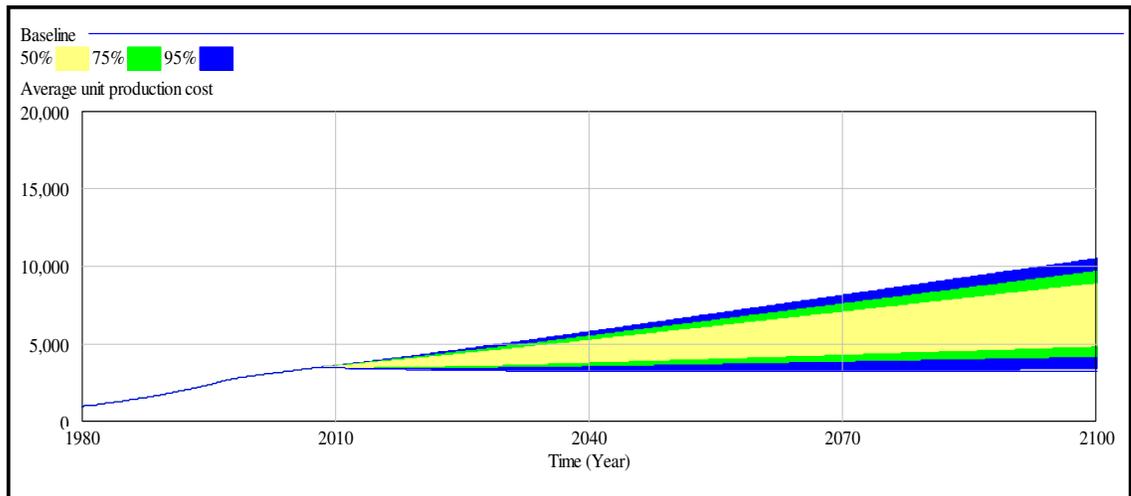
“Unit other production costs” is an exogenous input attributed to the cost effect on steel demand besides unit energy cost and unit R&D cost. From the statistical data series for steel production cost, we know that usually energy cost amounts to around 30% of the total production costs and R&D cost is only 1%. Even the rest costs grow steadily and slowly, it still has a significant influence on the steel demand.

The unit other production costs in this particular model includes labor and capital costs, raw material costs, administration costs and so on. It is not that realistic for the industry to invest even more or the same amount on capital when the steel demand reaches its saturation. When the steel demand declines, the demand for raw materials will decline correspondingly. All of the above reasons make us unconfident to set a high growth rate for unit other production costs. We test the unit other production costs increase as following:

Assuming that the unit other production costs may vary between its current level in 2007 and following its original increasing trend as usual until 2100, which means we will adjust the ramp slope between 0 and 0.1.

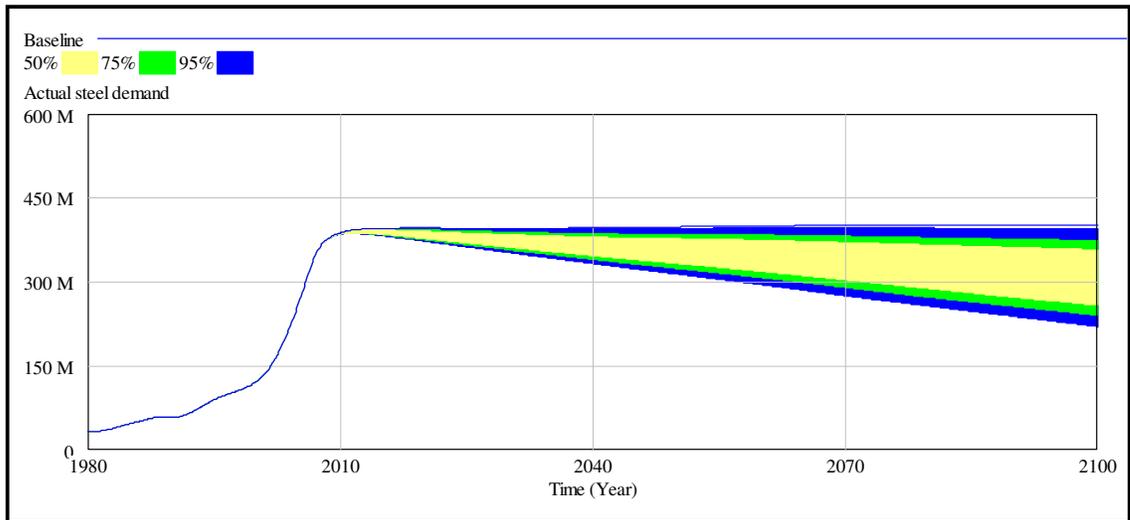


**Fig 6.26 Unit Other Production Cost in Sensitivity Testing 3**

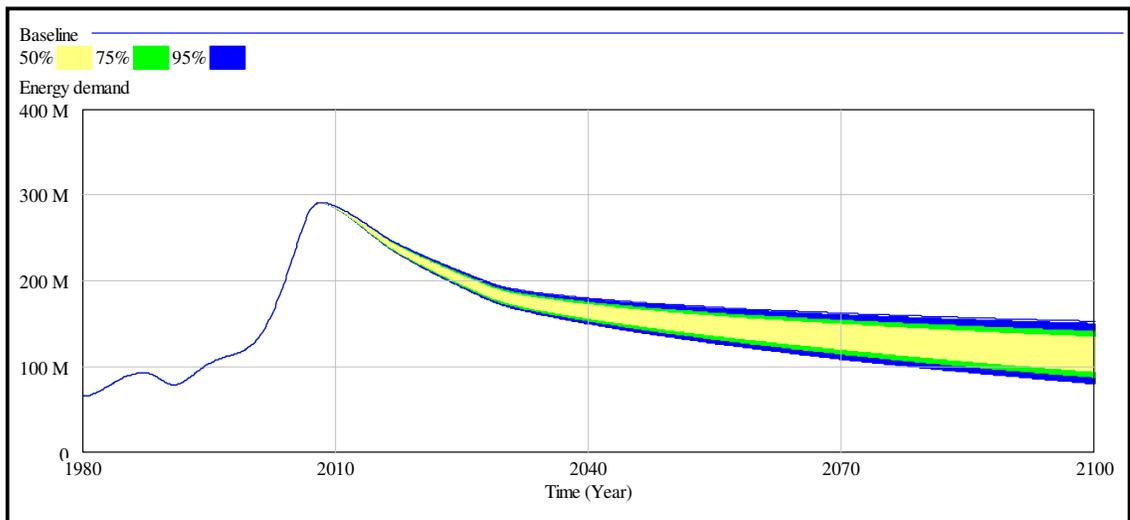


**Fig 6.27 Average Unit Production Cost in Sensitivity Testing 3**

As figure 6.27 shows, not like energy cost, there is no measure to offset the unit other costs in this model, so the increment on other unit costs will completely be calculated into the whole unit production costs. Such substantial cost increase will have dramatic impact on steel demand, see the figure 6.28 below:

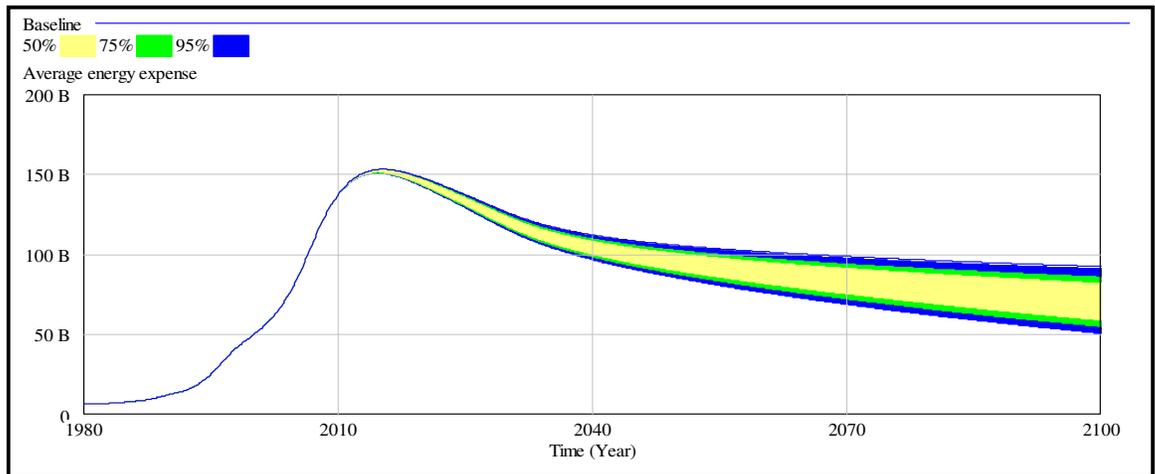


**Fig 6.28 Actual Steel Demand in Sensitivity Testing 3**



**Fig 6.29 Energy Demand in Sensitivity Testing 3**

The above behaviors of steel demand and energy demand are quite similar as they are in pure energy price increase testing though the magnitude of the behavior are somehow different. The reason for that is both testing try to influence demand through raising production cost.



**Fig 6.30 Average Energy Expense in Sensitivity Testing 3**

Similar to the condition in sensitivity testing 2, energy expense in this testing depends on energy demand since the energy price is assumed to remain constant as it behaves in baseline scenario.

#### 6.7.4 Sensitivity Testing IV: Combined scenarios

The former three tests are aimed to test the sensitivity of each isolated effect. While in reality, all three exogenous factors happen at the same time, we will combine these three exogenous inputs in this testing. The combined scenarios will be categorized into three different conditions in terms of different settings of each respective factor. They include medium GDP medium cost development, high GDP high cost development and low GDP low cost development. The detailed settings for each case are listed below.

##### 1. Low GDP growth, low cost development (Low Scenario)

- GDP growth rate: From 7% in 2007 to 1% in 2100
- **Energy price=Energy price table (Time)\*Input**, in which, **Input=1+ramp (0.1, 2007, 2100)**
- Other unit production costs: Keep constant at the level of 2006 after 2007 to 2100.

##### 2. Medium GDP growth, medium cost development (Medium Scenario)

- GDP growth rate: From 8% in 2007 to 2% in 2100.
- **Energy price=Energy price table (Time)\*Input**, in which, **Input=1+ramp (0.1, 2007, 2100)**

- Other unit production costs: Increasing slowly after 2007: Half ramp slope (0.05) as the one (0.1) used before 2007.

### 3. High GDP growth, high cost development (High Scenario)

- GDP growth rate: From 9% in 2007 to 3% in 2100
- Energy price=Energy price table (Time)\*Input, in which, Input=1+ramp (0.2, 2007, 2100)
- Other unit production costs: Increasing just as fast as it grows before 2007.

The three conditions focus on the effect of GDP and costs, while the costs include both the energy cost affected by the rising energy price and other production costs. The results from the combined scenarios are compared below:

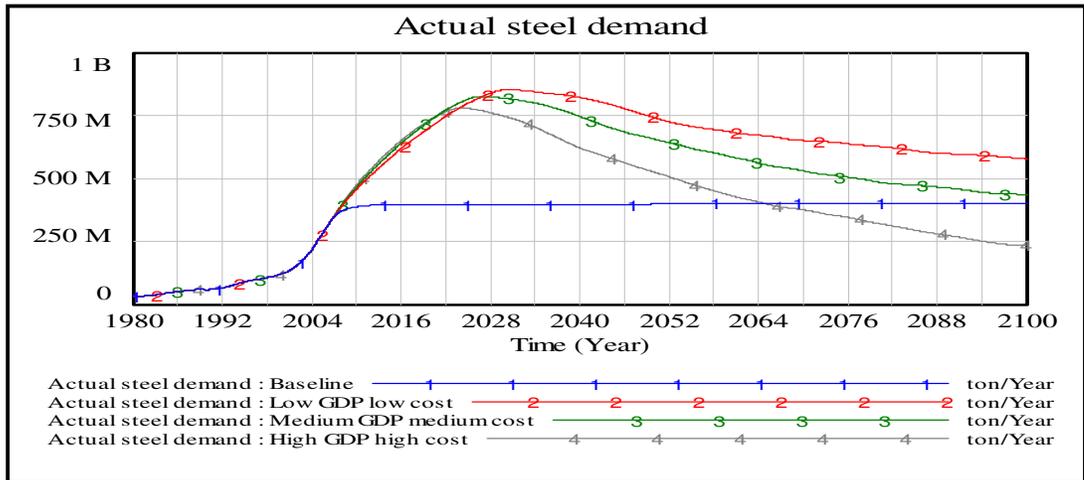
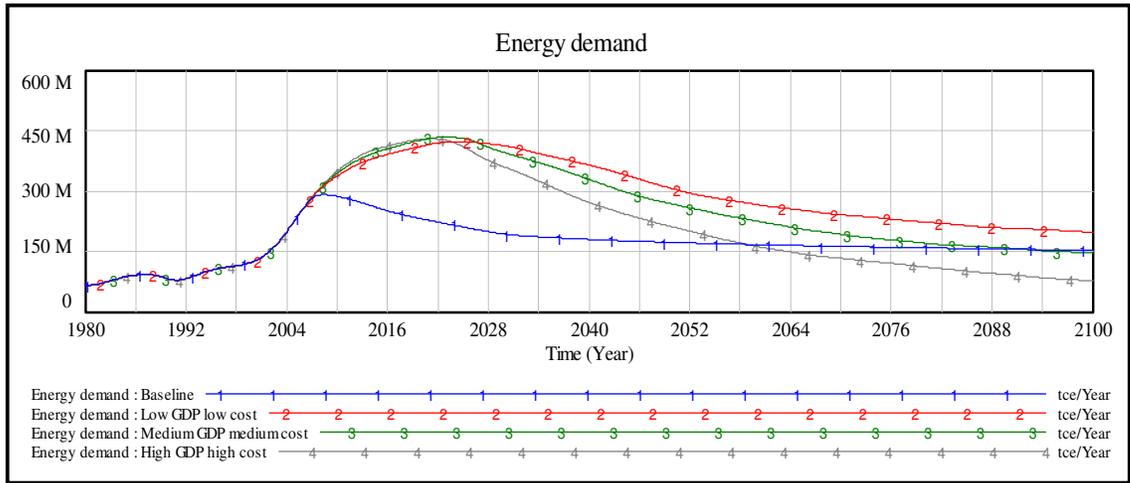


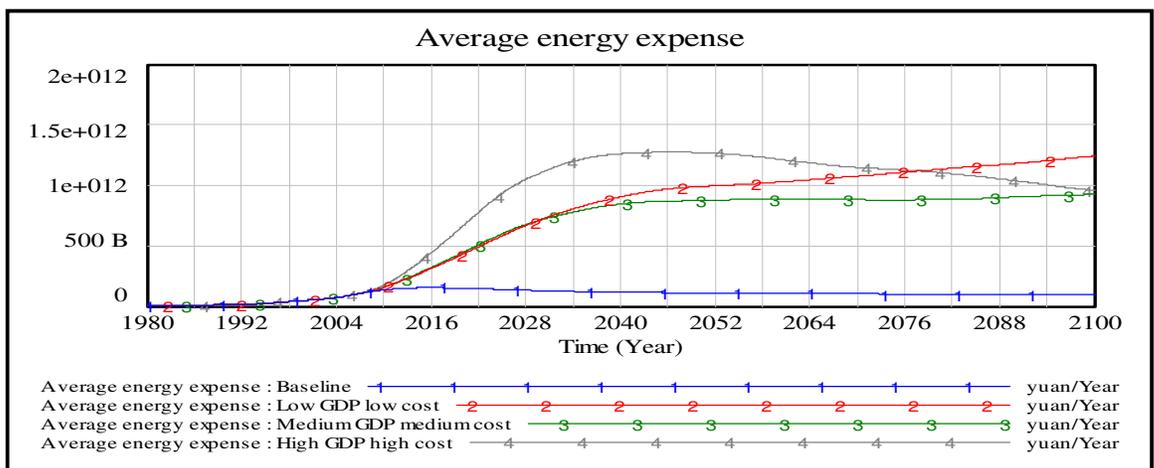
Fig 6.31 Actual Steel Demand under Combined Scenarios of Sensitivity Testing 4

As figure 6.31 shows, the general growth trend of the steel demand under above three combined scenarios are quite similar, they all have experienced S-shape growth then slowly declines. Such growth trend is mainly due to the GDP growth compared to the baseline case. Different rates of costs limit the development of the demand. As we explained in the sensitivity test 2 about the isolated effect of GDP growth, it is easy to conclude the higher the GDP grows, the earlier the demand will reach its peak. On the other hand, cost will influence the demand, the higher the cost to produce steel, the more quickly the demand will decline. The low scenario changes more smoothly than the other two, because it only has the cost effect from energy price rising, which means the cost effect has the least impact on its demand.



**Fig 6.32 Energy Demand under Combined Scenarios of Sensitivity Testing 4**

Figure 6.32 indicates that energy demand grows like steel demand. As we explained in the former tests, it is influenced by the steel demand. Although in the very short term, the energy demand in the low scenario is lower than the other two cases, the low cost and consequent slowly decreasing steel demand extend the time for the industry to require more energy. On the contrary, the cost in the high scenario may put a heavy pressure on steel industry. Such situation will not last forever; people would seek more efficient materials to replace steels due to high cost. In this sense, energy conservation can achieve a better result in the high scenario.



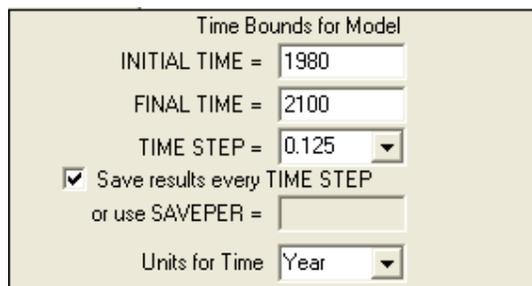
**Fig 6.33 Average Energy Expense under Combined Scenarios of Sensitivity Testing 4**

In the combined scenario, the energy expense will depend on both the energy demand and the energy price. (See figure 6.33) The behavior of each scenario in the above figure looks quite different from each other; the growth trends no longer follow the way the steel demand grows. First reason is that high energy price setting will lead to high energy expense; hence the energy expense in the high scenario grows much faster in the growth period of industrialization than that in the other two scenarios. After the steel demand reaches its peak, the condition will be slowly eased for all three scenarios. Due to faster decreasing energy demand in the high scenario, even though its energy price is quickly increasing, the energy expense is somehow offset by the decreasing demand, and slowly decreasing overtime. In the low scenario, the energy expense grows quite similar as it does in the medium case before the energy demand reaches it peak. The reason is that they have the same energy price setting; the difference will be only dependent on the energy demand. From Figure 6.32, it is easy to explain why the energy expense in low scenario will eventually increase faster than the medium case because of its higher energy demand.

Another purpose of introducing the combined scenarios is to provide typical problematic condition for policy analysis. We will raise it later in the policy chapter.

## 6.8 INTEGRATION ERROR TESTS

The System Dynamics model is usually formulated in continuous time. A time step needs to be selected for your model to yield an approximation of the underlying continuous dynamics accurate enough for your purpose. This test aims to find out whether the model behaviors are sensitive to the settings of time step. The test is taken by cutting the time step in half and running the model again.



Time Bounds for Model

INITIAL TIME = 1980

FINAL TIME = 2100

TIME STEP = 0.125

Save results every TIME STEP

or use SAVEPER =

Units for Time Year

**Fig 6.34 Time step setting in the model**

As the graph is shown above, the current time step used in the model is set at 0.125, and then we cut it into half and run the model at a time step of 0.0625. The results show that the model is not sensitive to the choice of time step.

## **6.9 SUMMARY**

Testing is an integral part of the iterative process of modeling. By continuously testing the assumptions and the sensitivity of results of the model, we can uncover important errors early, avoid costly rework, and generate insights throughout the project.

Based on the purpose of testing, we implement several tests in this chapter. After all kinds of tests, we can say, in general, the model is appropriate for the purpose of showing the dynamic mechanism of Chinese steel industry sub sector. As the structure assessment test shows, the structure of the model can properly represent the real world system with interrelationships according to our knowledge from the real world. Boundary and level of aggregation of the model are appropriate for the purpose of the study reflected from boundary adequacy test and structure assessment test. Moreover, the model has passed the dimensional consistency tests and integration error tests, and is able to work under extreme conditions. The sensitivity of behavior modes under different assumptions of exogenous inputs is tested to show the robustness of our conclusions to uncertainty of our assumptions.

# Chapter 7

## Policy Development

### 7.1 INTRODUCTION

In this chapter, policies aiming at easing high energy demand, CO<sub>2</sub> emissions and high energy expense during the transition period of steel industry are studied by means of simulation. Assessments and comments on the cost-effectiveness and implementation of policies are made in the conclusion part of the chapter.

The key variables that we want to show for the policy analysis are *Energy Demand* and *Average Energy Expense*. There are several reasons for doing this: Firstly, energy demand is an indicator that reflects how much energy is needed for steel industry, and is always a number of considerable concerns. Lower energy consumption in high energy intensive sectors contributes to energy conservation from the sustainable development point of view. In addition, reducing energy consumption perhaps is the most economical way for environmental protection, and the most effective solution for reducing energy expenditure because of increasing energy price. Secondly, energy expense for an energy intensive industry is vital; it can reflect the cost-effectiveness of policy regarding energy conservation.

We introduce a typical transition condition for the policy design. It is just the medium combined scenario in the sensitivity test of the former chapter.

- GDP growth rate: From 8% in 2007 to 2% in 2100.
- Energy price:=Energy price table (Time)\*Input, in which, Input=1+ramp (0.1, 2007, 2100)
- Other unit production costs: Increasing slowly after 2007. Half slope as the one used before 2007.

The scenario above will be depicted as “Without Policy” in model behavioral graphs. We will compare the no policy scenario with scenarios of policies.

There are two ways for steel industry to save energy and reduce energy expense: continuously develop energy efficiency technology with more powerful measures and adjusting steelmaking process by raising the proportion of more energy efficient way of steelmaking. Thus, Policies here are categorized into two kinds: energy efficiency technology development policy and steelmaking process improvement policy.

## **7.2 ENERGY EFFICIENCY TECHNOLOGY DEVELOPMENT POLICY**

Policies at this stage are intended to stimulate technological development. R&D investment, energy price and CO<sub>2</sub> emission are assumed to be the only incentives for energy-saving technology development in this particular model. Since it is hard to say which of these incentives is more important or more effective for technological improvement, we assume they have the same weight at beginning. The optimization and analysis on the weight for each of the incentives is studied after the individual policy analysis.

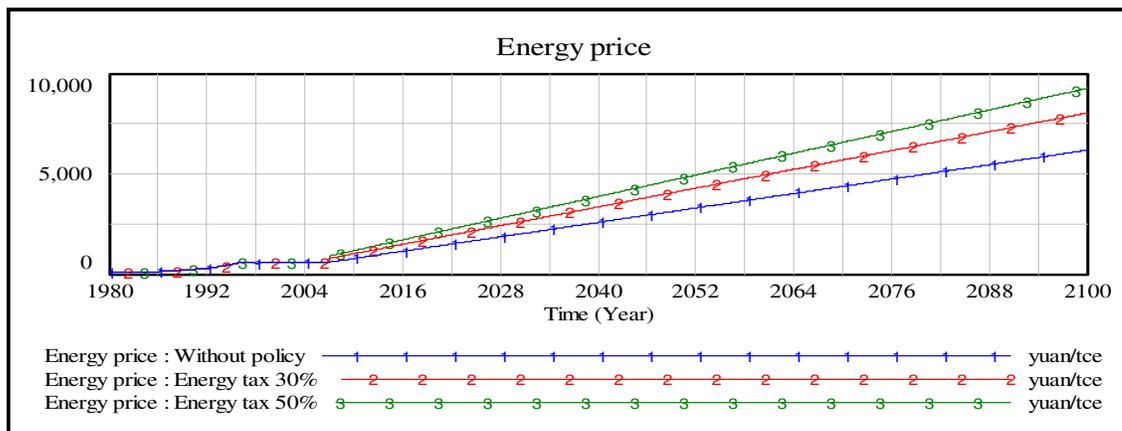
### **7.2.1 Policy 1: Energy Tax**

With respect to energy tax, the government in China so far has not levied carbon tax, namely the CO<sub>2</sub> tax. Besides the carbon tax, the energy tax, which is called resource tax in China, is levied at a low rate compared to its real price. While the government thinks that the current energy price can not reflect its economic value and scarcity of natural resources, pollution tax aiming at reduce CO<sub>2</sub> is scheduled to be levied and even higher resource tax rate is going to be raised in the near future. In this particular model, we combined pollution tax with resource tax to simplify the model, and the combined tax is just called energy tax. We consider “energy tax” as one of the policies. In order to find its practicability and effect, we may also need to consider to what extent should we levy on energy price and when shall we implement the policy? Does it help if we implement the policy in the early period?

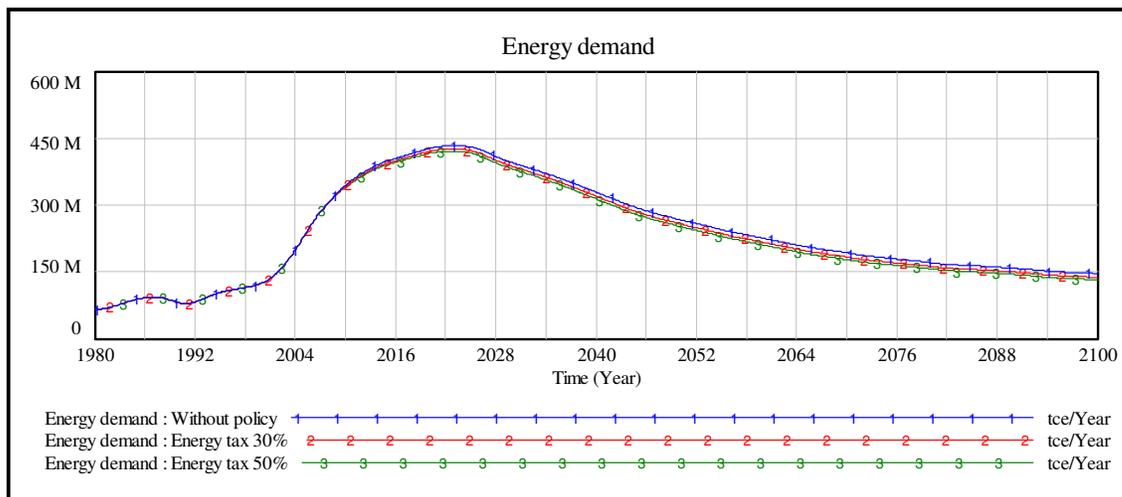
We will test the magnitude of tax rate first from 2007;

- Run1: Energy tax rate =30%
- Run2: Energy tax rate =50%

Simulation results are shown as below:

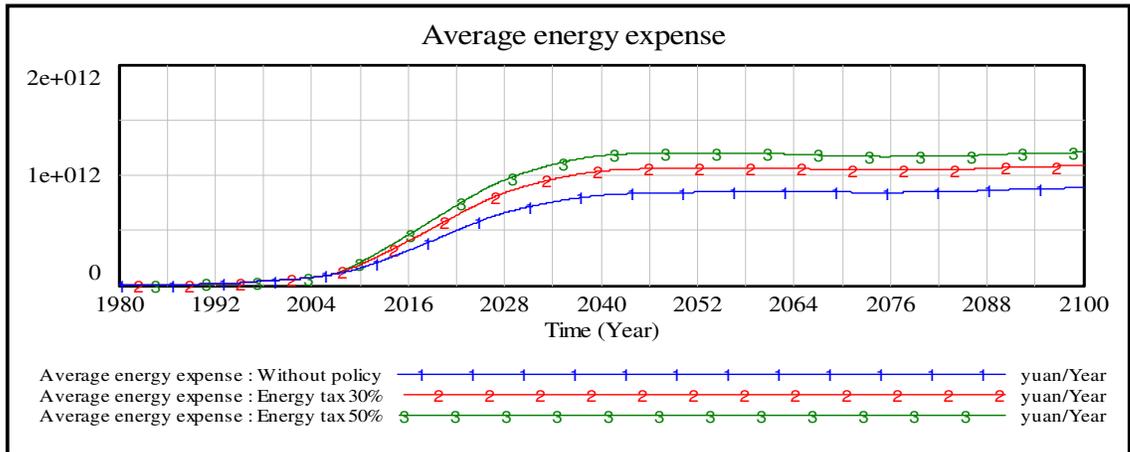


**Fig 7.1 Energy Price under Different Tax Rate for Policy 1**



**Fig 7.2 Energy Demand under Different Tax Rate for Policy 1**

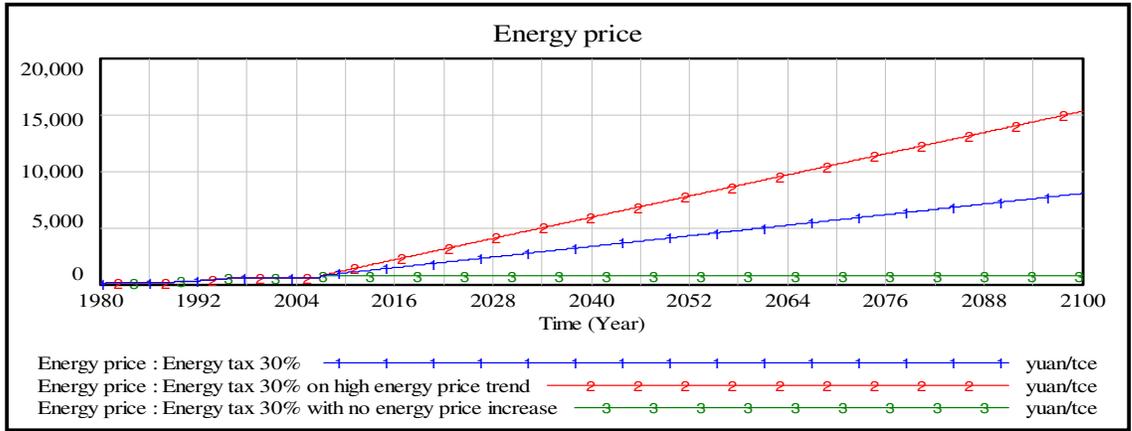
From figure 7.1, we know that the energy price in the tax scenarios increases proportional to the original energy price increase. The higher the tax rate, the higher it increases over time. Figure 7.2 shows even with 50% tax, the energy demand seems to drop at a rather small extent from the condition without policy.



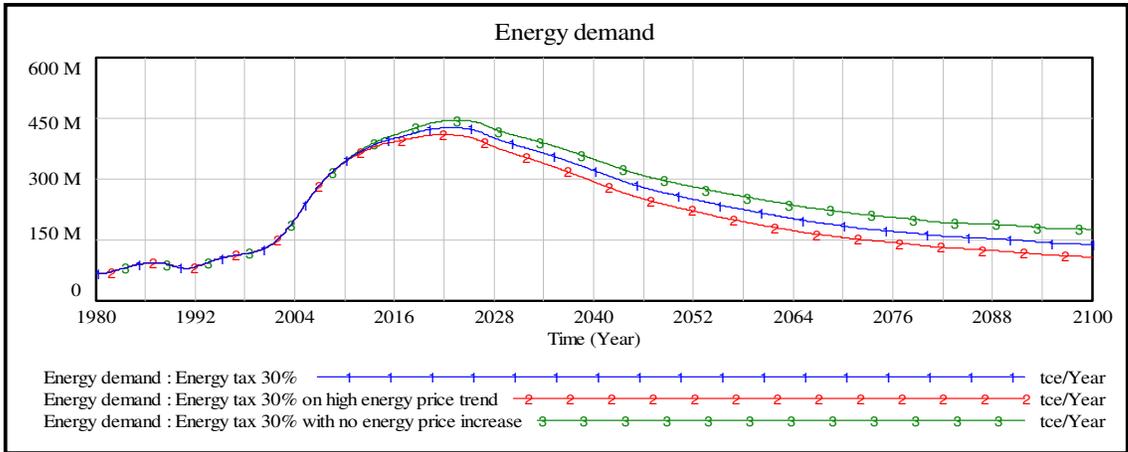
**Fig 7.3 Average Energy Expense under Different Tax Rate for Policy 1**

The policy aims at raising energy cost in order to influence the steel demand, and then eventually leads to a reduction on the energy demand. Figure 7.2 and 7.3 show that energy tax in this case can not effectively achieve expected result; on the contrary, it largely increases the energy expense of steel industry. Energy cost amounts to around 30% of the production cost, and the other production costs are increasing at the same time. The increment of energy cost only influence the 30% of production cost, and to large extent, the increment is offset by the improvement of energy efficiency technology (by consuming less energy to make a saving on energy cost). Hence only if the proportion of energy cost increases largely among the production cost can the energy demand be reduced substantially by implementing energy tax. In order to test whether energy tax policy takes effect depending on different growth trend of energy price, the assumption that we made for energy price increase at the beginning of this chapter as a typical transition condition needs to be changed. Both high energy price growth trend and constant energy price pattern will be tested as the problematic condition for testing energy tax policy. The tax rate is set at 30% for all scenarios. The simulation is run as following:

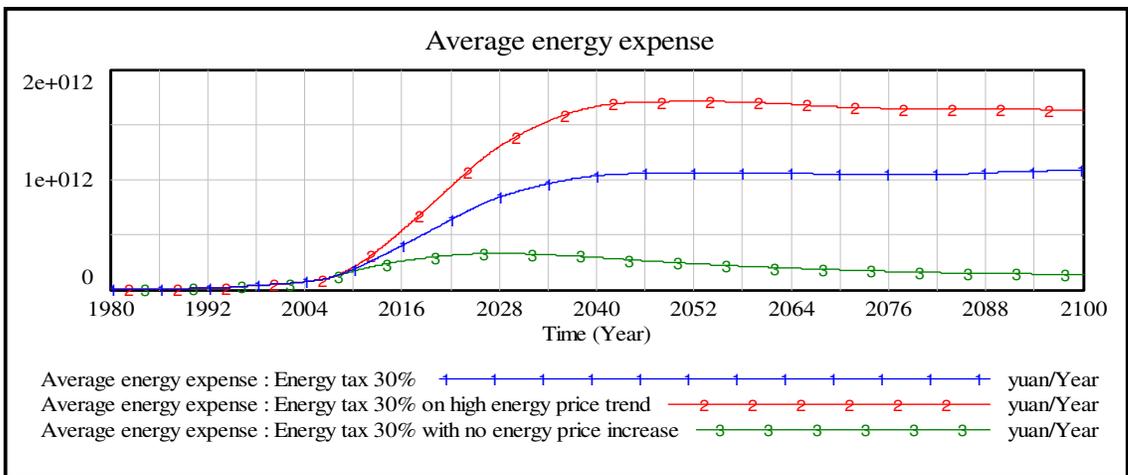
- Energy tax 30% (Reference energy price increase trend, ramp slope = 0.1)
- Energy tax on high energy price trend (ramp slope = 0.2)
- Energy tax with no energy price increase (ramp slope = 0)



**Fig 7.4 Energy Price under Different Price Pattern**



**Fig 7.5 Energy Demand with Energy Tax under Different Price Pattern**



**Fig 7.6 Average Energy Expense with Energy Tax under Different Price Pattern**

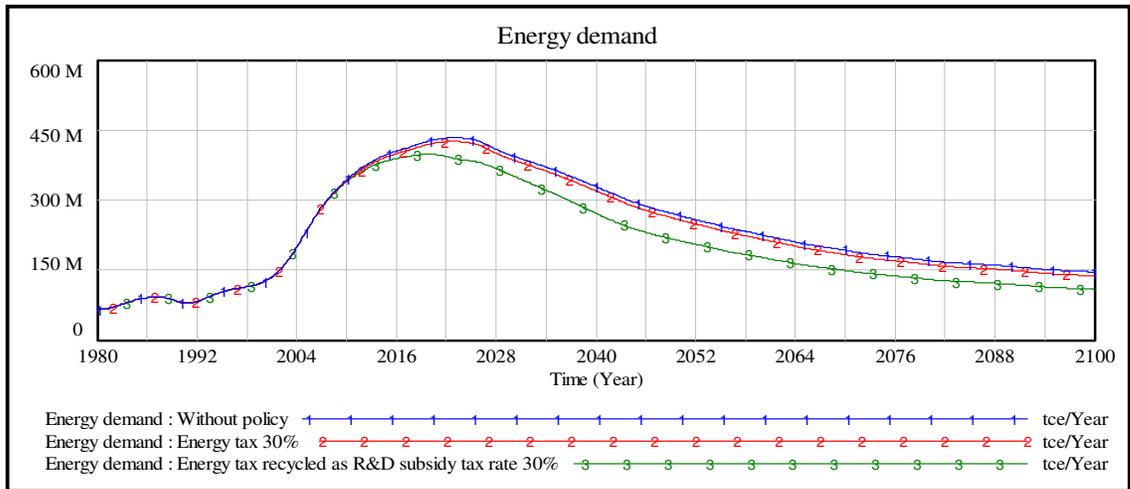
Figure 7.5 and 7.6 indicate that different energy price future settings with same energy tax rate produce fairly different behavior patterns. With high energy growth trend, the policy has the greatest impact on energy demand, which effectively promotes the energy conservation. While the expense is correspondingly the highest among the three behavior patterns due to proportional energy tax increase. Thus, if the energy price increases quickly in the future, implementing energy tax will not be a cost-effective policy. For the case with no energy price increase, energy tax policy will have almost no effect. The reason is that the energy tax will always be kept at a constant and low rate; too low energy tax can not attract much attention from the steel industry. Instead, the industry will be willing to pay the tax in order to consume more energy because of low extra expenditure on energy. Thus, constant energy price pattern with energy tax implemented can not achieve the original purpose of energy conservation.

The tax policy for such situation in this particular study can not be called cost-effective. If we test such policy in the early period, the result obviously can be imagined: the industry may spend a lot on energy expense with unapparent effect on energy conservation. So in this case, we do not test the policy in the early period.

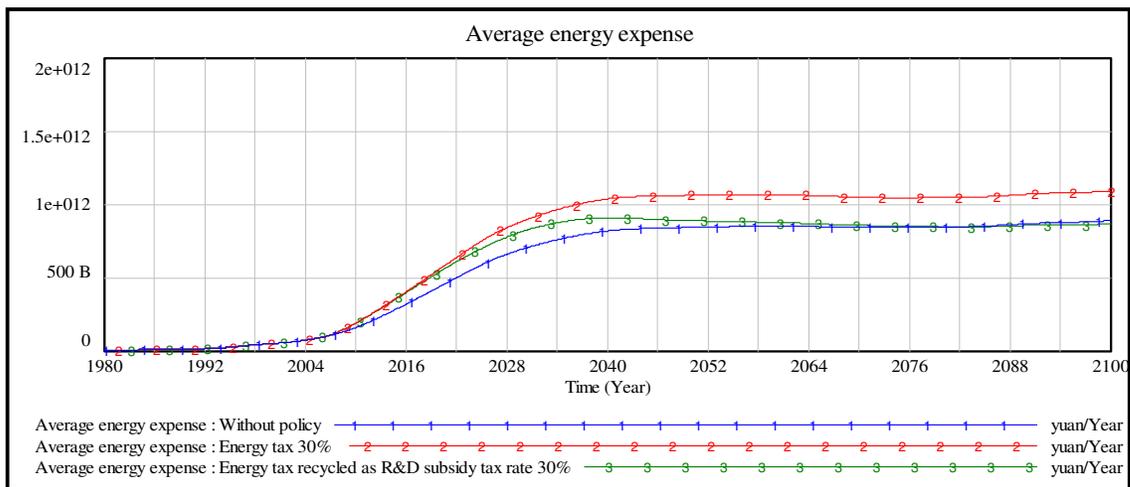
### **7.2.2 Policy 2: Energy Tax Recycled as R&D Subsidy**

R&D investment could be subsidized by the government in order to promote the energy efficiency technological development. But to develop technology needs a long time and it may cost a lot, which in turn puts financial pressure on government's budget. There is no such thing as a free lunch, the energy tax revenue from the first policy could be transformed or recycled in the form of subsidy on R&D investment.

So we test the policy in the following way: the tax rate is set at 30% in order to compare the case in the energy tax policy. All this tax revenue will be transformed into R&D subsidy from 2007. See the behaviors below for details:



**Fig 7.7 Energy Demand under Policy 2**

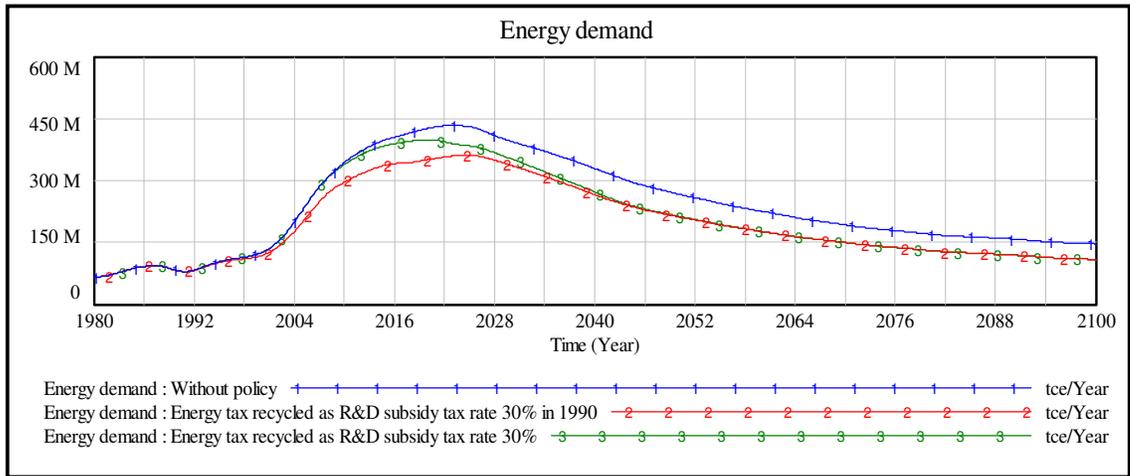


**Fig 7.8 Average Energy Expense under Policy 2**

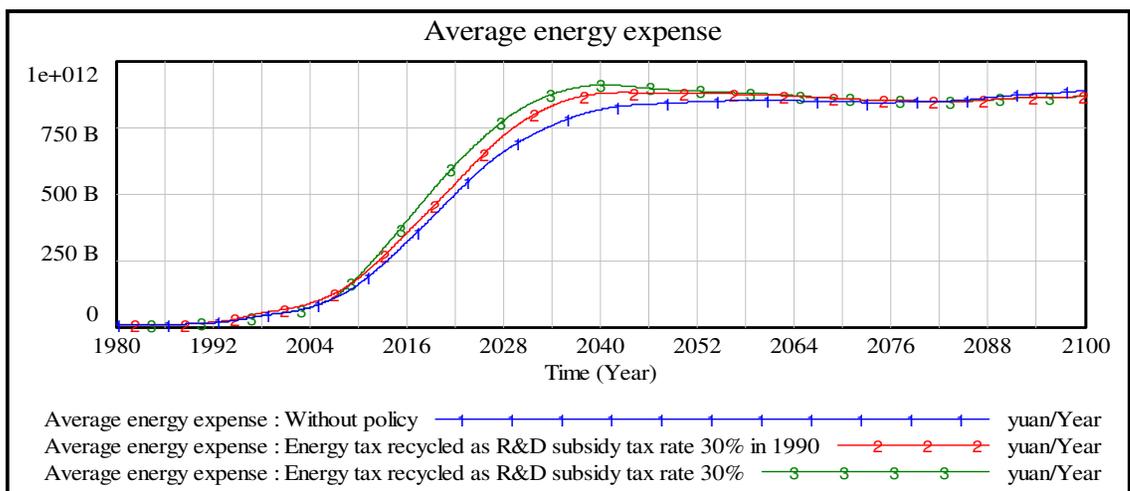
Figure 7.7 and 7.8 indicate that the policy of converting energy tax to R&D subsidy has a remarkable improvement than the tax policy alone. Energy demand has been cut both through the tax effect and more efficient energy use due to faster advancement of technology subsidized by government. As for the energy expense, both tax and efficient use of energy have impacts as well, they offset each other. Not like the tax policy alone, current policy with tax recycled only put a small weight on the industry's energy expense. But the discrepancy in energy expense between the policy scenario and without policy increases over time during the transition period. That's because the energy demand keeps increasing in any scenario during the transition period and the energy price is assumed to increase as well with proportional tax

added. The average energy expense will reach its peak after the transition period has just passed because no more energy demand is needed. In a long run after the transition period, with limited technological development, the potential to improve energy efficiency is small, and the energy price with tax still increases. Hence the industry can not reduce its energy expenditure a lot from the case without policy. While in general, current policy can be called cost-effective, energy conservation has been achieved to a large degree with comparatively small portion of energy expense increasing.

What if we implement the same policy in early period? (In 1990)



**Fig 7.9 Energy Demand when the tax recycled policy implemented in early period**



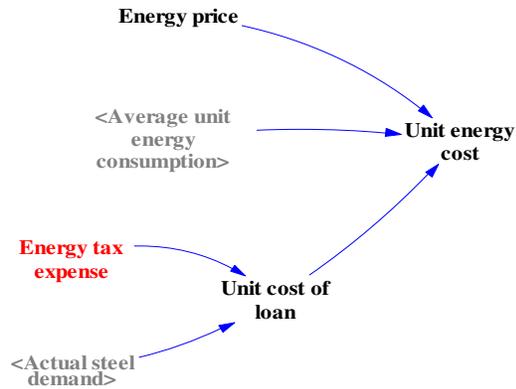
**Fig 7.10 Average Energy Expense when the tax recycled policy implemented in early period**

From figure 7.9 and 7.10, obviously, policy implemented in the early period could produce better results during the transition period. The behavior of energy demand during the transition period looks more smoothly, which means the industry can pass the transition period easily without higher energy demand needed. Since energy efficiency was low in early 90s, the policy introduced large amount of R&D investment from tax revenue in early 90s, which promotes the energy efficiency technology development quickly to a level that can only be reached late after 2007. In this case, energy conservation can be further achieved in the early period. Even the energy expense did increase more than that in the other cases because of early tax levied; the condition will be eased when the industry can produce steel with less energy compared to the condition in which policy is implemented later.

For the tax recycled as subsidy policy, there is an underlying assumption: the government will invest all the tax revenue from industry as the subsidy back to the industry. While in the real world, it does not need to do like that, tax revenue from steel industry or part of it can be given to other sectors in order to achieve more significant effect in energy conservation or other needs. Just based on energy conservation and environmental purpose, the government will have to investigate which sector or industry has comparatively larger potential to improve its energy efficiency or pollution condition with R&D subsidy.

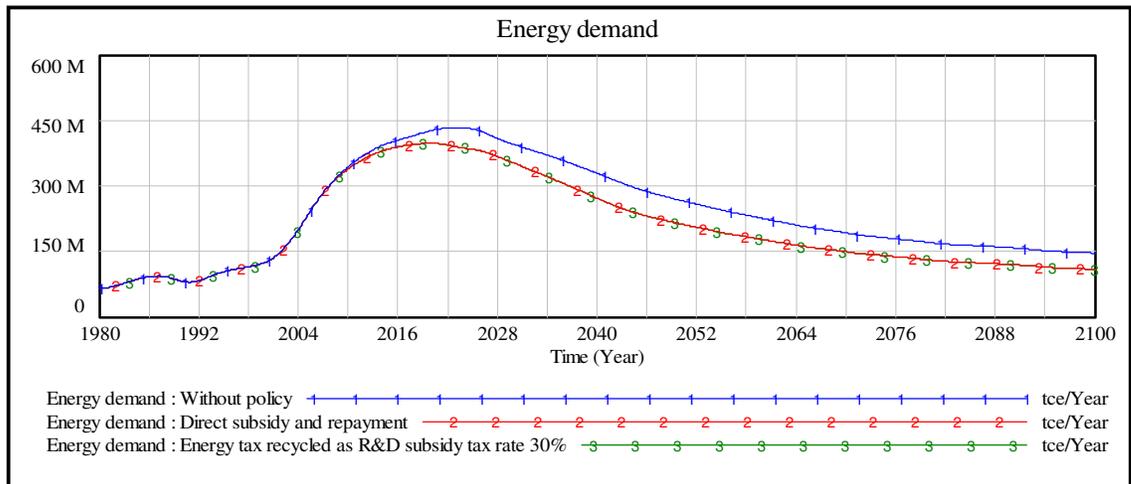
### **7.2.3 Policy 3: Direct Government Subsidy and Repayment from the Steel Industry**

Direct Government subsidy is mostly common, while doing that probably will produce social welfare loss. To keep balance in social welfare, we test the policy by making the steel industry pay back the subsidy at the same time when there is subsidy provided by the government on R&D. This is a way to test the cost-effectiveness of subsidy on energy conservation. In this case, the government subsidy can be regarded as a loan to the steel industry; it is paid back at the same year, which will become an additional expenditure on the industry's energy expense. Since we want to find out the effectiveness of this policy, so we assume the industry will accept this "loan" from the government. When the steel industry pays back the loan to the government, it is distributed as a part of unit cost. We classify such unit cost into the unit energy cost. Thus the above idea is formulated by adding additional policy structure to the original energy cost sub sector. See the structure below for more details:

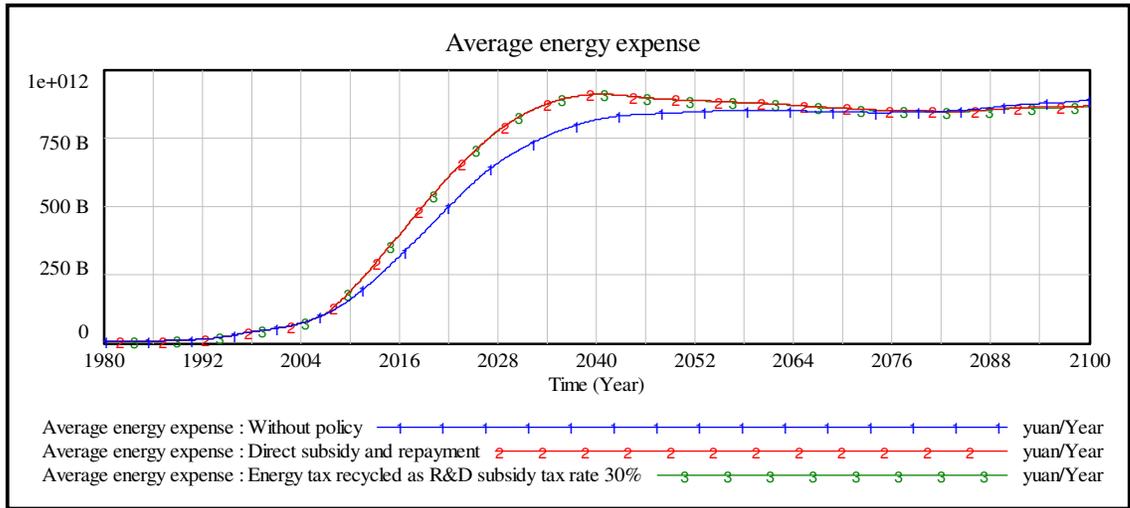


**Fig 7.11 Formulation of Unit Energy Cost When Industry Pay back Subsidy as a Loan**

The direct government subsidy is set to be equal to the energy tax expense introduced in the former policy numerically (Tax rate =30%). So the energy tax expense in the above graph will be the energy tax times the energy demand. Then the additional unit cost of loan will be the energy tax expense divided by the steel demand. See the figures below as a result of the current policy:



**Fig 7.12 Energy Demand under Policy 3**



**Fig 7.13 Average Energy Expense under Policy 3**

From figure 7.12 and 7.13, we almost can not see any difference between the policy 2 and policy 3, the behaviors look like identical. The reason is that the two policies are just opposite in the way that they pay tax or loan and benefit from subsidy. For the energy tax recycled as subsidy policy, the industry pay the tax first, and benefits from what it actually paid through other form of financial return as a subsidy, the amount are just the same. When the tax is levied, the energy cost is raised due to the price increase. The current policy as it is illustrated above is actually a loan to the steel industry, the industry benefits from the subsidy to the R&D, but the repayment of this subsidy will be converted as an additional cost into the energy cost. Both the tax and the unit loan cost aim to raise the energy cost, so the equation in the current policy for unit energy cost can be converted to a form which is equal to the result of energy price with tax.

$$\begin{aligned}
 \text{Unit energy cost} &= \text{Average unit energy consumption} * \text{Energy price} + \text{Unit cost of loan} \\
 &= \text{Average unit energy consumption} * \text{Energy price} + \frac{\text{Energy tax expense}}{\text{Actual Steel Demand}} \\
 &= \text{Average unit energy consumption} * \text{Energy price} + \frac{\text{Energy tax} * \text{Total energy demand}}{\text{Actual Steel Demand}} \\
 &= \text{Average unit energy consumption} * \text{Energy price} + \text{Energy tax} * \text{Average unit energy consumption} \\
 &= \text{Average unit energy consumption} * (\text{Energy price} + \text{Energy tax})
 \end{aligned}$$

Although the results are the same, but it does not mean they can be treated in the same way. For the subsidy as a loan policy, it is hard to say whether the steel industry will accept this

loan, since the benefit can only be seen in a long run, while people are usually myopic. Therefore, it turns out to be the government's responsibility to enhance stronger or even compulsory energy conservation measures.

Since the current policy has almost the same behavior as the tax recycled as subsidy policy, the result of early implementation will be same as well, thus there is no need to show it here.

#### **7.2.4 Policy Optimization**

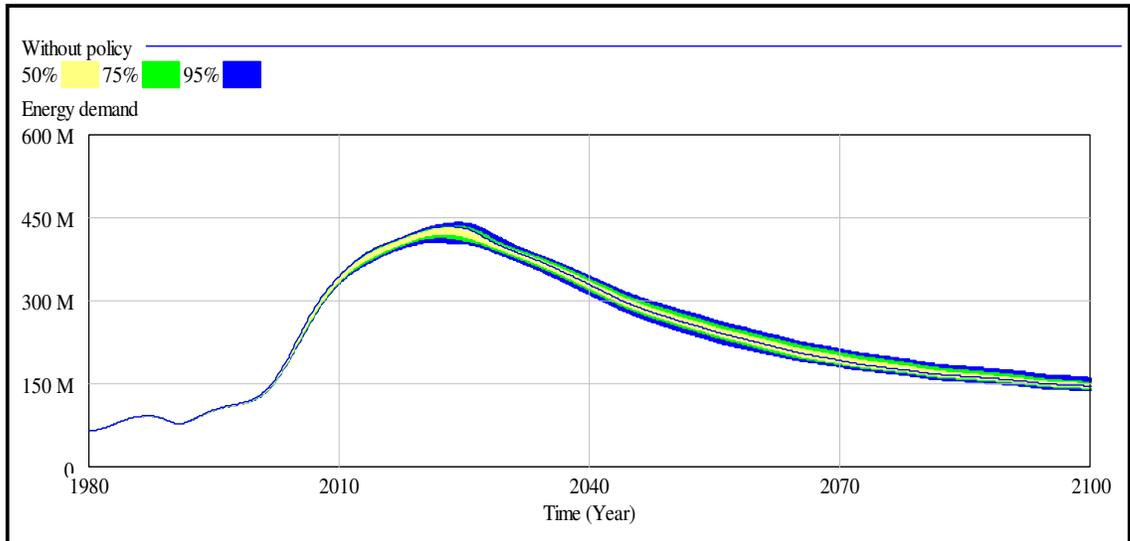
Former policy analysis with same weight on three incentives shows that it is hard to reduce energy demand with lower energy expense. The default weights for three incentives are set at 1 at beginning, and the technological change depend on the incentive times its respective weight. The incentives in this particular model like R&D investment, energy price and CO<sub>2</sub> emissions are modeled using their relative value compared to the level in the initial year, namely 1980. Hence the bigger the relative value it is, the more the importance we should attach to. In this case, we will try to adjust the values of each weight in order to maximize the technological improvement. Before we start to find out the optimal weights combination, we would like to see sensitivity of weights changing on model behaviors.

##### **Weight Sensitivity Testing:**

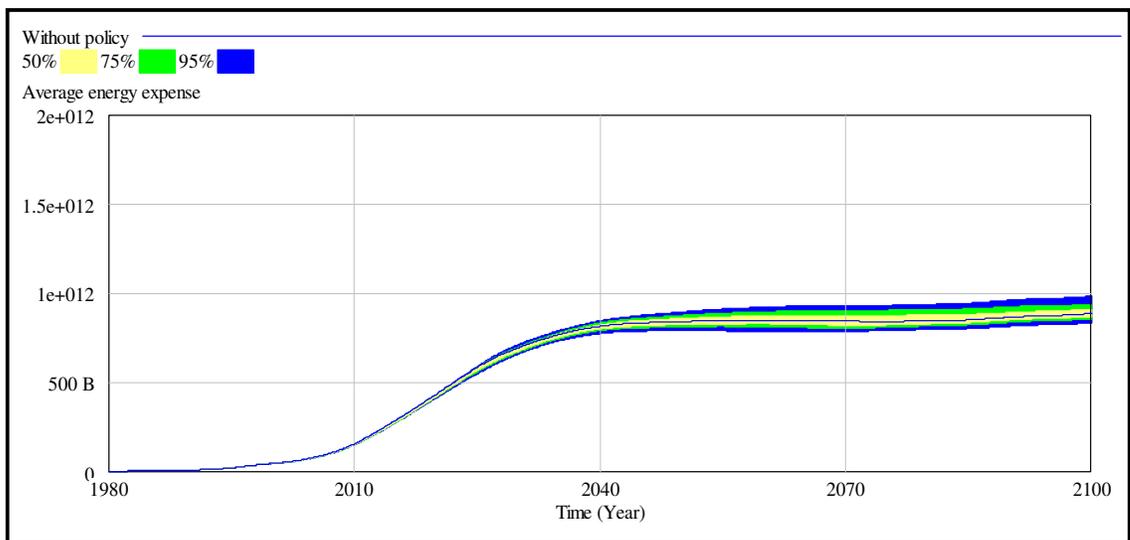
The normalized sum of the three weights is 1, before we do the weight optimization, all three weights equal to each other, so each of its normalized weight is around 33% at beginning. Now we will do a sensitivity test on all three weights, each will change between 0 and 1. The results will show a scale ranging from best result to the worst based on the combination of the three weights. We do the test in the following way:

- "Weight for CO<sub>2</sub>" ranges from 0 to 1
- "Weight for energy price" ranges from 0 to 1
- "Weight for R&D" ranges from 0 to 1

The sensitivity test is simulated based on the combination of above weights. The simulation results are shown below:



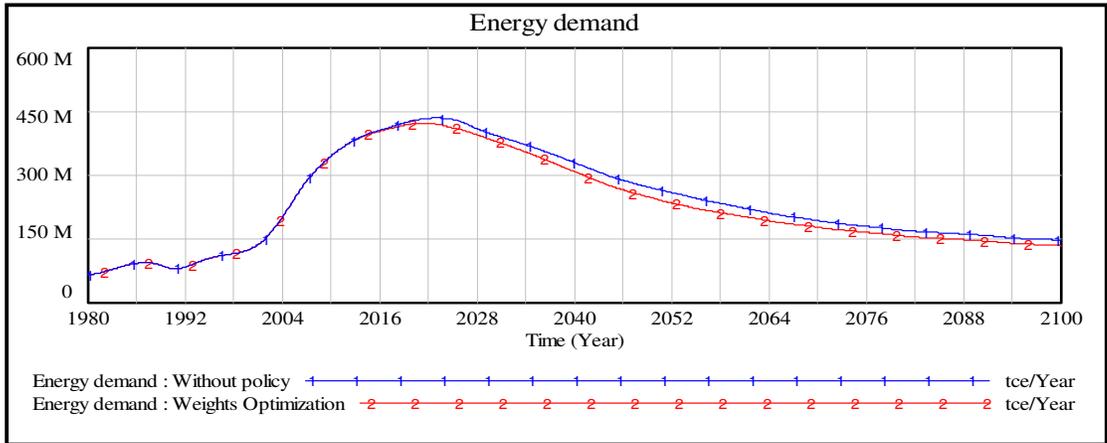
**Fig 7.14 Energy Demand under Weight Sensitivity Testing**



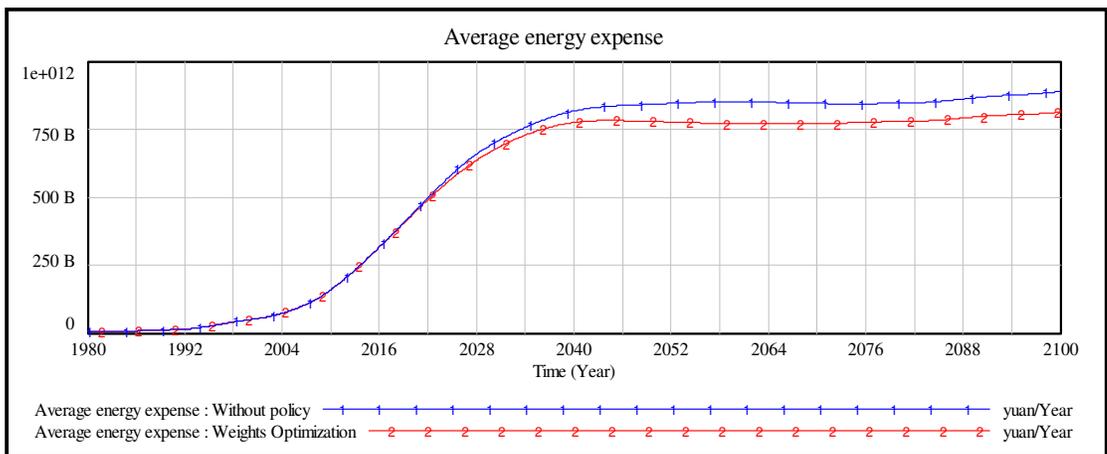
**Fig 7.15 Average Energy Expense under Weight Sensitivity Testing**

Figure 7.14 and 7.15 indicate there is obvious change in terms of different weights combinations. Optimal weights can lead to maximum reduction on energy demand and energy expense. In reality, the weights here refer to the importance of incentives (including R&D investment) on technological change. By raising or reducing the weight of respective incentive, steel industry adjusts its emphasis, taking measures to favor its emphasis and thinking little of other incentives.

By optimizing the weights, the former policies can be implemented based on the “improved” model behavior. By looking at the behaviors of these three incentives, we find that the relative R&D investment has the biggest increment in the future. So we set the weight for R&D to 100, keep the other two weights at 1 as usual from 2007, which mean the industry will attach more importance on the R&D investment, thinking little of other incentives. The model behaviors with optimal weights settings are shown below with no other policies implemented.



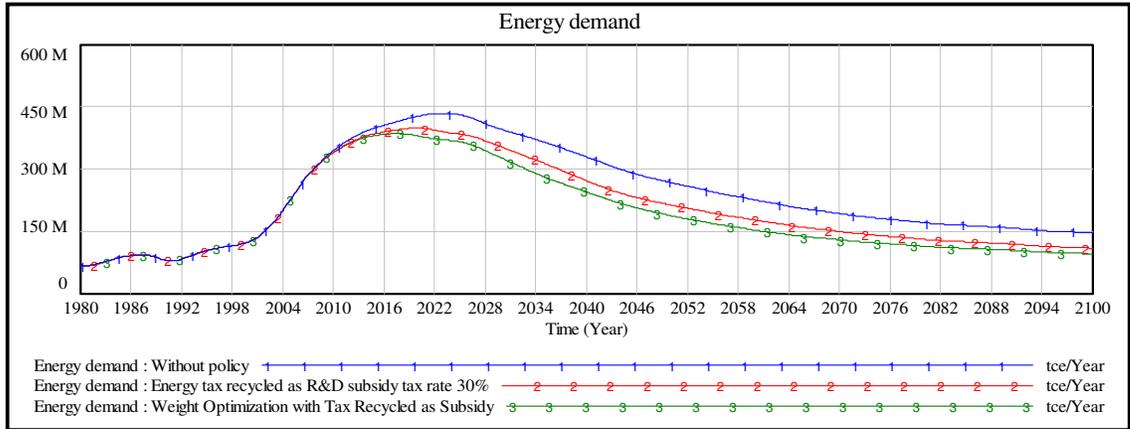
**Fig 7.16 Energy Demand under Optimal Weights**



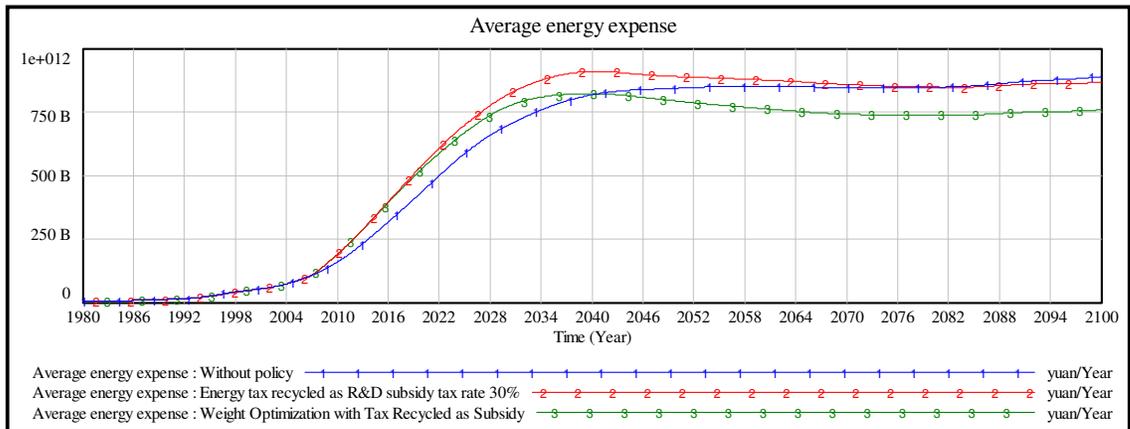
**Fig 7.17 Average Energy Expense under Optimal Weights**

The behaviors of these key variables have little improvement. While when we have raised the weight for R&D investment to 100, the other two weights become insignificant, so incentives from energy price increase and CO<sub>2</sub> emission can almost be neglected. In this case, subsidizing R&D investment will be much more effective than levying energy tax. Among the policies regarding subsidy, the tax recycled as subsidy should be the most cost-effective. So

we will show such policy with optimal weights compared to the policy without weights changed. See the behavioral graphs below:



**Fig 7.18 Energy Demand under Tax Recycled to Subsidy with Optimal Weight**



**Fig 7.19 Average Energy Expense under Tax Recycled to Subsidy with Optimal Weight**

Figure 7.18 shows that the energy demand in the optimal policy is further reduced; this improvement makes the industry spend less on its energy expense. After the transition period, the energy expense will become lower than the case without policy. Note that whatever policy is implemented, the energy expense in a long run will slowly increase due to continuously energy price increasing and almost no potential of technical improvement on energy efficiency.

Different weights of incentives should be treated in different ways. More attention should be attached to the incentive with the highest weight. In the real world, the importance of incentives for the steel industry to develop energy efficiency technology varies in terms of different time period or government policies. If the incentive from energy price increases rather rapidly in the future due to resource scarcity or market supply and demand, policies related to energy tax may become more effective.

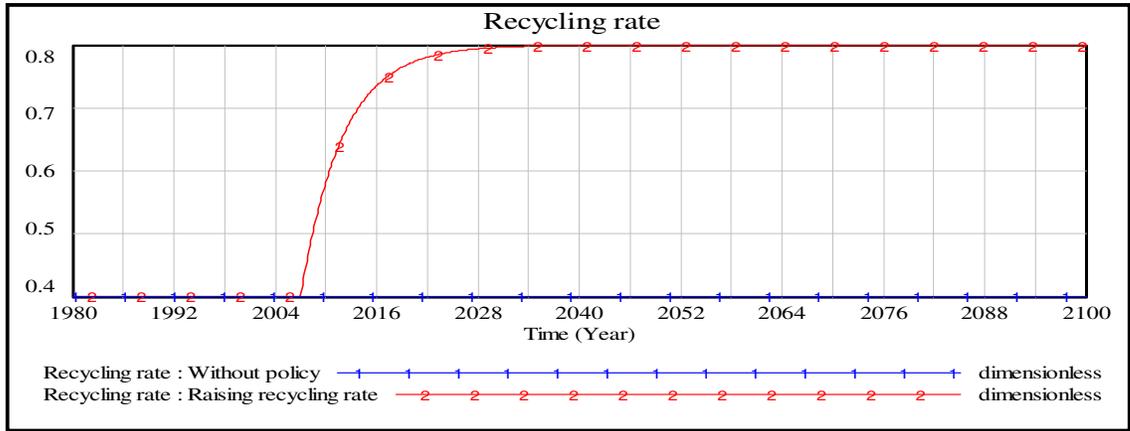
### **7.3 STEELMAKING PROCESS IMPROVEMENT POLICY**

Energy efficient steelmaking process is encouraged from sustainable development point of view. Among all three steelmaking process, EAF is regarded as the one that promotes energy conservation and environmental protection. As it is explained in the problem description chapter, scrapped steel resource is the main obstacle to develop EAF in China for the current time period. Scrapped steel mainly comes from the recycling of depreciated social capitals; the cycle period is around 18 years in China. Taking the loss and recycling rate of the current level into account, the situation described in the former chapter will be greatly eased in 10 to 15 years. Besides the gradual increment of depreciated steels, the steel industry can raise another technical factor: the scrapped steel recycling rate. The recycling rate has been kept around 40% in the past 2 decades, while this technical parameter in developed countries is high. For instance, the recycling rate in Germany and United States is 80% and 67% respectively in 2004. This condition indicates China has large potential to raise this technical parameter.

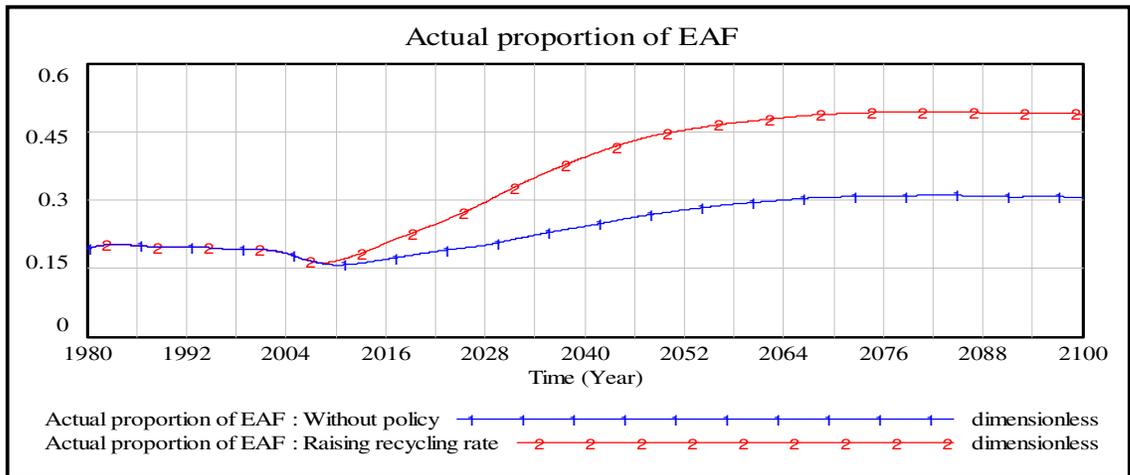
The policy at this stage aims to raise the proportion of EAF among steelmaking process. Raising the recycling rate is the main policy of improving steelmaking process for this particular model. Such a technical improvement needs more attention from the industry, and the government may need to make relevant regulations to help the industry recycle more scrapped steels from social capitals. All of which take time to occur, so no body has the idea to what extent we can raise the recycling rate. Suppose the improvement of recycling rate doubled in several decades, to reach this purpose, we adjust the step height in the step function which is the exogenous input on the recycling rate and run the model as following:

- Step height = 1, due to the long delay, the recycling rate will be raised to 0.8 eventually

Simulation results are shown as below:



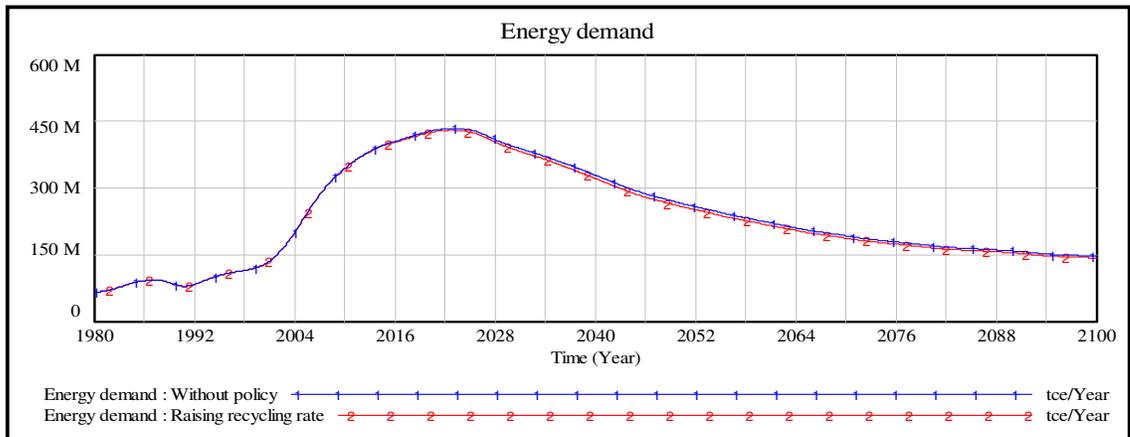
**Fig 7.20 Recycling Rate under Technical Process Improvement Policy**



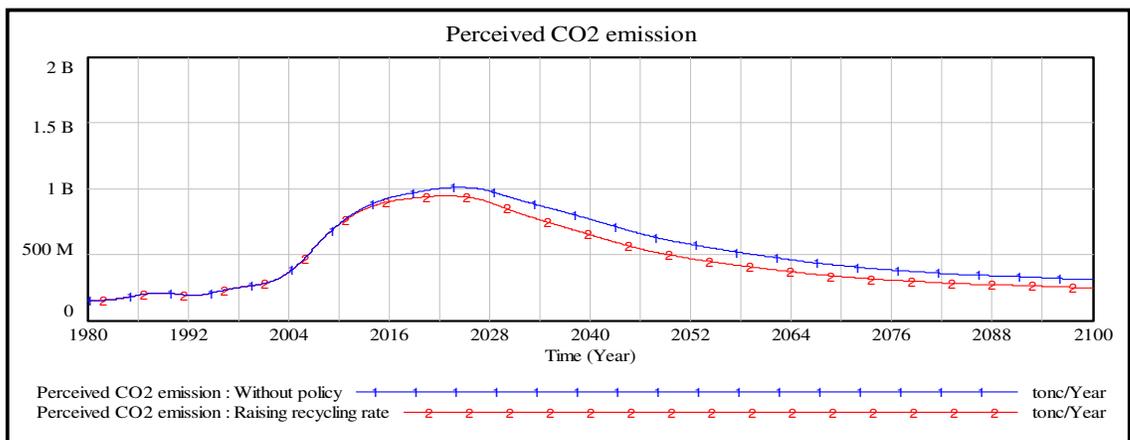
**Fig 7.21 Actual Proportion of EAF under Technical Process Improvement Policy**

Figure 7.20 shows a gradual step increase in doubling the recycling rate in around 30 years. Such a long time delay reflects that it takes a long time to develop technology and realize practical implementation. Note that we do not know the actual time to develop and implement the technology regarding recycling rate, this policy test is merely to find out the effectiveness of raising the proportion of EAF on energy conservation and CO<sub>2</sub> emission. When the recycling rate is raised, more recycled scrapped steels are available; the industry becomes not as dependent on importing scrapped steels as past. The increasing scrapped steel resource will meet the domestic need and eventually steel industry will be self-sufficient in its scrapped steels resource. When the supply of scrapped steels increase, the price of scrapped steels will

drop, which makes steel plants invest more on scrapped steels based steelmaking way, namely EAF to replace the others. Such condition leads to a gradual increase on the proportion of EAF. When the time has passed the transition period, the steel demand will gradually decrease, which leads to a reduction on steel scrapping rate each year. No more recycled scrapped steels will eventually limit the EAF proportion.



**Fig 7.22 Energy Demand under Technical Process Improvement Policy**



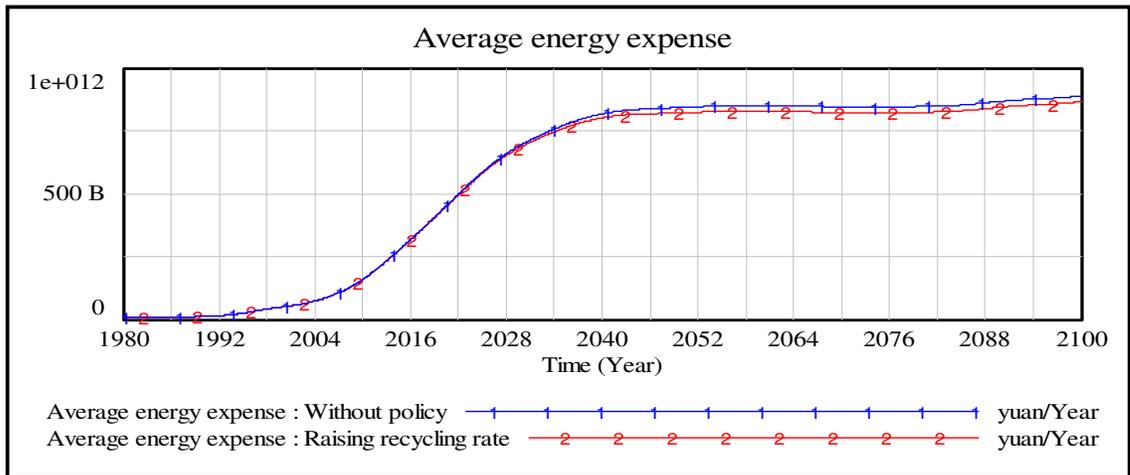
**Fig 7.23 Perceived CO2 Emission under Technical Process Improvement Policy**

In the former policy analysis or testing in chapter 6, we do not show the behavior of CO<sub>2</sub> emission, because it is closely related to energy demand and unit carbon emission. Different steelmaking ways decide the carbon emission per unit energy used, since no former policy or testing has strong impact on the proportion of steelmaking ways, the index of carbon emission is almost kept constant. Thus, the behavior of CO<sub>2</sub> emission looks quite similar to the total

energy demand. In this case, raising EAF proportion will not only reduce the energy consumption but also significantly reduce the CO<sub>2</sub> emission.

From figure 7.22 and 7.23, it is obvious to see different impacts of the policy on energy demand and CO<sub>2</sub> emission. Adjusting the proportions of different steelmaking processes influences the energy demand through improving energy efficiency. But the potential to improve energy efficiency becomes low in a long run, in addition, EAF only avoid the iron making process which is not a big saving compared to the total energy consumption for the whole steelmaking process. Thus we can not see substantial improving in energy conservation.

The condition is different for CO<sub>2</sub> emission, using EAF to make steel can save ¾ of the energy required by OHF or BOF. If the proportion of EAF is raised as figure 7.23 shows, then a dramatic reduction on carbon emission per unit energy used can be achieved. Thus, there is a significant reduction on CO<sub>2</sub> emission.



**Fig 7.24 Average Energy Expense under Technical Process Improvement Policy**

Current policy can to some extent reduce energy expense through reducing energy demand even though the reduction is small. We do not consider the policy implemented in early period in this case. Due to low cumulative steel resource in historical time, the depreciation of social capital is low. Even though the recycling rate is high; there are not sufficient scrapped steels to recycle. Thus the policy is not appropriate to be implemented in early period.

## 7.4 CONCLUSIONS AND IMPLEMENTATIONS

From the graphs shown in all kinds of policy analysis above, we know that the energy demand will eventually decline due to no more need of steels even there is no policy implemented. This will happen during the later stage of industrialization. As a main energy source for steelmaking and electricity generation, the reserve of coal is limited. For sustainable development, the country can not wait until the energy demand declines itself. The above policies aim to promote energy conservation and CO<sub>2</sub> emission reduction. While not all of them have its realistic sense, some of them can achieve good results but with high expenditure, some of them are only policy suggestions, which mean they are hard to be implemented in reality. To assess all the policies we described above, cost-effective and difficulties in implementation are our judgment index. A summary table is listed below:

CATEGORY	POLICY	ENERGY CONSERVATION	CO <sub>2</sub> EMISSION	ENERGY EXPENSE INCREMENT	IMPLEMENTATION
Energy Efficiency Technology Development Policy	Energy Tax	Little	Little	High	Medium
	Energy Tax Recycled as Subsidy	Large	Large	Low	Medium
	Direct Subsidy with Repayment	Large	Large	Low	Difficult
	Policies with Optimal Weights	Large	Large	Low	Medium
Steelmaking Process Improvement Policy	Raising EAF Proportion	Little	Large	Low	Easy

**Table 7.1 Policy Assessment**

Note the above policy assessment is made based on our assumptions about the future energy price, GDP and unit other cost growth setting in the beginning of this chapter. It is hard to say what happens to these factors in the future in reality. The effectiveness of the policies may to some extent depend on the future behavior of such factors. Just based on the settings in this beginning of this policy chapter, energy tax converting into subsidy seems to be the most effective policy though difficult to implement. While policy designs always need to take real

world issues into consideration. Discussions about implementations of above policies are raised below:

Energy taxes, based either on carbon content or particular fuels, would allow energy users to trade off the relative merits of paying the penalties versus adopting new kinds of energy or technologies to limit scarce and carbon intensive energy use and avoid carbon emissions. Some countries have already proposed energy tax, more specifically carbon tax. Finland has gone the furthest by introducing a \$6 per ton tax on fossil fuels in its 1990 Finance Act; Sweden is considering a much higher tax of \$40 per ton. Even so, taxes of greater magnitude will most likely be required to achieve dramatic reductions in the future.

The effect of energy tax is little both in energy conservation and in limiting CO<sub>2</sub> emission in this particular model; on the contrary, the expense is high. In reality, if there is energy tax levied at such a high rate like the model does, the steel industry may feel its financial pressure in energy expenditure, which forces it to consider low carbon emitted energy sources (natural gas) to gradually replace coal as its main energy source even though the technical application of producing steel with other kinds of energy are immature and usually with a high production cost. Such situation will somehow be eased in the future when the low carbon energy based production process is popularized. While whatever kind of energy is used, the energy demand required for steel industry will not be reduced that much because of the same high steel demand during the transition period.

Policies related to subsidy can achieve good results with low expense in this particular model. From the weight sensitivity tests, we know the consequent reason. It is simply because of comparatively bigger incentive of R&D investment on technological change than other incentives (energy price and CO<sub>2</sub> emissions). Such condition may vary in the future if the energy price increases much more rapidly than expected or aggravated environmental destruction from carbon pollution. In this case, other policies like carbon tax, setting strict standard to control toxic gas emission or reforestation may become more effective.

Besides the cost-effectiveness, we have to admit that it is not realistic for the government to subsidize on steel industry in the way that the model does. The policy only analyzes the situation once the policy is implemented, it will take effect until 2100. Such a long period makes us unconfident to believe the government will continuously support subsidy. Once the

steel industry has passed the transition period, the energy demand will decline correspondingly; in addition, there will be rather low potential to improve the energy efficiency in a long run, all of which makes the continuous subsidy become impossible. The way that we did in the model is just want to show the effect during the transition period and assuming continuous subsidy is just to simplify the model structure.

Raising EAF proportion is a focus that has been concerned about during recent years due to continuously increasing iron ore price and sustainable development. China has large potential to raise its recycling rate compared to the level of advanced steelmaking countries. The policy may take a long time to see the effect, but it can be developed quickly compared to the energy efficiency technology due to low advancement cost. Since the policy can limit CO<sub>2</sub> emission quite well and comparatively easy implementation, it is worthwhile and beneficial for the steel industry to invest more on recycling technology and adjust its steelmaking way.

Last but not least, the model is a tool to test policy and scenarios instead of a way of forecasting or predicting the future. Policies here provide new ways of thinking something in “what if” manner for the policymakers to move the system outside the limited range of historical experience. Most of these single polices have their limitations to achieve significant reductions in a cost-effective manner with easy implementation, policymakers need to seek a combination of different policies.

# *Chapter 8*

## **Conclusions**

This work presents the dynamic mechanism of Chinese steel industry. A System Dynamics model and related testing and policy design are described in the previous chapters. We conclude the work with forming an overview of the research, major findings and limitations are raised thereafter.

The study presents a System Dynamics model with endogenous technological change in a sub sector regional way. The model is built to help understand the dynamic energy problems evoked by high steel demand during economy transition and increasing energy price in steel industry in China. Scenarios and policies are tested as examples of possible situations and practical applications.

The present model can be used for analysis in the following major problems:

1. Development of energy efficiency technology in energy intensive industries
2. Substitution among different steelmaking ways

### **8.1 MAJOR FEATURES AND FINDINGS**

1. The research analyzes energy related problem in China, such problem was (and still is) a good problem area in which to apply System Dynamics. A typical energy intensive industry such as steel industry in this case has many properties that can be described easily using System Dynamic model: for the model presented in this study, nonlinearities (such as reference steel demand formulation), stock and flows (of technology and cumulative steel resource), feedback loops (through energy demand and technology development), emphasis on dynamic behavior and the need for policy analysis.

2. Increasing energy demand due to economic transition and related CO<sub>2</sub> emission with rising energy expenditure are mutual characteristics among almost all the coal intensive industries in China. Since System Dynamics has been found appropriate to support the integrated planning and management of problems related to energy efficiency issues, the current developed model structure in this research may be adaptable to other industries shared with above features.
3. The model is designed to test policies that could help ease the transition problem in energy demand and expenditure under a range of assumptions. Results suggest that most policies introduced in this research are cost-effective. However, implementation of these policies remains a critical issue, and the viability of energy tax and R&D subsidy is still questionable in the real world. Developing the technology of recycling scrapped steel is found to be useful in limiting carbon emission with easy implementation.
4. With a long time horizon for the model, the industry will have to switch from coal to other energy sources for steelmaking due to the scarcity of resource and increasing price of coal in the future. An inexpensive, reliable, and environmentally benign fuel source is required to be the substitute. This rule is also applicable to other coal-intensive industries or other sectors like electricity.
5. Many structures from earlier system dynamics models were omitted or abstracted in this particular model for simplicity. While such a simple model still can capture the main structure of the real system. Simplified model structure helps the readers get a better understanding, and they can test different policies in different ways without spending long time on digesting the structure of the model.

## **8.2 LIMITATIONS AND FUTURE WORK**

The model is built in a simplified way; it deals with some structures in a highly aggregated level due to limited time and resources. Model boundary and assumptions are listed in the former chapters; both of them determine the limitations of the work. For the future work, some exogenous variables can be reconstructed in an endogenous way and some assumptions like other unit production costs can be relaxed to make the model more convincing.

Some of the parameters such as steel demand intensity, energy tax rate in the model are estimated from other country's experience. With the issuance of real data in the near future, those parameters should be re-estimated or even replaced with detailed structures.

Problems such as energy substitution, endogenous way of modeling the R&D investment from industry are not included in the model. Such problems may not be serious for the time being since coal is still the dominant energy source for the whole Chinese industry. But coal will be gradually replaced by other cheaper and low carbon emitted energy sources such as natural gas or renewable energy sooner or later. In that case, industry will have to invest more on R&D regarding other energy resources. All these issues should be included in the future work.

Limited by the boundary of the work, interactions between sectors are excluded. Policies designed in one sector could ignore their influence to other sectors. So the policies in this model can not be regarded as realistic forecasts, they just provide the hypothetical view for the policymakers to move the system outside the limited range of historical experience. The future work can be extended to other energy intensive industries to form a comprehensive energy model for industry sector in China.

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# Reference

- Du, T and Cai, J. (2006) Analysis on Energy Consumption and Environmental Load of Steel Industry in China and Their Measures
- Fiddaman, T. (2002). Exploring Policy Options with a Behavioral Climate-Economy Model.
- Ford, Andrew. (1999). *Modeling the Environment: 'An Introduction to System Dynamics Models of Environmental Systems'*: 289-301
- Huang, D. (2004). Exploring effective combinations of Steel Industry Energy Conservation with Environmental Protection: 9-12
- International Iron and Steel Institute. Steel statistics of developing countries, 1999 ed. IISI: Brussels, 1999.
- I.Dyner, I. M. Giraldo, A. Lobo and D. Valencia. (1990). Regional energy planning. *In proceedings of the System Dynamics Conference*. (E. Zepeda and J. Machuca, Eds) pp. 83-92. System Dynamics Society, Boston, MA.
- Liu, Z., and Jiang, H. (2000). Environmental Impact of Raising Energy Efficiency in Steel Industry
- Li, K., Zeng, X., and Han, S. (2006). An analysis of Scrapped Steel Resource Based on Scrapped Index of U.S., Japan and China
- Lynn, P, Phylipsen and Ernst. Worrell (2001). Energy Use and Carbon Emissions in the Steel Sector in Key Developing Countries. U. S. D. o. Energy, Climate Portection Division, Office of Air and Radiation, U.S. Environmental Protection Agency: 5-12.
- L. Price, J. Sinton, E. Worrell. (2005). Energy use and carbon dioxide emissions from steel production in China. U. S. D. o. Energy, Climate Protection Division, Office of Air and Radiation, U.S. Environmental Protection Agency: 3-18.
- Meadows, D. a. J., Randers and Meadows, Dennis (2005). *Limits to Growth: The 30-Year Update*.
- Ministry of Metallurgical Industry. Yearbook of iron and steel industry of China. Beijing: MMI, 2005
- Moxnes, Erling. (1992). "Positive Feedback Economics and the Competition between 'Hard' and 'Soft' Energy Supplies". *Journal of Scientific and Industrial Research*, 51(March), 257-265.
- N. Gregory Mankiw. (2006). *Brief Principles of Macroeconomics*: 133-159

- 
- Naill, R. F. (1992). "An analysis of the cost effectiveness of US energy policies to mitigate global warming." *Syst.Dynamics Rev* **8**: 111-128.
- Naill, R. F. (1992). "A system dynamics model for national energy policy planning." *Syst.Dynamics Rev* **8**: 1-19.
- Peter, F. D. (1968). *The Age of Discoutinuity*.
- Rudiger, D, Stanley, F and Richard, S. (2004). *Macroeconomics*: 77-91
- Shan, Y. (2001). Adoption of Scrapped Steel as a Sustainable Resource in Steel Industry. *Iron and Steel* **36, No.10**
- State Statistical Bureau. (2005). *China energy statistical yearbook*. Beijing: China Statistical Publishing House
- Sterman, John D. (2000). *Business Dynamics: System Thinking and Modeling for a Complex World*. U.S.: McGraw-Hill
- Wang, W. (1999). "Metallurgy Energy-Saving at the Beginning OF the New Century".
- Wang, W. (2003). Supply and Demand Condition and Perspective of Scrapped Steel Resource in China
- William, W. B. (1972). *Toward Global Equilibrium: Collected Papers*, Chapter 6.
- Wirl, F. (1991). "Dynamics of commodity taxation: an example of an energy tax." *Syst.Dynamics Rev* **7**: 145-158
- Zhang, H. (2003). Sustainable Development Policies of Scrapped Steel Resources in China
- Zheng, L. (2005). *China's Industrial Development Report*: 162-174
- Zhou, Z. (2006). Perspective view of main economic features on Chinese steel and iron industry.

Internet Resource:

- |   |  |
|---|--|
| <a href="http://www.iea.org">www.iea.org</a>                                      | (International Energy Agency)                      |
| <a href="http://www.imf.org/">http://www.imf.org/</a>                             | (International Monetary Fund)                      |
| <a href="http://www.eia.doe.gov/">http://www.eia.doe.gov/</a>                     | (Energy Information Administration)                |
| <a href="http://www.worldsteel.org/">http://www.worldsteel.org/</a>               | (International Iron and Steel Institute)           |
| <a href="http://www.cpirc.org.cn/index.asp">http://www.cpirc.org.cn/index.asp</a> | (China Population Information and Research Center) |
| <a href="http://www.chinaisa.org.cn/">http://www.chinaisa.org.cn/</a>             | (China Iron & Steel Association)                   |

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# Appendix

## Model Equations and Annotations

\*\*\*\*\*

.Steel Demand

\*\*\*\*\*~

|

Actual steel demand=

SMOOTH (Indicated steel demand, Demand adjustment delay, Reference steel demand)

~ ton/Year

~ Actual steel demand from the indicated one, it takes time to get data for the steel demand change after cost effect.

|

Average unit production cost=Smooth (Unit production cost, Time to average unit cost)

~ yuan/ton

~ The unit cost averaged in one year

|

Billion yuan as conversion variable=1e+009

~ yuan/billion yuan

~ A conversion variable, set in order to convert GDP (Yuan) into billion Yuan as its unit.

|

Demand adjustment delay=1

~ Year

~ We assume the estimation time of steel demand is 1 year

|

Effect of cost on demand=

Effect of cost on demand table (Relative unit cost)

~ Dimensionless

~ The effect is estimated based on chapter 6 of the book: Toward Global Equilibrium: Collected Papers, by William W. Behrens III, Dynamics of natural resource utilization. Assuming that when cost increases at the beginning, small effect will influence the steel demand, cost effect becomes more significant when production costs increases even higher than before.

|

Effect of cost on demand table=

([(0,0)-(20,1)],(1,1),(1.46789,0.960526),(1.95719,0.912281),(2.75229,0.864035),

---

(3.73089, 0.802632), (5.50459, 0.710526), (8.13456, 0.570175), (20, 0))

~ Dimensionless

~ The cost effect table is used to model the cost effect; its input is the relative cost while the output the effect of cost on the demand

|

Effect of gdp per capita on steel demand intensity=

Effect of gdp per capita on steel demand intensity table (Relative gdp per capita)

~ Dimensionless

~ |

Effect of gdp per capita on steel demand intensity table=

([(0,0)-(3000,0.3)],(1.037,1),(1.119,0.99),(1.227,0.97),(1.395,0.91),(1.557,0.89),(1.66  
.087),(1.83,0.86),(1.99,0.78),(2.05,0.77),(2.11,0.71),(2.27,0.69),(2.56,0.76),(2.87  
.075),(3.14,0.71),(3.19,0.75),(3.45,0.74),(4,0.67),(4.3,0.66),(4.58,0.66),(4.93,0.69),  
(5.33639, 0.723684), (5.33639, 0.767105), (5.8104, 0.855263), (6.29969, 0.934211),  
(6.78899,1.00526),(7.52294,1.06842),(8.25688,1.11579),(9.11315,1.13816),(9.96942,  
1.15263),(11.055,1.13246),(12.0642,1.10482),(13.578,1.06316),(15.2599,1.01579),(16  
.6055,0.978947),(18.1193,0.926316),(19.8012,0.884211),(22.6606,0.821053),(25.519  
9,0.757895),(29.052,0.689474),(33.7615,0.610526),(37.63,0.536842),(41.8349,0.4789  
47),(48.3884,0.412281),(56.5902,0.350877),(64.792,0.302632),(74.3609,0.258772),(8  
7.1193,0.214912),(103.976,0.175439),(125.459,0.144737),(155.046,0.116228),(196.8  
81,0.0899123),(250.765,0.0701754),(311.927,0.0548246),(403.67,0.0416667),(477.06  
4,0.03547),(571.865,0.02887),(697.248,0.02432),(850.153,0.01954),(906.728,0.01885  
96),(970.948,0.0175439),(1056.57,0.0157895),(1227.83,0.0135965),(1480.12,0.01116  
) ,(1981.65,0.008311),(2299.69,0.007495))

~ Dimensionless

~ The relationship between GDP per capita and the steel demand intensity. Such a complex relationship is modeled using table function in terms of literature.

|

GDP= INTEG (GDP change, 1.41966e+012)

~ yuan/Year

~ Exogenous input to model the GDP per capita, it is imported from data series (provided by IMF) before 2007, and assume 3 scenarios for the GDP growth rate between 2007 and 2100

|

GDP change=GDP growth rate\*GDP

~ yuan/Year/Year

~ The net flow of the GDP stock, it refers to the GDP growth each year

|

---

GDP growth rate=GDP growth rate table (Time)

- ~ Dimensionless
  - ~ The output of the GDP growth rate table
- |

GDP growth rate table=

([(1980, 0)-(2100, 1)], (1980, 0.0517237), (1981, 0.0926267), (1982, 0.111776), (1983,0.153175),(1984,0.132241),(1985,0.0847539),(1986,0.115292),(1987,0.11277), (1988,0.0422287),(1989,0.0423565),(1990,0.0911653),(1991,0.140544),(1992,0.131176),(1993,0.126256),(1994,0.090037),(1995,0.0975268),(1996,0.0858786),(1997,0.0780579),(1998,0.0717702),(1999,0.0838896),(2000,0.0720543),(2001,0.0890671),(2002,0.101957),(2003,0.0990221),(2004,0.111893),(2005,0.1),(2006,0.1),(2007,0.08),(2100,0.02))

- ~ Dimensionless
  - ~ Using real GDP at price 1995, easy to calculate the growth rate. In order to correspond with the GDP growth in reality, it is hard to assume growth rate between 2006 and 2100. Even you assume an average growth rate during such long time period; it may produce large discrepancy from the actual GDP growth. We assume several conditions for the growth rate after 2007. For the baseline scenario after 2007, it is assumed to be 0. Several sensitivity tests will have to been done to test the robustness of the model behavior.
- |

GDP measure as billion yuan=GDP/Billion yuan as conversion variable

- ~ billion yuan/Year
  - ~ Converted from GDP, it is set to get the reference steel demand
- |

Gdp per capita=GDP/Population

- ~ yuan/(Year\*person)
  - ~ Simply the GDP divided by population.
- |

Indicated steel demand=Reference steel demand\*Effect of cost on demand

- ~ ton/Year
  - ~ The reference steel demand after the cost effect.
- |

Initial GDP per capita= INITIAL (GDP per capita)

- ~ yuan/(Year\*person)
  - ~ The initial value of GDP per capita in 1980. It is modeled to get the relative value of GDP per capita.
- |

Initial steel demand intensity=22681.5

- ~ ton/billion yuan

---

~ The initial steel demand intensity in 1980.  
|

Initial unit cost= INITIAL (Unit other production costs +Initial unit energy cost)

~ yuan/ton  
~ Assuming no R&D costs before 1980. So it only includes other production costs and energy costs  
|

Initial unit other costs=800

~ yuan/ton  
~ Around 5 times of the unit energy cost in 1980.  
|

Perceived steel demand intensity=

Smooth (Steel demand intensity, Time to perceived steel demand intensity)

~ ton/billion yuan  
~ Peoples' perception of steel demand intensity. It takes some time for people to perceive the real steel demand intensity by estimation or calculation.  
|

"Perceived unit R&D cost"=

DELAY N ("Unit R&D cost", "Time to perceived unit R&D cost", 12.36, 1)

~ yuan/ton  
~ People's perception of the R&D cost  
|

Population=Population table (Time)

~ Person  
~ Formulated by importing the data series of population from IMF and the prediction from "China Population & Development Research Center".  
|

Population table=

([(1900, 0)-(2100, 1e+010)], (1980, 9.98877e+008), (1981, 1.0124e+009), (1982, 1.02601e+009), (1983, 1.03998e+009), (1984, 1.05464e+009), (1985, 1.07017e+009), (1986, 1.08677e+009), (1987, 1.10426e+009), (1988, 1.12205e+009), (1989, 1.13926e+009), (1990, 1.15531e+009), (1991, 1.16993e+009), (1992, 1.1833e+009), (1993, 1.1957e+009), (1994, 1.2076e+009), (1995, 1.21933e+009), (1996, 1.23098e+009), (1997, 1.24241e+009), (1998, 1.25351e+009), (1999, 1.26407e+009), (2000, 1.27398e+009), (2001, 1.2832e+009), (2002, 1.29184e+009), (2003, 1.30004e+009), (2004, 1.30799e+009), (2005, 1.31584e+009), (2020, 1.43498e+009), (2030, 1.46956e+009), (2040, 1.469e+009), (2050, 1.43229e+009), (2060, 1.4e+009))

~ person  
~ The data before 2007 is introduced from IMF country database. After 2007, since the population growth rate is rather low, from the literature and China

---

Population & Development Research Center, the population will reach its peak at 1.45 billion at the middle of this century and slowly drop to 1.4 billion and keep it into the future.

|

Reference steel demand=

GDP measure as billion yuan\*Perceived steel demand intensity

~ ton/Year

~ This variable is to large extent based on the data series. It is just a reference steel demand without taking the cost effect into consideration. It is formulated to get the actual steel demand.

|

Relative gdp per capita=

GDP per capita/Initial GDP per capita

~ Dimensionless

~ Relative change from the Initial GDP per capita, it is modeled in order to get the steel demand intensity through the relationship between each other.

|

Relative unit cost=Average unit production cost/Initial unit cost

~ Dimensionless

~ The way to measure the increasing extent of cost. This is for the purpose of modeling effect of cost on demand.

|

Steel demand intensity=

Effect of GDP per capita on steel demand intensity\*Initial steel demand intensity

~ ton/billion yuan

~ It is related to the GDP per capita, the outcome of the effect on the initial steel demand intensity. It is formulated to model the reference steel demand.

|

Time to average unit cost=1

~ Year

~ Assuming the unit production cost is averaging into 1 year

|

Time to perceived steel demand intensity=2

~ Year

~ Assuming it takes 2 year to perceive the steel demand intensity

|

"Time to perceived unit R&D cost"=1

~ Year

~ Time for people to perceive the unit R&D cost

|

Unit other production costs=Initial unit other costs\*Input for other units production costs

~ yuan/ton

---

~ Exogenous input in this particular model. We only focus on unit energy cost, from the historical data, other production costs increase in a very flat and slow trend, which is expressed using exogenous inputs like ramp function. Needs further sensitivity tests.

|

Unit production cost=

Perceived unit energy cost Unit other production costs+"Perceived unit R&D cost"

~ yuan/ton

~ Unit cost, namely the production cost for one ton of steel produced. It includes other production costs, energy costs and R&D costs.

|

"Unit R&D cost"="R&D investment"/Actual steel demand

~ yuan/ton

~ Since we assume steel demand almost equals to sales rate and production rate, so unit R&D cost is simply the R&D investment divided by demand.

|

\*\*\*\*\*

.Technology

\*\*\*\*\*~

|

Average unit energy consumption= INTEG (Change in unit energy consumption, 2.04)

~ tce/ton

~ The expression of energy efficiency in this particular model. The initial value is the level in 1980

|

Change in unit energy consumption=

(Desired average unit energy consumption-Average unit energy consumption)/Desired average unit energy consumption realization time

~ tce/(Year\*ton)

~ Modeled as a net flow for the average unit energy consumption, refers to the change in unit energy consumption each year.

|

Desired average unit energy consumption=

Effect of technology on unit energy consumption\*Reference average unit energy consumption

~ tce/ton

~ Indicated value of energy efficiency, taking effect from technology development into consideration.

|

Desired average unit energy consumption realization time=2

~ Year

~ Assuming it takes 2 years to realize the developed technology.

|

---

Effect of cost on technology advance=

Effect of cost on technology advance table (Relative technology level)

~ Dimensionless

~ The cost of affecting an incremental advance in technology, the cost is assumed to gradually increase as more investment is required for each marginal increase in technology.

|

Effect of cost on technology advance table=

(((1,0)-(20,200)),(1,1),(1.34067,1.11),(1.91315,1.2),(2.43792,1.3),(2.89908,1.6),

(3.39205,2.63158),(3.99633,4.12281),(4.39388,5.78947),(4.79144,7.80702),(5.37982,

10.5263),(5.96697,12.2807),(6.4367,15.7895),(7.08257,21.0526),(7.90459,28.0702),(8

.72661,35.0877),(9.43119,42.9825),(10.3119,54.386),(11.0752,63.1579),(11.7798,71.

9298),(12.5431,82.4561),(13.1303,91.2281),(13.8349,103.509),(15.0092,119.298),(16.

0661,135.965),(17.8862,162.281), (18.767, 178.07), (19.8826, 199.123))

~ Dimensionless

~ A table function used to model the cost of technology advancement.

|

Effect of technology on unit energy consumption=

Effect of technology on unit energy consumption table (Perceived technology level)

~ Dimensionless

~ A function of relative technology level, increase in technology yields a corresponding decrease in energy use per ton of steel produced.

|

Effect of technology on unit energy consumption table=

(((0,0)-(50,1)),(1,1),(1.001,0.907895),(1.01,0.8046),(1.02,0.7012),(1.05,0.6067),

(1.22324, 0.535088), (1.83486, 0.434211), (2.29358, 0.364035), (3.36391, 0.298246),

(5.19878,0.236842),(7.95107,0.20614),(11.1621,0.175439),(14.6789,0.157895),(18.50

15,0.140351),(22.63,0.127193),(27.5229,0.118421),(35.0153,0.109649),(50.3058,0.09

64912),(53.7615,0.0877193))

~ Dimensionless

~ It is modeled as a table function to express the effect of technology on energy efficiency. Technology change level is the input of the table function, while its output will be the effect

|

Indicated technology change=

(Normal technology change/Effect of cost on technology advance)\*

((("Relative R&D investment"\*"Normalized weight for R&D investment")+

(Normalized weight for energy price\*Perceived relative energy price)+

(Perceived relative CO2 emission\*Normalized weight for CO2 emission\*Initial Technology))

~ technology/Year

---

~ Assume that changes in the energy efficiency technology result from investments in research and development, energy price increment, CO2 emission influence the technology development as two motivations as well, while it is affected by the increasing costs of technology advancement.

|

Initial Technology=1

~ Technology

~ The initial technology level, assuming it is 1 in the beginning for the virtual technology level

|

Initial unit energy consumption of BOF=2.107

~ tce/ton

~ Initial energy usage to produce one ton of steel using basic oxygen furnace as a technical process

|

Initial unit energy consumption of EAF=1.757

~ tce/ton

~ Initial energy usage to produce one ton of steel using electrical arc furnace as a technical process

|

Initial unit energy consumption of OHF=2.107

~ tce/ton

~ Initial energy usage to produce one ton of steel using open hearth furnaces as a technical process

|

Normal technology change= INITIAL (0.1)

~ 1/Year

~ Nominal fraction in technology change each year without any effect from incentives

|

Normalized weight for CO2 emission=

$$\frac{\text{Weight for CO2 emission}}{\text{Weight for CO2 emission} + \text{Weight for energy price} + \text{Weight for R\&D}}$$

~ Dimensionless

~ The weight for CO2 emission can be set at any value, while the sum of all the weights should be 100%. In order to reach this purpose, the weight for CO2 emission needs to be converted to Normalized weight for CO2 emission

|

Normalized weight for energy price=

$$\frac{\text{Weight for energy price}}{\text{Weight for CO2 emission} + \text{Weight for energy price} + \text{Weight for R\&D}}$$

|

- 
- ~ Dimensionless
  - ~ The weight for energy price can be set at any value, while the sum of all the weights should be 100%. In order to reach this purpose, the weight for energy price needs to be converted to Normalized weight for energy price

|

"Normalized weight for R&D investment" =

"Weight for R&D" / (Weight for CO2 emission Weight for energy price + "Weight for R&D")

- ~ Dimensionless
- ~ The weight for R&D can be set at any value, while the sum of all the weights should be 100%, in order to reach this purpose, the weight for R&D needs to be converted to Normalized weight for R&D investment.

|

OHF proportion = OHF proportion table (Time)

- ~ Dimensionless
- ~ From the historical data, the proportion decreasing trend looks like linearly, it almost went obsolescent in 2000.

|

OHF proportion table [(0, 0)-(2000, 10)], (1980, 0.32), (2000, 0)

- ~ Dimensionless

|

Perceived technology level =

DELAY3 (Relative technology level, Time to adapt new technology)

- ~ Dimensionless
- ~ People's perception of new technology level for the time being

|

Reference average unit energy consumption =

Initial unit energy consumption of BOF \* (1 - Actual proportion of EAF - OHF proportion) + Initial unit energy consumption of EAF \* Actual proportion of EAF + Initial unit energy consumption of OHF \* OHF proportion

- ~ tce/ton
- ~ Reference average energy efficiency, average value of EAF, BOF and OHF's energy efficiency times their own proportion

|

Relative technology level = Technology / Initial Technology

- ~ Dimensionless
- ~ Relative technology level, initial technology in 1980 as a reference

|

Technology = INTEG (Technology change rate, Initial Technology)

- ~ technology
- ~ A way to represent accumulated research and knowledge, modeled as a level

---

variable, using "technology" as a virtual unit. In this particular research, technology refers to energy efficiency technology, such as making use of waste heat,

|

Technology change rate=Indicated technology change

~ technology/Year

~ Modeled as a net flow to the Technology stock, refers to the technology change each year.

|

Time to adapt new technology=20

~ Year

~ Time between the research and actual implementation of the new technology.

|

Weight for CO2 emission=1

~ Dimensionless

~ A virtual variable. It refers to the importance of the CO2 as an incentive to improve energy saving technology. It is used to model normalized weight for CO2. The value of this constant can be changed during the policy Optimization. The initial value is 1 for the equilibrium condition.

|

Weight for energy price=1

~ Dimensionless

~ A virtual variable. It refers to the importance of the energy price as an incentive to improve energy saving technology. It is used to model normalized weight for energy price. The value of this constant can be changed during the policy optimization. The initial value is 1 for the equilibrium condition.

|

"Weight for R&D"=IF THEN ELSE (Time>POLICY YEAR," Weight R&D", 1)

~ Dimensionless

~ A virtual variable. It refers to the importance of the R&D as an incentive to improve energy saving technology. It is used to model normalized weight for R&D The value of this constant can be changed during the policy optimization. The initial value is 1 for the equilibrium condition.

|

"Weight R&D"=1

~ Dimensionless

~ Used only during the technological improvement policy optimization. The reason we only use this structure to model the "weight for R&D" is that R&D change has been found to have the most impact on technological development among all the incentives.

|

\*\*\*\*\*

.Unit Energy Cost

\*\*\*\*\*~

|

Energy price=IF THEN ELSE (Time >= POLICY YEAR, Reference average energy price  
Energy tax\*1, Reference average energy price)

~ yuan/tce

~ The ultimate energy price including the crude price and the tax levied by  
government

|

Energy price table=

((1980,0)-(3000,4000)],(1980,100),(1981,106),(1982,108),(1983,110),(1984,113),  
(1985,117),(1986,120),(1987,130),(1988,160),(1989,205),(1990,240),(1991,250),(199  
2,290),(1993,350),(1994,410),(1995,470),(1996,567),(1997,587),(1998,549),(2006,60  
0),(2007,600), (2100.37, 600))

~ yuan/tce

~ Exogenous input variable, we introduced the data series directly from 1980  
to 2006. Needs sensitivity tests for future behavior analysis.

|

Energy tax=

IF THEN ELSE (Time>=POLICY YEAR, Energy tax rate\*Reference average energy  
price, 0)

~ yuan/tce

~ Assumed to be the tax rate times the energy price, which means it is  
proportional to the energy price. And the energy tax policy can be  
implemented from 2007 or 1990 to see whether the condition will be  
improved if we implemented the policy earlier.

|

Energy tax expense=Energy demand\*Energy tax

~ yuan/Year

~ It is an output to R&D investment sector formed as a recycled subsidy on  
R&D investment and output to Energy demand sector as a policy repayment.

|

Energy tax rate=0.3

~ Dimensionless

~ Policy variable, the key variable to implement the energy tax policy. The  
tax rate can be adjusted to see the effect from magnitude of the policy.

|

Initial energy price= INITIAL (Energy price)

~ yuan/tce

~ The energy price in 1980

|

Initial unit energy cost= INITIAL (Unit energy cost)

---

~ yuan/ton  
~ The unit energy cost among production cost in 1980.  
|

Perceived relative energy price=Smooth (Relative energy price, Time to perceived relative energy price)

~ Dimensionless  
~ Peoples' perception of energy price change  
|

Perceived unit energy cost=Smooth (Unit energy cost, Time to perceived unit energy cost)

~ yuan/ton  
~ People's perception of unit energy cost.  
|

POLICY YEAR=2007

~ Year  
~ Initial year to implement policy, 2007 or 1990 for the time selection of the policy implementation  
|

Reference average energy price=Energy price table (Time)\*Input for energy price

~ yuan/tce  
~ The reference energy price introduced directly from historical data series Between 1980 and 2007, needs sensitivity tests for the behavior after 2007.  
|

Relative energy price=Energy price/Initial energy price

~ Dimensionless  
~ Relative value of energy price, the price 1980 as its initial value.  
|

Time to perceived relative energy price=1

~ Year  
~ The time that people needed to perceive the real energy price change.  
|

Time to perceived unit energy cost=1

~ Year  
~ Assuming it takes 1 year for people to perceive the unit energy cost  
|

Unit cost of loan=Energy tax expense/Actual steel demand

~ yuan/ton  
~ Used in the subsidy pay off policy, in this case, the subsidy will have to be paid back, namely a loan. This loan will be distributed into the industry's energy cost.  
|

Unit energy cost=Average unit energy consumption\*Energy price Unit cost of loan\*0

- ~ yuan/ton
- ~ It is simply the energy price times the unit energy consumption, this variable means how much energy is needed to produce one ton of steel. When there is subsidy repayment policy implemented, the unit energy cost should also include the pay off.

\*\*\*\*\*

.Energy Demand & CO2 Emission

\*\*\*\*\*~

- Average carbon emission per unit energy used=
- Actual proportion of EAF\*Carbon emission from EAF per tce+ (1-Actual proportion of EAF)\*"Carbon emission from BOF&OHF per tce"
- ~ C/tce
  - ~ The average carbon emission per unit energy used based on three steelmaking ways, it is influence by the proportion of different steelmaking ways.

Average energy expense=Smooth (Energy expense, Time to average energy expense)

- ~ yuan/Year
- ~ The energy expense averaged in a certain period of time.
- ~ :SUPPLEMENTARY

"Carbon emission from BOF&OHF per tce"=0.743

- ~ C/tce
- ~ Both of BOF and OHF have included the iron making process, from historical data, their carbon emission per unit energy used are quite similar. We use the same value for both of them.

Carbon emission from EAF per tce=0.186

- ~ C/tce
- ~ An estimated value, should be 1/4 of value when using BOF or OHF

Carbon index=3.666

- ~ tonc/C
- ~ The ratio between "CO2" molecular weight and "C" atomic weight. It is used to calculate the CO2 generation rate.

CO2 generation rate=

Total energy consumption\*Average carbon emission per unit energy used\*Carbon index

- ~ tonc/Year
- ~ Closely related to the energy demand, while it is also dependent on the steelmaking ways, since different production way has its own carbon

---

emission per energy used.

|

Energy expense=Energy demand\*Energy price Energy tax expense\*0

~ yuan/Year

~ The energy expenditure for the steel industry to spend on, it is closely related to the energy demand and energy price. In the policy analysis of subsidy repayment, the repayment needs to be added.

|

Initial CO2 emission= INITIAL (Perceived CO2 emission)

~ tonc/Year

~ The initial CO2 emission in 1980

|

Perceived CO2 emission=Smooth (CO2 generation rate, Time to perceived CO2 emission)

~ tonc/Year

~ People's perception of CO2 emission.

|

Perceived relative CO2 emission=Smooth (Relative CO2 emission, Time to perceive CO2 emission)

~ Dimensionless

~ People's perception of relative CO2 emission

|

Relative CO2 emission=Perceived CO2 emission/Initial CO2 emission

~ Dimensionless

~ The current CO2 emission relative to the initial CO2 emission reflecting the actual CO2 emission change.

|

Time to actual energy demand=1

~ Year

~ Assuming there is a one year delay before the energy is consumed and after the energy is demanded.

|

Time to average energy expense=5

~ Year

~ Assuming that time to get an average value of energy expense is 5 years.

|

Time to perceive CO2 emission=1

~ Year

~ Assuming it takes 1 year for people to perceive the relative CO2 emission change

|

Time to perceived CO2 emission=1

---

~ Year  
~ Assuming it takes 1 year for people to perceive the CO2 emission  
|

Total energy consumption=Smooth (Energy demand, Time to actual energy demand)  
~ tce/Year  
~ It is assumed to be the 1 year delayed value of energy demand. It is modeled to get the CO2 emission.  
|

Energy demand=Actual steel demand\*Average unit energy consumption  
~ tce/Year  
~ The energy demand required for the whole steel industry.  
|

\*\*\*\*\*  
.EAF & Scrapped Steel  
\*\*\*\*\*~  
|

Actual proportion of EAF=  
DELAY N (Indicated proportion of EAF, Time to actual proportion of EAF, 0.192, 1)  
~ Dimensionless  
~ The actual EAF proportion that people can estimate or calculate in the future.  
|

Actual recycled scrapped steel=Smooth (Recycled scrapped steel, Time to actual scrapped steel recycled)  
~ ton/Year  
~ The actual recycled scrapped steels that people estimate.  
|

Cumulative steel= INTEG (Steel production-Steel scrapping rate, 4.17707e+008)  
~ ton  
~ An expression of the steel resource and accumulation.  
|

Depreciation time=18+step (1e+008, 2007)\*0  
~ Year  
~ For the situation in China, the depreciation time is around 18 years. Extreme testing about the deprecation time is implemented on this variable.  
|

Effect of scrapped steel ratio on proportion of EAF=  
Effect of scrapped steel ratio on proportion of EAF table (Ratio between demand and actual recycled)  
~ Dimensionless  
~ |

Effect of scrapped steel ratio on proportion of EAF table=

---

$((0,0)-(10,10]),(0.339,3.55263),(0.389,3.37719),(0.459,2.9386),(0.564,2.41228),$   
 $(0.681,1.88596),(0.721713,1.71053),(0.795107,1.44737),(0.869,1.31579),(0.985,1.228$   
 $07),(1.105,1.1),(1.68,0.9),(2,0.756),(3,0.5),(10,0))$

- ~ Dimensionless
- ~ From the literature, more scrapped steel resource leads to a low cost, which eventually make steel industry to use more scrapped steel as raw materials to make steel. This means people may increase the proportion of EAF to save energy.

|

Indicated proportion of EAF=

Initial proportion of EAF\*Effect of scrapped steel ratio on proportion of EAF

- ~ Dimensionless
- ~ Indicated EAF proportion after the effect of scrapped steels supply and demand.

|

Initial proportion of EAF=0.192

- ~ Dimensionless
- ~ The initial proportion of EAF in 1980, introduced from "ANALYSIS OF ENERGY SAVING AND ENERGY CONSUMPTION IN CHINESE STEEL INDUSTRY FOR LAST 20 YEARS AND NEXT 5 YEARS"

|

Ratio between demand and actual recycled=Scrapped steel demand/Actual recycled scrapped steel

- ~ Dimensionless
- ~ The input of the table function in order to get the effect from scrapped steel supply & demand ratio on the EAF development, namely EAF proportion among steelmaking ways.

|

Recycled scrapped steel=Steel scrapping rate\*Recycling rate

- ~ ton/Year
- ~ Recycled scrapped steels from the social capital.

|

Recycling rate=

Reference recycling rate\*Smooth (Input for EAF recycling rate, Time to realize the recycling rate)

- ~ Dimensionless
- ~ Modeled in an exogenous way, using some input to predict the future development. Policy is designed with regarding to this parameter for the steelmaking process improvement.

|

Reference recycling rate=0.4

- ~ Dimensionless
- ~ The reference recycling rate of scrapped steels for the past.

---

Scrapped steel consumption by BOF=0.1

~ ton/ton

~ The scrapped steels consumed to make steel when use BOF

|

Scrapped steel consumption by EAF=0.9

~ ton/ton

~ The scrapped steels consumed to make steel when use EAF

|

Scrapped steel consumption by OHF=0.25

~ ton/ton

~ The scrapped steels consumed to make steel when use OHF

|

Scrapped steel demand=

Actual steel demand\*Actual proportion of EAF\*Scrapped steel consumption by EAF+  
Actual steel demand\*(1-Actual proportion of EAF-OHF proportion)\*Scrapped steel  
consumption by BOF+ Actual steel demand\*Scrapped steel consumption by  
OHF\*OHF proportion

~ ton/Year

~ It is dependent on the each steelmaking way's scrapped steel consumption  
times the proportion respectively.

|

Steel production=Actual steel demand

~ ton/Year

~ Assuming the demand equals the actual production rate

|

Steel scrapping rate= Cumulative steel/Depreciation time

~ ton/Year

~ It is modeled using a material delay, simply the cumulative steel depreciated  
after a certain time period.

|

Time to actual proportion of EAF=5

~ Year

~ The time for the industry to realize the proportion

|

Time to actual scrapped steel recycled=1

~ Year

~ The time for people to estimate the actual recycled scrapped steels

|

Time to realize the recycling rate=5

~ Year

---

~ Time to realize the recycling rate from technology development.  
|

\*\*\*\*\*  
.R&D Investment  
\*\*\*\*\*~  
|

"Initial R&D investment"= INITIAL ("R&D investment")  
~ yuan/Year  
~ The initial R&D investment as a percentage of sales revenues in 1980  
|

"R&D investment"=  
"R&D investment by steel industry"+ "R&D investment subsidized by government"  
~ yuan/Year  
~ The sum of industry R&D investment and the investment from government  
|

"R&D investment by steel industry"=  
"Reference percentage investment in R&D by steel industry" \*sales revenues  
~ yuan/Year  
~ R&D investment implemented by the steel industry itself, the industry set aside a certain percentage of its revenue each year as the investment on R&D.  
|

"R&D investment subsidized by government"=  
IF THEN ELSE (Time>=POLICY YEAR, Energy tax expense\*0, 0)  
~ yuan/Year  
~ R&D invested by the government in a form of subsidy. Since the R&D subsidy is a policy variable, the subsidy is only given after the policy year.  
|

"Reference percentage investment in R&D by steel industry"= 0.01  
~ Dimensionless  
~ percentage of sales revenue on R&D investment. As the "Yearbook of technology of China" shows, R&D percentage for iron and steel industry has been kept at around 0.01 for a long time.  
|

"Relative R&D investment"="R&D investment"/"Initial R&D investment"  
~ Dimensionless  
~ The relative R&D investment change from the initial year  
|

Sales revenues=Average unit production cost\*Actual steel demand  
~ yuan/Year  
~ We assume that cost equals to price, without the consideration of markup and demand equals to the sales rate.  
|

\*\*\*\*\*

.Exogenous Input

\*\*\*\*\*~

|

Input for EAF recycling rate=1+step (Step height, Step time)

~ Dimensionless

~ Policy input for EAF recycling rate. Since no body knows how it behaves in the future, several reasonable conditions for this policy input will be given.

|

Input for energy price=1+ramp (Ramp slope 3, Ramp start time 3, Ramp end time 3)

~ Dimensionless

~ Exogenous input for energy price. Assuming that it grows like using a ramp function. The slope needs sensitivity tests.

|

Input for other units production costs=

1+ramp (Ramp slope 1, Ramp start time 1, Ramp end time1) +ramp (Ramp slope 2, Ramp start time 2, Ramp end time 2)

~ Dimensionless

~ Exogenous input for other unit production costs. Assuming that it grows like using a ramp function when the slope 1 is 0.1.The slope 2 is the assumption for its future behavior, it needs sensitivity tests.

|

Ramp end time 2= 2100

~ Year

~ The end time of the time horizon

|

Ramp end time 3=2100

~ Year

~ The end time of the time horizon

|

Ramp end time1=2007

~ Year

~ The end time of the ramp function 1

|

Ramp slope 1=0.1

~ Dimensionless

~ Normal ramp slope value for other units production costs is set at 0.1 for the time period 1980-2007.

|

Ramp slope 2=0.05

~ Dimensionless

---

~ After 2007, the growth trend of other units production costs could be different, we assume there are two cases which may happen in the future: first case: it grows as usual; second case: it grows at half rate as the it does before. Base run scenario: 0.

|

Ramp slope 3=0.1

~ Dimensionless  
~ The ramp slope of the input for energy price, needs sensitivity testing to analysis future behavior of the energy price growth

|

Ramp start time 1=1980

~ Year  
~ The start time of the time horizon

|

Ramp start time 2=2007

~ Year  
~ The start time to use the ramp function 2

|

Ramp start time 3=2007

~ Year  
~ The start time to use the ramp function 3

|

Step height=0

~ Dimensionless  
~ Exogenous input as a policy. Different situations are considered. For the Step function, we test the height 1, and then the recycling rate will eventually reach 0.8.

|

Step time=2007

~ Year  
~ The time to add step function as an input on the EAF recycling rate.

|