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On simulation and optimization of one polysilicon industry system under system dynamic*

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Abstract. With the increase of global climate disaster, more and more people are concerned about low carbon economy. Therefore, as a raw material for solar cells, polysilicon became the focus of a low carbon economy. As a representative industry of low carbon economy, production process of polysilicon consumes a lot of energy. This paper studies the polysilicon industry planning of Leshan in the upper course of the Yangtze River in China. Firstly, we select and optimize the main factors affecting planning by fuzzy multiple objective programming. Then, we simulate and analyze the whole industry chain using system dynamic. Finally, We compare performance with different models, the results show how decision-making is improved by the insight the model provides.

Keywords: polysilicon industry, fuzzy set, multiple objective programming, system dynamics

1 Introduction

There is an overwhelming amount of research performed on polysilicon-related topics as new resources. These studies include information about new technologies, products and analytic methods. D. Lysacek (2010) researches on Thermal stability of boron-doped polycrystalline silicon layers on antimony and boron-doped substrates[9]. Timothy J. Foxon (2010)studies Developing transition pathways for a low carbon electricity system[5]. Daniel Sperling (2009)researches a global low carbon fuel standard[13]. S. K. Ghosh (2010) researches On the Cu precipitation behavior in thermomechanically processed low carbon microalloyed steels[6]. R. H. Buitrago (2008) researches Polycrystalline silicon thin film solar cells prepared by PECVD-SPC[2]. T. Kojima, T. Kimura and M. Matsukata (2007) research Development of numerical model for reactions in fluidized bed grid zone-application to chemical vapor deposition of polycrystalline silicon by monosilane pyrolysis[8]. L. Yin (2004) researches High-quality grinding of polycrystalline silicon carbide spherical surfaces[18]. A. Slaoui (2006) researches Passivation and etching of fine-grained polycrystalline silicon films by hydrogen treatment[12]. G. Andersson (2005) researches Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance[1]. The above mentioned research, say little or nothing about the construction of the polysilicon industry chains and their respective economies; this remains a research. In this paper, we present findings on planning the polysilicon industry in a city, its effect on the city's economy and obtain future developmental directions by model analysis.

The city we have chosen has been one of the most representative cities on the polysilicon industry in China and the only area sustained 40 years of semiconductor silicon materials research and production. Based on the capacity expansion by the technology progress, the planning polysilicon capacity in this city reaches 35000 tons stere as the administration report on 2010 and form a significant part of polysilicon industry in the

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west of China. As a result, development of the polysilicon industry in this city; to clarify its future direction, we must understand the regional polysilicon industry. In the quantitative analysis of our findings, we must obtain quantitative data such as those pertaining to the product's distribution, the price of the product. These variables are normally decided by the authority leading the industry and are subjected to many external influences as well. We introduce system dynamic to circumvent the uncertainties inherent to the quantitative variables.

2 The polysilicon industry system

Polysilicon, known as the basis for microelectronics is a form of elemental silicon. Polysilicon is the raw materials of single crystal silicon, which is also a basic materials of artificial intelligence, automation, information processing and photoelectric devices. At present, crystalline silicon materials, including polysilicon and single crystal silicon, is the most important photovoltaic material. Its market share exceeds 90%, and is still the main solar cell materials in a long time. Polysilicon is mainly used for semiconductor and solar cell. According to the purity, it is divided into electronic and solar grade. The world production of solar cells increases 17-fold in only 10 years from 69MW in 1994 to 1200MW 2004. Experts predict that solar PV industry will exceed nuclear power as one of the most important basic energy in the first half of the twenty-first century.

In this section, we describe the polysilicon industry system studied in our paper. The system is described diagrammatically in Fig. 1.

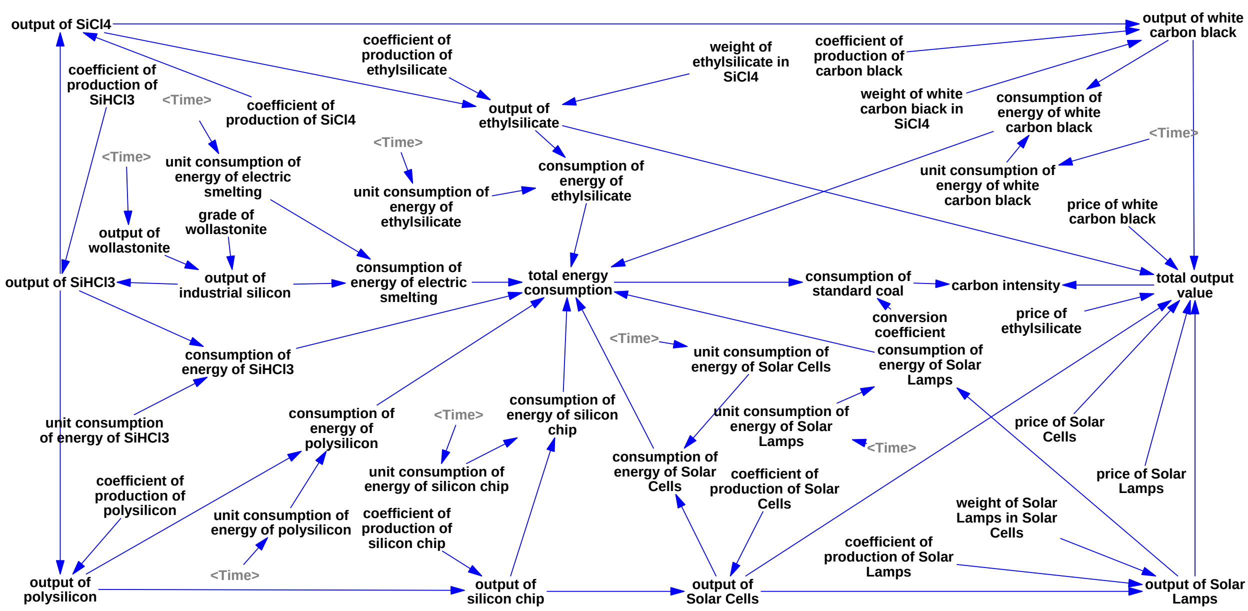

Fig. 1. The polysilicon industry system

2.1 Price and unit energy consumption of products

Factors that affect the prices of products and unit energy consumption of products include technology restraints, market factors and relationship between supply and demand, etc. We should consider the cost of products, demand, competition, and many other factors to estimate price which will be closer to the market price. As noted earlier, a fundamental assumption made in the application of fuzzy set theory is that any object can be perceived through available information, while it may be insufficient for an exact characterization. We approximate it by other sets.

In the polysilicon system of this region, there are 7 variables expressed by p_1 to p_7. The fuzzy variables of the polysilicon system are given in Tab. 2.

Table 1. The fuzzy variables of the polysilicon industry

p_1	price of ethylsilicate
p_2	price of white carbon black
p_3	price of Solar Cells
p_4	price of Solar Lamps
p_5	unit consumption of energy of ethylsilicate
p_6	unit consumption of energy of white carbon black
p_7	unit consumption of energy of Solar Lamps

Table 2. The control variables of the polysilicon industry

x_1	weight of ethylsilicate in $SiCl_4$
x_2	weight of white carbon black in $SiCl_4$
x_3	weight of Solar Lamps in Solar Cells
x_4	weight of Solar Cells for sale
$f(x)$	total output value
$g(x)$	total energy consumption

2.2 The weight of distribution

The weight of distribution x_i, is an important parameter for the polysilicon industry; its value decides the future direction of product development. An example: x_1 expresses weight of ethylsilicate in $SiCl_4$ and x_2 expresses weight of white carbon black in $SiCl_4$.

In this polysilicon industry system, there are 2 objectives and 2 objective equations to optimize 4 parameters. Then we input the optimum parameters into the system dynamic (SD) model to simulate and forecast the output value of products in the following years. Below is a list of the objectives and restrictions considered:

3 Modelling

3.1 Problem definition

Polysilicon is not only the basic materials of information industry, but the photovoltaic material. Promoting the sustainable and rapid development of China's photovoltaic industry and electronic information industry, "silicon photovoltaic technology development" has been listed in "renewable resource industry Catalogue" by the National Development and Reform Commission; 6 inches polysilicon was the priority production, listed in "Guidance Catalogue for industrial restructuring" which was released by the National Development and Reform Commission in 2005. These policies tend to promote the development of the industry. Polysilicon industry as a representative of the low carbon economy, but its production process costs high energy consumption. Polysilicon production process consumes a lot of power, and generate a large number of $SiCl_4$, SiH_2C1_2, $SiHCl_3$ and other. Therefore reducing energy consumption and increasing output and ultimately improving the carbon intensity need to be solved immediately.

System dynamics (SD) is a simulation technology based on feedback control theory that is used to study large complex system by M. Kang[7]. This method is a new-style subject, established by Forrester[3, 4, 10, 14] from MIT in mid-1950s. The method stems from operational research and the synthesis of system theory, cybernetics, information theory, information feedback theory, decision-making theory, system dynamics simulation, elements of computer science, etc. System dynamics combines systems analysis and systems synthesis to study complex systemic questions by G. Vedat[15]. SD has a particular emphasis on the behaviors and trends of a complex system. Simulation technology is only used to forecast the trends in the future years according to certain parameters, and thus cannot be used to estimate exact levels reliably. Therefore, we also introduce multiple objective programming based on the SD to work through the uncertain variables and get optimized results from the simulation.

3.2 Solution approach

System dynamics combines multiple objective programming to study complex systemic questions by N. Repening[11] and J. Xu[16, 17]. The general SD-MOP model is that factors affect each other, which means the system develops nonstoppably. By the analysis above, we observed that complex interactions between inherent components can cause the growth of the system: steering and governance are limited by knowledge of these interactions. To study them, we divided the system into four sets: total energy consumption set, production set, fuzzy variables and total output value set. We define $g(x)$ to be the total energy consumption set, X be the production set, P be the fuzzy variables and $f(x)$ be the total output value set.

3.2.1 Model formulation

We form the parameter statistics by studying polysilicon industry chains and analyzing the flows of processing technique and show the results in Tab. 2. The settled values for the substance transforming rates, and some settled parameters in the system dynamic model are mainly based on: (1) the administration annual report for the region, (2) the programming reports on correlative industries, and (3) present market situation. The settled values were obtained via equilibration, linearity regression, index smoothness and other related mathematical models. We define the parameters used to describe and analyze the system, and the parameters of the polysilicon industry system are presented in Tab. 3.

Table 3. The chart of parameters on industry chain of polysilicon

Number	Meaning	Unit
1	price of white carbon black	6000 yuan/T
2	price of ethylsilicate	3000 yuan/T
3	unit consumption of energy of electric smelting	12000 kwh/T
4	unit consumption of energy of $SiHCl_3$	70 kwh/T
5	unit consumption of energy of polysilicon	1800000 kwh/T
6	unit consumption of energy of silicon chip	40000 kwh/T
7	unit consumption of energy of Solar Cells	1400 kwh/T
8	unit consumption of energy of Solar Lamps	2000 kwh/T
9	unit consumption of energy of white carbon black	80000 kwh/T
10	unit consumption of energy of ethylsilicate	70000 kwh/T
11	grade of wollastonite	0.33 No dimension
12	coefficient of production of $SiHCl_3$	4 No dimension
13	coefficient of production of polysilicon	0.067 No dimension
14	coefficient of production of $SiCl_4$	0.93No dimension
15	coefficient of production of ethylsilicate	0.775 No dimension
16	coefficient of production of carbon black	0.037 No dimension
17	conversion coefficient	1.227 No dimension

Previously, we were accustomed to setting parameters based on subjective experience, which led to inaccuracy, vague decision making and bias. Our integrated model of system dynamics and fuzzy multi-objective programming can reduce experimenter bias, for better qualitative analysis the rate parameters x_i are optimized via fuzzy multi-objective programming. The rate parameters and fuzzy variables are both included in this system. The initial and rate parameters determine the corresponding level parameter. Every objective parameter is compared to a fuzzy multi-objective programming model. Therefore, we set up the fuzzy multi-objective programming models according to every objective parameter. For $f(x)$ and $g(x)$ we set up fuzzy multi-objective programming (FMOP). The following are the optimizing formulas for the polysilicon industry system of this region.

We select triangular fuzzy numbers and 0.8 as its measure for this model. $f(x)$ expresses total output value and $g(x)$ expresses total energy consumption. $a_1\tilde{p}_1x_1$ expresses value of ethylsilicate. $a_2\tilde{p}_2x_2$, value of white carbon black. $a_3\tilde{p}_3x_3$, value of Solar Cells. $a_4\tilde{p}_4x_4$, value of Solar Lamps. $a_1\tilde{p}_5x_1$, consumption of energy of ethylsilicate. $a_2\tilde{p}_6x_2$, consumption of energy of white carbon black. $a_3\tilde{p}_7x_3$, consumption of energy of Solar Lamps respectively. The data of fuzzy variables the polysilicon system are given in Tab. 4.

We model the FMOP using the government planing data, and the planned production capacity of polysilicon will amount to 35,000 ton. For example, $a_1 = \text{output of polysilicon/coefficient of polysilicon} *$ coefficient of $SiCl_4$ $*$ coefficient of ethylsilicate. The parameter of the FMOP are given in Tab. 5.

Table 4. Data of the fuzzy variables

$\tilde{p_1}$	$\tilde{p_2}$	$\tilde{p_3}$	$\tilde{p_4}$
$(200, 6000, 200)$	$(100, 3000, 100)$	$(50, 1400, 50)$	$(80, 2500, 80)$
$\tilde{p_5}$	$\tilde{p_6}$	$\tilde{p_7}$	
$(70, 2000, 70)$	$(3000, 80000, 3000)$	$(2000, 60000, 2000)$	

Table 5. The parameter of the FMOP

a_1	a_2	a_3	a_4
36.8298	1.7596	4031.6	4031.6

Table 6. The optimization results of polysilicon industry chain

Variable	x_1	x_2	x_3	x_4
Value	0.7245154	0.2754846	0.3657044	0.6342956

$$\begin{aligned}
&\max\ f(x) = 36.8298\tilde{p}_1 x_1 + 1.7596\tilde{p}_2 x_2 + 4031.6\tilde{p}_3 x_3 + 4031.6\tilde{p}_4 x_4 \\
&\min\ g(x) = 36.8298\tilde{p}_5 x_1 + 1.7596\tilde{p}_6 x_2 + 4031.6\tilde{p}_7 x_3 \\
&\text{s.t.} \begin{cases}
x_1 + x_2 < 1 \\
x_3 + x_4 < 1 \\
36.8298x_1 + 1.7596x_2 + 4031.6x_4 > 2264.18 \\
1.7596x_2 + 4031.6x_3 + 4031.6x_4 > 1953.27 \\
1.7596x_2 + 4031.6x_4 > 1542.89 \\
36.8298x_1 + 1.7596x_2 + 4031.6x_3 < 3826.15 \\
36.8298x_1 + 4031.6x_3 < 3176.94 \\
1.7596x_2 + 4031.6x_3 < 2047.83 \\
0 < x_i < 1, i = 1, 2, 3, 4
\end{cases}
\end{aligned} \tag{1}$$

where p_i are $L - R$ fuzzy variables with the following membership function.

$$\mu_{\tilde{c}_i}(t) = \begin{cases} L(\frac{p_i - t}{\alpha_i}), t \leq p_i, \alpha_i > 0 \\ R(\frac{t - p_i}{\beta_i}), t \geq p_i, \beta_i > 0 \end{cases} \tag{2}$$

where α_i, β_i are positive numbers expressing the left and right spreads of p_i and reference functions L, R $[0, 1] \to [1, 0]$ with $L(1) = R(1) = 0$ and $L(0) = R(0) = 1$ are non-increasing continuous functions.

Since the uncertainty of fuzzy variables p_i, it is difficult for decision makers to reach an accurate decision and then we have to convert it into a deterministic one. The chance operator is an efficient tool to deal with it when decision makers only want to get the objective values at a given confidence level. Assume that a confidence level δ_i is given for objective $f(x)$ and $g(x)$, we get the following crisp programming model.

$$\begin{aligned}
&\max\ \{\bar{f}, -\bar{g}\} \\
&\text{s.t.} \begin{cases}
\mathrm{Pos}\{36.8298\tilde{\mathrm{p}}_1\mathrm{x}_1 + 1.7596\tilde{\mathrm{p}}_2\mathrm{x}_2 + 4031.6\tilde{\mathrm{p}}_3\mathrm{x}_3 + 4031.6\tilde{\mathrm{p}}_4\mathrm{x}_4 \geq\ \bar{\mathrm{f}}\} \geq \delta_1 \\
\mathrm{Pos}\{36.8298\tilde{\mathrm{p}}_5\mathrm{x}_1 + 1.7596\tilde{\mathrm{p}}_6\mathrm{x}_2 + 4031.6\tilde{\mathrm{p}}_7\mathrm{x}_3 \geq\ -\bar{\mathrm{g}}\} \geq \delta_2 \\
x_1 + x_2 < 1 \\
x_3 + x_4 < 1 \\
36.8298x_1 + 1.7596x_2 + 4031.6x_4 > 2264.18 \\
1.7596x_2 + 4031.6x_3 + 4031.6x_4 > 1953.27 \\
1.7596x_2 + 4031.6x_4 > 1542.89 \\
36.8298x_1 + 1.7596x_2 + 4031.6x_3 < 3826.15 \\
36.8298x_1 + 4031.6x_3 < 3176.94 \\
1.7596x_2 + 4031.6x_3 < 2047.83 \\
0 < x_i < 1, i = 1, 2, 3, 4
\end{cases}
\end{aligned} \tag{3}$$

We take $\mathrm{Pos}\{36.8298\tilde{p}_1x_1 + 1.7596\tilde{p}_2x_2 + 4031.6\tilde{p}_3x_3 + 4031.6\tilde{p}_4x_4 \geq \bar{f}\} \geq \delta_1$ as an example to show how we convert it into an equivalent constraint.

Since $\tilde{p_1}$ is an L-R fuzzy variable and x_i are all more than 0. In fact, assume that $w \in [0,1]$, let $L(\frac{p_1-t}{\alpha_1}) = w$, then $x = p_1 - \alpha_1 L^{-1}(w)$.

Take $36.8298\tilde{p}_1x_1 + 1.7596\tilde{p}_2x_2 + 4031.6\tilde{p}_3x_3 + 4031.6\tilde{p}_4x_4 = a$, $36.8298(\tilde{p}_1 + \beta_1)x_1 + 1.7596(\tilde{p}_2 + \beta_2)x_2 + 4031.6(\tilde{p}_3 + \beta_3)x_3 + 4031.6(\tilde{p}_4 + \beta_4)x_4 = b$. Then it follows that:

$$\mathrm{Pos}\{\mathrm{a} \geq \bar{\mathrm{f}}\} = \begin{cases} 1, \text{ if } \bar{f} \leq a \\ R(\frac{\bar{f}-a}{36.8298\beta_1x_1+1.7596\beta_2x_2+4031.6\beta_3x_3+4031.6\beta_4x_4}), \text{ if } a < \bar{f} \leq b \\ 0, \text{ if } \bar{f} > b \end{cases} \tag{4}$$

Since $0 < \delta_1 \leq 1$, we have that $\mathrm{Pos}\{36.8298\tilde{p}_1x_1 + 1.7596\tilde{p}_2x_2 + 4031.6\tilde{p}_3x_3 + 4031.6\tilde{p}_4x_4 \geq \bar{f}\}\} \geq \delta_1$ is equivalent to $\bar{f} \leq 36.8298[p_1 + R^{-1}(\delta_1)\beta_1]x_1 + 1.7596[p_2 + R^{-1}(\delta_2)\beta_2]x_2 + 4031.6[p_3 + R^{-1}(\delta_3)\beta_3]x_3 + 4031.6[p_4 + R^{-1}(\delta_4)\beta_4]x_4$

We can get the other equivalent constraints in the same way. Then the equivalent model of is as follows.

$$\max\ \{\bar{f}, -\bar{g}\}$$
$$\text{s.t.} \begin{cases} \bar{f} \leq 36.8298[p_1 + R^{-1}(\delta_1)\beta_1]x_1 + 1.7596[p_2 + R^{-1}(\delta_2)\beta_2]x_2 \\ +4031.6[p_3 + R^{-1}(\delta_3)\beta_3]x_3 + 4031.6[p_4 + R^{-1}(\delta_4)\beta_4]x_4 \\ -\bar{g} \leq 36.8298[p_5 + R^{-1}(\delta_5)\beta_5]x_1 + 1.7596[p_6 + R^{-1}(\delta_6)\beta_6]x_2 \\ +4031.6[p_7 + R^{-1}(\delta_7)\beta_7]x_3 \\ x_1 + x_2 < 1 \\ x_3 + x_4 < 1 \\ 36.8298x_1 + 1.7596x_2 + 4031.6x_4 > 2264.18 \\ 1.7596x_2 + 4031.6x_3 + 4031.6x_4 > 1953.27 \\ 1.7596x_2 + 4031.6x_4 > 1542.89 \\ 36.8298x_1 + 1.7596x_2 + 4031.6x_3 < 3826.15 \\ 36.8298x_1 + 4031.6x_3 < 3176.94 \\ 1.7596x_2 + 4031.6x_3 < 2047.83 \\ 0 < x_i < 1, i = 1,2,3,4 \end{cases} \tag{5}$$

We insert the data of fuzzy variables into the model by Matlab, and the optimization results was given in Tab. 6.

4 Optimization and simulation

We then inserted the parameter values into the system dynamics model. A system simulation was then performed using the simulation software VENSIM and marked the data from 2008 as the initial conditions, time=0. Our simulation spans 8 years, from 1 to 8, and results in data analysis for year 2008 to year 2015. We depict the main pattern from Figs. 2 and 3.

The polysilicon industrial clusters realized a revenue of 6.96 billion in 2008, producing 1,230 ton of polysilicon. From Fig. 3, the planned production capacity of poly-silicon will come to 35,000 ton, and the output value of poly-silicon industrial clusters will be more than 90 billion through the extension and improved industry chain by 2015.

From Fig. 2, total energy consumption of polysilicon industry will be 62.236, 53.951 and 49.809 billion KWH according to the three schemes by 2015. However, the total energy consumption is constantly increasing, the total output value grow faster. Therefore, the whole social benefit is increasing considerably.

From Fig. 3, while providing primary raw materials for industries and processing products, the poly-silicon industry are also recycling a growing amount of silicon tetrachloride from other industries year by

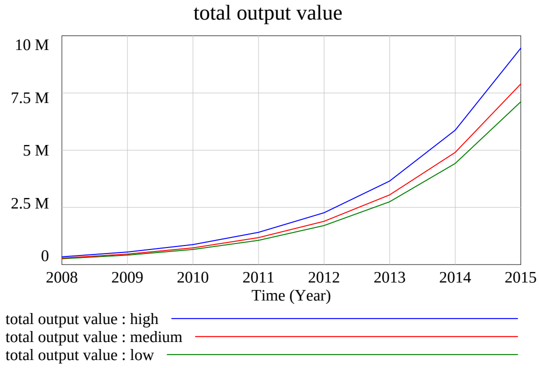

Fig. 2. Total output value

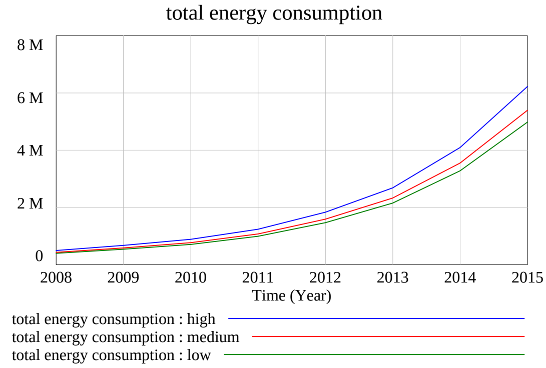

Fig. 3. Total energy consumption

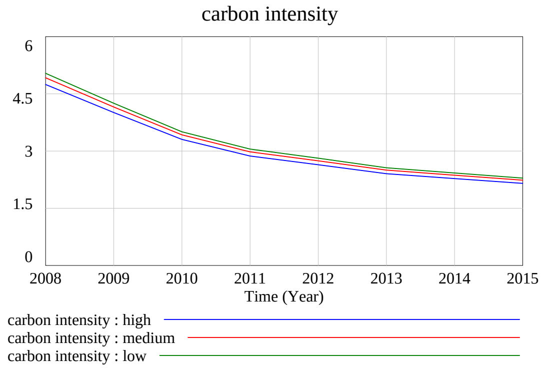

Fig. 4. Carbon intensity

year. Besides, the hydrochloric that is bound to come into being during the production process could also be recycled and reprocessed as raw material. Based on the three plans of high, medium and low, system simulation shows that the total output value of silicon industry will come up to 94.6, 78.9 and 71.1 billion RMB respectively. With the completion of industry chain extending, the realization of 90 Billion Poly-silicon Industry won't be far away.

From Fig. 4, environment will be greatly improved. Thanks to the technical improvement, carbon intensity is predicted to be reduced from 4.74 in 2008 to 2.15 in 2015, and plenty of cost will be cut down. Meanwhile, with the increased comprehensive utilization of solid and liquid waste, large quantities of downstream products will be developed and the cooperation between industries and companies will be strengthened as well. Environment would become better when economic benefits are generated. The studies of system simulation indicate that, the most effective way to maximize economic benefits while maintaining a low energy consumption, low emission and low carbon intensity is to extend the industry chain. In spite of the fact that emissions of carbon dioxide would be increased, the output value of poly-silicon industry would be greatly enhanced and carbon intensity decreased through the extending of industry chain.

5 Conclusions

In this paper, we studied the polysilicon industry with system dynamics, fuzzy set and multi-objective programming, and then developed a new model (SD-FMOP). The results from the SD-FMOP model are reasonable and credible. Through the analysis of the result, the overall course and the significance of certain elements of the polysilicon industry are clear. These results may help governments to establish more effective policy related to the polysilicon industry development. While SD-FMOP model used to study polysilicon systems planning is helpful in other areas and problems remain to be handled.

The next step of our feature research work is to improve the accuracy of calculation with other mathematical and statistical methods. For examplegrey theory is used to predict the parameter of industry system, and chaos theory is used to simulate the reaction of every element.

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