Renewable and Sustainable Energy Reviews 57 (2016) 999–1007

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Nuclear power development in China after the restart of new nuclear construction and approval: A system dynamics analysis

Xiaopeng Guo, Xiaodan Guo*

School of Economics and Management, North China Electric Power University, Hui Long Guan, Chang Ping District, Beijing 102206, China

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form
26 October 2015
Accepted 17 December 2015

Keywords:
Nuclear power development
Chinese nuclear policy
System dynamics
The restart of new nuclear construction and approval

ABSTRACT

After a three-year low valley caused by Fukushima nuclear accident, China finally restarted the approval of new coastal nuclear projects followed by the gradually matured new generation nuclear reactor technology and increasingly more supporting policies. Under this major shift of policy environment, China's nuclear power development would certainly stride on a new stage. This paper simulated the growth rate, development scale and evolvement path of China's nuclear power by establishing system dynamics models in the new-round construction. Under the background of changing nuclear power policy, this paper is helpful to master the dynamic development pattern of China's nuclear power system. These dynamic analyses also have reference meaning to the prediction of nuclear installed-capacity, nuclear generation, uranium import and other relevant factors. Further, the simulation results of this paper provide the Chinese government with suggestions of planning China's nuclear push, and deciding the strategy of uranium supply in order to secure the safe and steady nuclear power supply.

Contents

1. Introduction

After the Fukushima nuclear accident, people began to worry about the nuclear security and environmental issues. Although the nuclear power technology is advanced enough to ensure nuclear safety to a certain extent, China still had announced to suspend the approval of new nuclear plants since 2011 [1]. Under the pressure of rapid air-pollution growth and coal-dominated energy structure, after experiencing over 3 years cessation, China's nuclear power would begin its rapid development followed by the gradually matured new generation nuclear reactor technology and the increasing need of non-fossil energy. In December 2014, China

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* Corresponding author. Tel.: +86 15811440711.
E-mail addresses: 13520328997@163.com (X. Guo), 15811440711@163.com (X. Guo).

http://dx.doi.org/10.1016/j.rser.2015.12.190
1364-0321/

officially restarted the approval of new coastal nuclear power projects. This shift indicated that nuclear will act as a more and more important source of electric power in China [2].

As one of the world's largest energy consumers, China has focused quite much attention on the development of non-fossil energy [3]. In 2009, the Chinese government declared that the proportion of non-fossil energy in primary energy consumption should increase to 15% by 2020, and 20% by 2030. However, energy such as hydropower, solar energy and wind power still have developmental limitations or setbacks associated with cost and techniques in China. Therefore, considering the remarkable economic advantages compared to other clean energy resources, the Chinese government has given the nuclear power the top priority for development [4]. According to the data published by World Nuclear Association, there are 22 nuclear power units (19,095 MWe) currently in operation, and 26 units (28,528 MWe) under construction in China (December 2014). For the huge combined capacity of under construction, China is one of the countries with biggest potential in developing nuclear power [5]. But China's installed capacity ranks after tenth worldwide, which is far from the position of being the second biggest electric power country.

In order to speed up the development of nuclear power industry, Chinese government has launched many incentive policies and increased the target of installed nuclear power capacity several times. In China, the first policy mentioning nuclear power development is *The Medium- and Long-term Nuclear Power Development Plan* (*2005–2020*) approved by the China's State Council in October 2007. This development plan noted that nuclear power essentially does not produce gaseous pollutants, unlike thermal power. This plan also pointed out that China's operational nuclear installed capacity should reach 40,000 MWe by 2020, with 18,000 MWe under construction.

After noticing that developing nuclear energy is a feasible way for coordinating economy, energy and environment, China's National Energy Bureau raised the nuclear power development plan in November 2008. In order to promote the proportion of nuclear power to be above 5%, the installed capacity would be raised to above 70,000 MWe by 2020, with 30,000 MWe under construction [6].

Just after the Fukushima accident, Chinese government made a cessation of nuclear plant construction immediately and declared the suspended approval of new nuclear projects. This pause of new plant approvals leaded to the target adjustment of China's nuclear power development. The State Council cut the installed capacity to 60,000 MWe by 2020, and the capacity being under construction should reach 30,000 MWe. Moreover, the National nuclear power policy was moved from ‘positive development’ to ‘steady development with safety’.

In October 2012, the Chinese government has restarted a new-round nuclear power construction quickly after the Fukushima accident, but the approval of new projects is still suspended. *The Medium- and Long-term Development Plan for Nuclear Power* (*2011–2020*) issued by China's State Council announced that from 2011 to 2015, no nuclear power projects can be launched in inland provinces, and only the projects which have passed the adequate safety and environmental reviews can be constructed in coastal regions [7]. In the same month, China's State Council introduced a white paper on *Energy Policy* (*2012*). According to this white paper, more efforts will be put into the technological innovations of nuclear power, the application of advanced technology and the improvement of equipment level. The target of nuclear installed capacity was adjusted to 40,000 MWe by 2015.

With the increase of nuclear security technologies and the pressure of air-pollution mitigation, the Chinese government restarted the approval of new nuclear power projects three years after Fukushima accident. In November 2014, the National Development and Reform Commission officially declared to the State Council about the start of new nuclear projects approval. The reported nuclear units all belong to new coastal projects. In the same month, the State Council published the *Energy Development Strategy Action Plan* (*2014–2020*) adjusting the target of nuclear installed capacity to 58,000 MWe nuclear in 2020, with 30,000 MWe more under construction.

Due to the fast developed nuclear technologies, China's nuclear power will enjoy a rapid development in 2015 just after a three-year suspended approval of new plants. China's segment-leading nuclear technologies make nuclear wholesale price to grid to be less than thermal power plants with flue-gas desulfurization. China's nuclear installed capacity will get a significant boost from the 800-billion (CNY) investment of National Nuclear Corporation into new projects. After the restart of nuclear construction, China will probably set nuclear power as the foundation of power generation system result from its cost advantage and increasingly mature technologies [8]. Therefore, it is significant in analyzing and predicting the development path of China's nuclear power after the restart of new nuclear approval and construction.

This paper investigates the development route of nuclear power after the new-round nuclear construction, which helps explore the inherent relationship between policy support and nuclear power development. Taking China as a case, a system dynamics model was developed based on Vensim software, which offered a realistic platform for predicting the trends of China's nuclear power and power structure from 2012 to 2032. The simulation results measured the impact of the restart of new nuclear plants on nuclear power development and uranium resource utilization. Further this paper has reference meaning for the development of nuclear power and the import of uranium resources.

2. Literature review

2.1. Nuclear power development

China is the world's biggest energy consumer. The high levels of energy consumption have resulted in high PM10 emissions. Facing the increasing pressure of improving air-quality and meeting the rising electricity demand, the Chinese government has already set nuclear as a promising alternative energy.

Scholars have come to realize that politics will decide what direction and at what speed the country's nuclear energy development will take, how it should be done and who should lead the change [9]. In the past China's electricity development policies have led power industry to excessive investment in thermal power installed capacity and low operational efficiency [10,11]. Missing the first round of development, China began its nuclear energy industry only in the 1980s [12,13]. Along with the growth of energy conservation and emissions reduction awareness, the state council of China has promulgated many policies to guide the structure transformation of coal-fired power into new and efficient power such as nuclear power [14]. Generally speaking, China's nuclear power development has a promising future [15]. But on the other hand China's nuclear power development is still limited by nuclear technology diversity, shortage of uranium resources, and weak market competitiveness in the short term [16]. In order to promote nuclear development, some scholars have made suggestions that China should focus on enhancing domestic nuclear technology development and market competitiveness, accelerating the process of cleanly developing nuclear technology, and developing more efficient nuclear fuel cycle [17,18]. After the

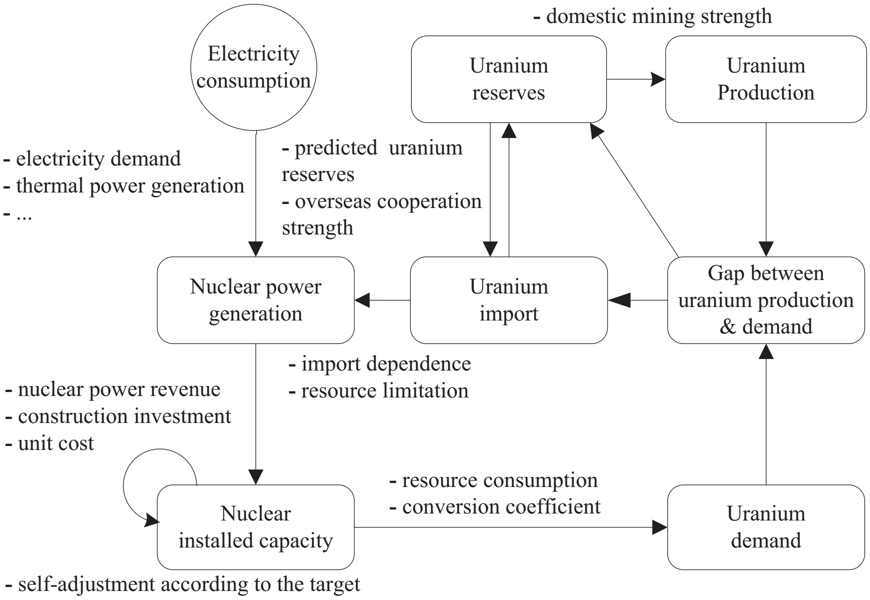

Fig. 1. Hypothesis model.

Fukushima nuclear accident, a number of scholars shifted their focus to the safe development and public acceptance [19–21].

Researches mentioned above mostly concentrate on the status of China's nuclear energy development using qualitative methods such as policy analysis, data charts and comparative analysis. So there is lack of studies on evaluating the development tendency of nuclear power quantitatively.

2.2. System dynamics (SD) method

Some scholars have used Long-range Energy Alternatives Planning (LEAP) model to investigate the development of electricity and energy sector under the influence of policies [22]. But the dynamic behavior of nuclear power system and the complicated feedback of uranium recourse are not taken into account in previous studies. In order to investigate the fundamental and dynamic process of nuclear power development driven by the restart of new nuclear approval, we should apply some descriptive and effective methodologies to simulate the transformation process. The development of nuclear power is a complex dynamic evolution process, which concerns many fields, so it has obvious nonlinear characteristics. The system dynamics (SD) method not only models the market's real behavior but also properly explains the relationship between main variables of the system [23]. Considering its advantages of integrity and dynamics, we set up a complete SD model by analyzing the factors of national economy, power generation, and uranium resource supply with stimulation of a new-round nuclear power construction to seek the development path of nuclear power industry.

The SD approach has been considered in the sustainable management of power systems, while it has not been addressed in the development prediction of nuclear power under China's latest energy development strategies. Scholars use SD methodology to simulate the process of energy efficiency improvement [23–26] and the behavior of the clean energy sectors [27,28]. SD models are also widely built to explore the effects of energy consumption and emission reduction policies [29–34].

With the changing nuclear developing goal, the construction and development path of China's nuclear power will receive tremendous influences. Under the new-round project approval, the former SD models are not suitable to predict China's current nuclear development. This paper investigates the development route of nuclear power after the new-round nuclear construction, which helps simulate the developing trends and explore the inherent relationship between policy support and nuclear power development.

3. Methodology

3.1. Model structure analysis

SD is a systems modeling and dynamic simulation methodology for analysis of dynamic complexity in socio-economic and biophysical systems [22]. Based on the principle of system thinking and feedback control theory, SD helps in understanding the time-varying behavior of complex systems [35]. Although other types of dynamic, quantitative modeling can predict the developing trends, SD model with the advantage of solving dynamic problems is the only method which can better simulate the process of nuclear power development. So this paper established a SD model to simulate the development of nuclear power system. The restart of new nuclear approval will influence the nuclear power system from six respects:

1) Restart the approval of new coastal nuclear projects;
2) Change the installed capacity goal again;
3) Accelerate nuclear development while preserving security;
4) Stimulate the new-round investment of nuclear power;
5) Absorb private capital into nuclear projects;
6) Start approvals for inland nuclear plants at the beginning of 13th Five-Year-Plan period (2016–2020).

As the first step of model structure analysis, the hypothesis of this SD model is represented by a major feedback loop, as shown in Fig. 1, which contains the principal blocks involved in. Blocks of ‘Nuclear power generation’, ‘Nuclear installed capacity’, ‘Uranium demand’, ‘Gap between uranium production and demand’, ‘Uranium import’, ‘Uranium reserves’ and ‘Uranium production’ are all depend on the its advanced block. The major feedback loop is completed by uranium resource limitation on ‘Nuclear power generation’ block produced by uranium import dependence. And on this base we built following analysis modules by integrating and expanding the hypothesis model.

Table 1
Description of key and external variables.

Variable	Unit	Initial value	Data source
GDP	10^8 Yuan	519,470	China Statistical Yearbook (2012)
Wind power generation	10^8 kW h	1164	Survey data of China Electricity Council
PV power generation	10^8 kW h	45	Survey data of China Electricity Council
Hydropower generation	10^8 kW h	8641	Survey data of China Electricity Council
Energy consumption	10^4 t	262,717	China Statistical Yearbook (2012)
Proportion of coal consumption in total energy consumption	–	0.668	China Statistical Yearbook (2012)
Coal consumption rate of power supply	g/kW h	321	China Statistical Yearbook (2012)
Coal consumption proportion of power industry	–	0.57	China Statistical Yearbook (2012)
Proportion of primary industry output	–	0.05	China Statistical Yearbook (2012)
Primary industrial electricity consumption intensity	kW h/Yuan	0.02	China Statistical Yearbook (2012)
Proportion of second industry output	–	0.5	China Statistical Yearbook (2012)
Second industrial electricity consumption intensity	kW h/Yuan	0.15	China Statistical Yearbook (2012)
Proportion of third industry output	–	0.45	China Statistical Yearbook (2012)
Third industrial electricity consumption intensity	kW h/Yuan	0.02	China Statistical Yearbook (2012)
Population increasing rate	–	0.005	China Statistical Yearbook (2012)
Population	10^8	13.5	China Statistical Yearbook (2012)
Per capita residential electricity consumption	kW h/person	443.83	survey data of China Electricity Council
Nuclear benchmark price	Yuan/kW h	[1]	Survey data of China Electricity Council
Construction cost of nuclear plants per capacity	Yuan/W	8.4965	Information-library of World Nuclear Association
Nuclear installed capacity	MW	12,570	Information-library of World Nuclear Association
Nuclear installed capacity target	MW	[2]	Action Plan for Energy Development
Conversion coefficient of uranium demand	kg/W	[3]	Information-library of World Nuclear Association
Uranium reserves	t	4273	Survey data of IAEA
Uranium production	t	1450	Survey data of IAEA
Changing rate of uranium recoverable resources	–	[4]	Information-library of World Nuclear Association
Uranium recoverable resources	t	199,100	Information-library of World Nuclear Association

[1] Initial value of nuclear benchmark price: ((2012, 0.45), (2013–2022, 0.42), (2023–2032, 0.39)).

[2] Initial value of nuclear installed capacity target: assumed to increase constantly based on target nodes set by *Action Plan for Energy Development*, ((2012, 12,570), (2013, 21,690), (2014, 30,810), (2015, 40,000), (2016, 43,600), (2017, 47,200), (2018, 50,800), (2019, 54,400), (2020, 58,000), (2021, 61,600), (2022, 65,200)).

[3] Initial value of conversion coefficient of uranium demand: ((2012–2020, 180), (2021–2032, 160)).

[4] Initial value of changing rate of uranium recoverable resources: ((2012, 0.03), (2013–2020, 0.04), (2021–2032, 0.05)).

(1) Electricity consumption module
It is general to divide the total electrical load into the primary industrial electricity consumption, the second industrial electricity consumption, the third industrial electricity consumption and the residential electricity consumption. Industrial electricity consumption can be predicted by the industrial output value and the industrial electricity consumption intensity. And residential electricity consumption can be predicted by population and per capita residential electricity consumption.

(2) Nuclear power generation module
From the perspective of electricity supply–demand balance, power generation can be predicted using electricity consumption data. Total generation can be generally divided into thermal power, hydropower, wind power, PV power and nuclear power generation. Thermal power generation is estimated from coal consumption rate of power supply and coal consumption of power industry. Hydropower generation, wind power generation and PV power generation can be predicted from historical data directly. Nuclear power generation is determined by the difference between predictions of electricity consumption and other power generation, and also limited by uranium resource shortage.

(3) Nuclear installed capacity module
Generation revenue of nuclear power can be estimated from power generation and nuclear benchmark price. Nuclear power plant will set aside a proportion of revenue to afford the investment of new capacity. After the new-round project approval, nuclear power will be China's key support project. The *Energy Development Strategy Action Plan* (*2014–2020*) has set target for the installed-capacity of nuclear power. In turn, the gap between capacity target and actual value will influence nuclear construction investment through policy adjustment factor.

(4) Uranium resource module
Uranium demand is determined by nuclear installed-capacity and conversion factor of nuclear demand. As an important strategic source, uranium has great significance to guarantee energy supply security. China built the strategic uranium reserves system in 2007 to ensure actual uranium reserves can meet the predicted value. And the uranium reserves gap will stimulate uranium import by strengthening overseas cooperation, and increase domestic uranium production by emphasizing uranium mining. Thus, we assume that uranium import is determined by the gap between uranium production and demand and overseas cooperation strength. This paper use uranium import dependence to weigh China's reliance on uranium import and the independent development of nuclear power. Further, uranium import dependence will have a limitation on the nuclear generation at the same time.

3.2. Model design

When it is considered that the analysis of causal relationship is finished, the result is a run model which is able to understand the development of nuclear power in China under the new policy environment. At this point, flow graph can be applied to simulate the development tendency of China's nuclear power depending on the simulated results. Firstly, we set the variables showing cumulative results to state variables (shown in boxes), the variables showing changing rate of state variables to rate variables (shown with double triangles), the rest relevant variables to auxiliary variables according to the characteristics of the factors. Rate variable is the differential of constant variable and has no essential difference with auxiliary variable. To reflect the current status of variables and the input of complex circular interactions, we provided initial values of key and external variables in Table 1. Most of the data used in this paper were collected from China Statistical

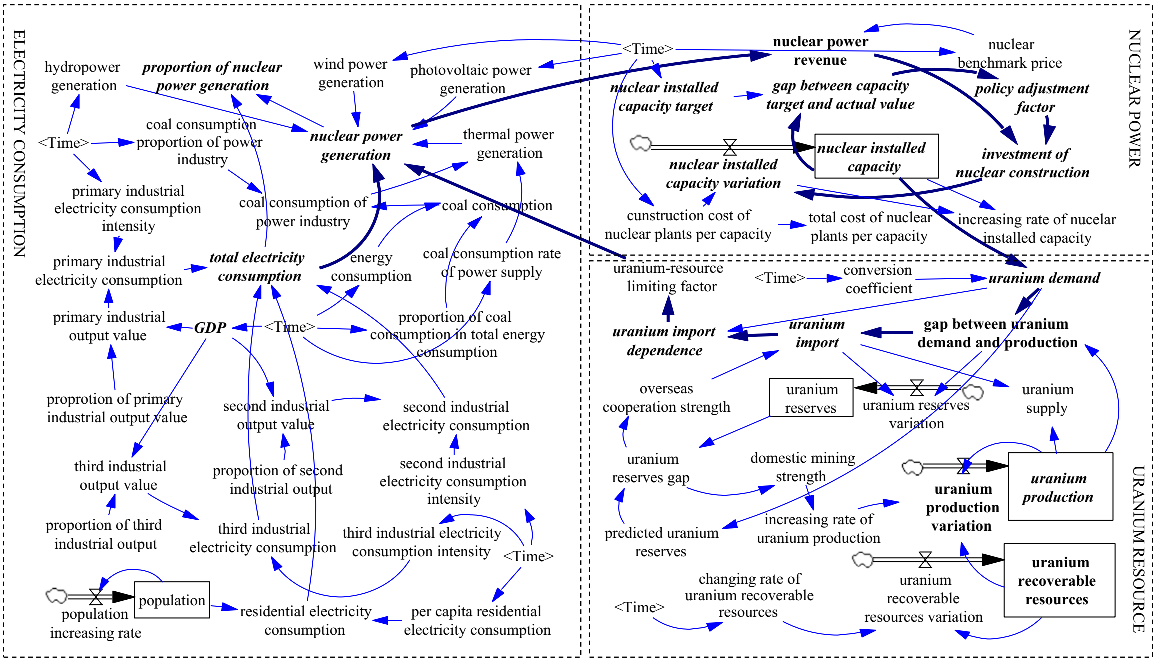

Fig. 2. Flow graph of China's nuclear power development after the restart of new project approval.

Yearbook, China Energy Statistical Yearbook, survey data of China Electricity Council, information-library of World Nuclear Association and survey data of International Atomic Energy Agency (IAEA).

Flow graph is a good tool to model the cause and effect relations between various components of the SD model. A flow graph of China's nuclear power development is established in this paper using Vensim software, as shown in Fig. 2. The directions of arrows indicate the influence interaction between those parameters. To create a more straight forward representation of Fig. 2, key loops and variables are shown in boldface.

There are more than 60 control equations in this flow chart used to express the quantitative relationships between parameters. Due to the limited length of the article, only the functional relationships with great significance and something unclear in the flow chart are enumerated as follows.

$$investment_{construction} = revenue_{nuclear} \times investment\_proportion_{discretionary} \times policy\_factor \tag{1}$$

$$capacity\_increase_{nuclear} = investment_{construction} \times 100/\ \cos t_{construction} \tag{2}$$

Investment of nuclear construction ($investment_{construction}$) is used as a basic valuation model to measure installed capacity, which depends on revenue of nuclear power industry ($revenue_{nuclear}$), discretionary investment proportion ($investment\_proportion_{discretionary}$) and influence coefficient of relevant policy ($policy\_factor$). Considering these factors, we can calculate the investment of nuclear construction as (1). The policy factor is a piecewise function of the gap between capacity target and actual value. The more the actual value lag behind target, the higher the policy factor. Thus, we set its expression in Vensim as 'IF THEN ELSE (gap between capacity target and actual value $>$20,000, 1.2, IF THEN ELSE (gap between capacity target and actual value $>$10,000, 1.1, IF THEN ELSE (gap between capacity target and actual value $>$0, 1, IF THEN ELSE (gap between capacity target and actual value $> -$20,000, 0.9, IF THEN ELSE (gap between capacity target and actual value $> -$40,000, 0.8, 0.7)))))'. With this assumption, the increasing rate of nuclear installed capacity ($capacity_increase_{nuclear}$) is as in (2), where construction cost of nuclear plants per capacity ($\cos\ t_{construction}$) changes over time.

$$capacity_{nuclear}(t) = capacity_{nuclear}(t-dt) + (capacity\_increase_{nuclear})dt \tag{3}$$

$$demand_{uranium} = conversion\_coefficient_{uranium} \times DELAY1(capacity_{nuclear}, 1)/1000 \tag{4}$$

Considering its characters, we employ an integral function to describe and forecast the nuclear installed capacity. Nuclear installed capacity at time t ($capacity_{nuclear}(t)$) depends on the capacity at time $t-dt$ and the increasing rate of nuclear installed capacity. Because of the interval between the finish of construction and the beginning of operation, uranium demand ($demand_{uranium}$) is influenced by the first-delay of nuclear installed capacity with a delay-period of one year and conversion coefficient as (4).

$$production\_variation_{uranium} = production_{uranium} \times production\_increase_{uranium} \times (1 - production_{uranium}/recoverable\_reserves_{uranium}) \tag{5}$$

$$import_{uranium} = gap_{demand\_production} \times cefficient_{overseas} = (demand_{uranium} - production_{uranium}) \times (1 + (reserves_{predicted} - reserves_{actual})/1000) \tag{6}$$

$$reserves_{actual}(t) = reserves_{actual}(t-dt) + (import_{uranium} - gap_{demand\_production})dt \tag{7}$$

Uranium production ($production_{uranium}$) is the integral of uranium production variation ($production\_variation_{uranium}$). Uranium production variation is a function of increasing rate of uranium production ($production\_increase_{uranium}$), uranium production and uranium recoverable reserves ($recoverable\_reserves_{uranium}$). And we assume that uranium import depends on the gap between uranium demand and production and coefficient of overseas cooperation strength ($cefficient_{overseas}$), which is a liner function of the gap between predicted uranium reserves and actual value as (6). The gap between predicted uranium reserves and actual value can also influence the increasing rate of uranium production by emphasizing the intensity of domestic uranium mining. Different from uranium recoverable resources, uranium reserves are strategic resources of uranium stored by government and enterprises, which can be readily used, in order to deal with short-term uranium supply shocks. In turn uranium import decides the variation of uranium reserves as (7). Uranium import dependence, the percentage that uranium import contribute to whole uranium demand, is used to reflect China's dependence on imported uranium resource.

3.3. *Model reality check*

The validity of the model needs to be tested by model debugging and verification when model design is finished. This paper used reality check to justify the appropriateness of the proposed model selecting historical data of four variables, which have overall situation and representativeness, in 2012–2014. The inspection results of reality check are shown in Table 2.

Reality check results indicate that the relative errors are all controlled within −10% to 10%. Thus the simulated results of our SD model are basically in line with the actual development situation of China's nuclear power. Overall, our SD model, which has good simulation ability, is an accurate reflection of nuclear power's development tendency under China's ever-changing policy and economic environment. It can be used as the basis of nuclear power developing scenario simulation and forecasting in China.

4. Results and discussion

First in this section, simulation is realized using Vensim software by establishing a SD model of nuclear power development after the restart of new nuclear approvals. Chinese government restarted a new-round nuclear power construction in 2012, and committed to peak carbon emission in 2030. Nuclear power is extremely necessary for achieving China's carbon emission reduction commitments. On the other hand, China makes the national economic and social development plan every five years, which can significantly change the development trend of nuclear power. Thus, we set the length of time horizon as 20 years, and set 2032 as the end year in order to simulate nuclear development in this typical period. Simulated results can help seek the applicable development tendency of China's nuclear power. Later, the sensitivity of key parameters is analyzed to know how they affect this SD system.

4.1. *Nuclear power generation*

The nuclear power generation and its proportion are shown in Fig. 3. Influenced by the restriction of nuclear security and new-project approval, between 2012 and 2016 China's nuclear generation will remain stable and relatively low. In this stage, the proportion of nuclear power generation accounts for less than 5% of the entire national power. By contrast, this proportion for developed countries, such as France, will be over 60% during the same period. Simulated by the new-round nuclear construction and the development of inland nuclear power, the growth of nuclear power generation will accelerate by 2016. By the end of 13th five-year, China's nuclear power generation will reach 682.98 billion kW h. The proportion of nuclear power generation will be 7.22% at that time. Starting from 2024, China's nuclear power will enter into new rising period. From that time the growth rate of nuclear power generation will continuously increase driven by relatively less dependence on uranium import. But the proportion of nuclear generation will maintain at about 10% with slight fluctuations in this stage. Due to China's booming renewable energy generation, this proportion will not be changed greatly in short term unless there are further policy incentives.

It is worth noting that nuclear power generation alone with its proportion seems to drop every other year. This is because that the electricity consumption intensities of primary and second industry are assumed to be ladder-shaped decreasing functions, but their output values enjoy accelerating growth. Thus, their electricity consumptions drop precipitously at jumping points, and total electricity consumption fluctuates. Finally, linear interactions bring these fluctuations to nuclear power generation, to revenue, to construction investment, eventually to installed-capacity growth.

4.2. *Nuclear installed capacity*

Nuclear power revenue will keep its growth momentum during the whole simulation, and reach its peak at 986.3 billion (CNY) at 2032. Nuclear power investment growth has dropped sharply in 2012 affected by the Fukushima accident. The restart of new nuclear approval can stimulate a new-round of investment. We can know from Fig. 4 that nuclear power revenue and construction investment will both enjoy significant boosts during the 13th Five-Year-Plan period. As private capital absorbed into nuclear projects, the investment will remain at about 90 billion (CNY) during the 14th Five-Year-Plan period. After this round of nuclear-investment boom, the investment will start to remain steady by 2025, at about 100 billion Yuan per year, because of the gradual progress toward nuclear power's maturity.

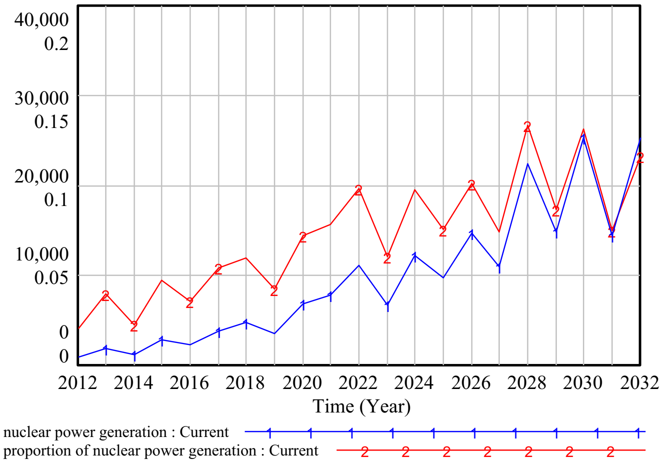

Fig. 3. Nuclear power generation (10^8 kW h) and proportion.

Table 2
Model reality check.

Year	GDP (10^8 Yuan)			Total electricity generation (10^8 kW h)			Nuclear installed capacity (MWe)			Uranium production (t)		
	True value	Simulation	Error (%)	True value	Simulation	Error (%)	True value	Simulation	Error (%)	True value	Simulation	Error (%)
2012	519,470	493,902	−4.92	49,865	47,855	−4.03	12,570	12,570	0.00	1450	1450	0.00
2013	568,845	562,470	−1.12	53,720	48,406	−9.89	14,660	13,754	−6.18	1500	1519	1.27
2014	636,463	640,557	0.64	54,638	51,860	−5.08	19,880	17,956	−9.68	1500	1594	6.27

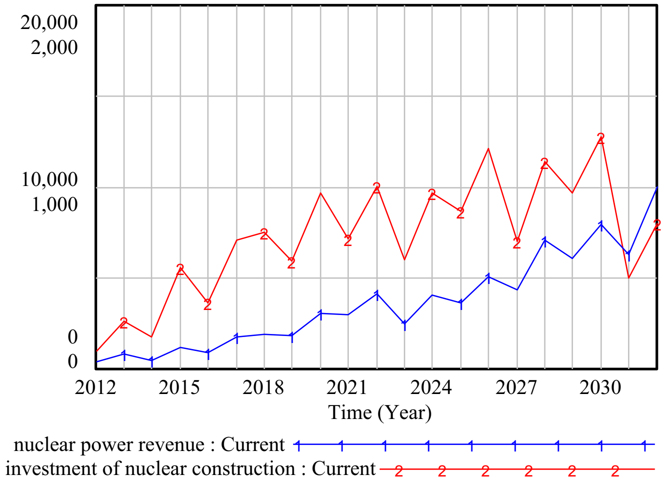

Fig. 4. Nuclear power revenue and investment of nuclear construction (10^8 Yuan).

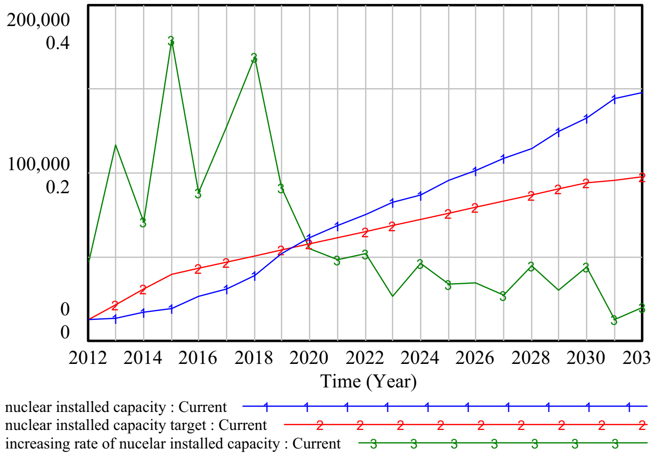

Fig. 5. Nuclear installed capacity and capacity target (MW).

Nuclear installed capacity is directly impacted by the investment. In 2012 China's nuclear installed capacity is only 12,570 MWe accounting for 1.09% of the total installed capacity. As shown in Fig. 5, this capacity will experience accelerated growth since 2014 because of the restart of new project approval. But by 2015, it can hardly met the target set by *Action Plan for Energy Development* (50,000 MWe). In turn, the huge gap between capacity target and actual value will stimulate construction investment though various adjustment policies. Under investment incentives, the capacity will basically maintain an over 20% growth in 2015–2018. By 2020, the capacity will reach 61,609.05 MWe, with an annual increasing speed of 10.99%, which exceeds the installed-capacity target set by the *Energy Development Strategy Action Plan* (*2014–2020*) (58,000 MWe) for the first time. At that time nuclear installed-capacity will account for 4.02% of China's total installed-capacity. Since then, this exceedance will gradually expand. After 2023, the increasing rate of nuclear installed-capacity will remain under 10%. By 2030, nuclear installed capacity will reach 132,379 MWe, and nuclear power will replace about 500 million tons of coal and about 900 million tons of carbon dioxide. During the simulation period, the capacity will reach its peak in 2032 at 147,757 MWe.

4.3. Uranium resource

As shown in Fig. 6, China's uranium production was 1450 μt in 2012. It will increase to 2375.24 μt by 2020, with an annual increasing speed of 7.29%. Compared with mass demand and amazing developing speed, China's uranium production is not enough to satisfy the ever-increasing demand, accounting for less than 10% of world total.

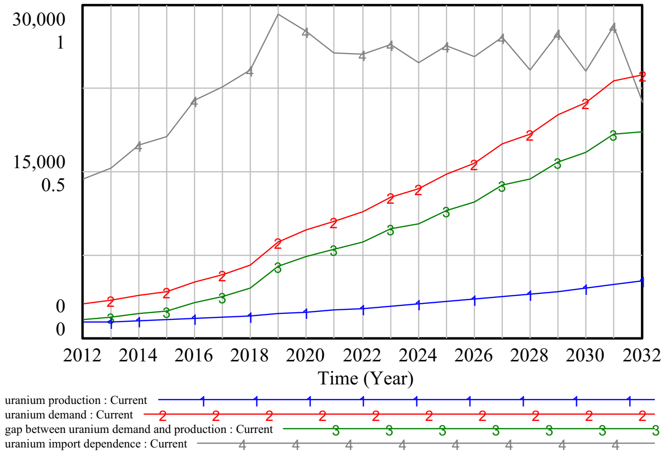

Fig. 6. Uranium production, demand, gap between demand and production (t) and import dependence.

In 2012, the uranium demand is 3142.5 μt, the gap between demand and production is 1692.5 μt, and uranium import dependence is 47.77%. Fig. 6 indicates that even though China's uranium production continues to increase, there will still be an enlarging demand–production gap. By 2015, China's uranium demand will be 4170.56 μt, demand–production gap will be 2464.25 μt, and import dependence will reach 60.49%. This dependence is lower than earlier estimates of 65% made by WNA, because nuclear installed-capacity fails to perform as expected. With the significant boost of installed capacity, import dependence will peak at 97.32% in 2019, uranium demand will reach 8692.40 μt, and the gap between production & demand will be 6488.14 μt. But China's gradually mature uranium reserves system will stop this rapid growth of import dependence, and keep the dependence remain at around 80% since 2021. The great poorness of uranium-resource will seriously restrict China's nuclear power development [6]. Under this severe situation, it is urgent for China to quickly build an efficient uranium reserve system early to ensure the safety of uranium and strengthen the cooperation with resource-rich countries.

4.4. Sensitivity analysis

The present parameters setting of transfer functions have certain degrees of subjectivity, so it would be interesting to see the variation ranges of the system's simulated results for different settings of key parameters at this point. These variation ranges are obtained by sensitivity analysis on the basis of existing SD model. This paper analyzed the sensitivities of nuclear power generation, nuclear installed capacity and uranium import in single-factor changes of nuclear benchmark price (raised by 2%, 5% and 10%), nuclear installed-capacity target (raised by 2%, 5% and 10%) and coal consumption (reduced by 2%, 5% and 10%) respectively. The results of sensitivity analysis are shown in Table 3.

The analysis results provide the Chinese government with suggestions of planning China's nuclear push. We can tell from Table 3 that: 1) Raising nuclear benchmark price will led to greater dependence on uranium import while adding nuclear installed-capacity before 2020, which will limit nuclear power generation. After 2020 China's uranium reserve system will be relatively mature to ensure harmonious development of nuclear installed-capacity and generation. 2) Raising nuclear installed-capacity

Table 3
The results of sensitivity analysis.

Parameter		Nuclear benchmark price			Nuclear installed-capacity target			Coal consumption		
		2%	5%	10%	2%	5%	10%	−2%	−5%	−10%
Nuclear power generation	2015	−0.51	−1.27	−2.52	−1.22	−1.22	−1.22	9.63	15.29	29.21
	2020	−0.50	−1.20	−2.26	0.08	0.08	−7.26	2.96	8.11	29.90
	2030	3.85	4.17	5.08	0.07	0.07	0.79	0.10	16.95	24.60
Nuclear installed capacity	2015	0.62	1.54	3.07	1.57	1.57	1.57	15.36	21.13	39.28
	2020	0.85	2.11	4.15	0.25	0.25	3.83	4.30	12.63	21.79
	2030	0.48	1.17	3.97	0.12	0.12	1.89	0.05	1.44	4.84
Uranium import dependence	2015	0.80	1.98	3.91	1.94	1.94	1.94	18.10	23.96	37.83
	2020	0.19	0.45	0.86	−0.03	−0.03	2.98	1.10	2.28	0.30
	2030	−1.99	−2.15	−2.63	−0.04	−0.04	−0.49	1.66	5.63	5.54

target will face the similar problem as raising nuclear benchmark price. But the former can speed up the forming of uranium reserve system. So that nuclear generation growth will be restored earlier, with a simultaneous growth in installed-capacity. 3) Reducing coal consumption can significantly increase nuclear installed capacity without decreasing generation. Thus, coal consumption controlling is an available mean to stimulate China's nuclear power development. Unfortunately, coal consumption reduction seems to be impossible in the short run, because of China's high reliance on coal resource.

5. Conclusions

After the restart of new nuclear approval, China's nuclear power would move out of a three-year low valley caused by Fukushima nuclear accident. The simulation results of this paper indicate that:

1) By 2020 China's nuclear power generation will reach 682.98 billion kW h accounting for 7.22% of total power generation. But due to China's booming renewable energy generation, this proportion will not be changed greatly in short term unless there are further policy incentives.
2) Influence by Fukushima accident, by 2015 China can hardly meet the nuclear capacity target set before. The lifting of inland nuclear restriction will bring an unprecedented developmental opportunity. The capacity will begin its accelerated growth since 2015, and reach 61,609.5 MWe by 2020 with an annual increasing speed of 10.99% accounting for 4.02% of total installed-capacity, which is higher than the installed-capacity target set by government.
3) Considering the insufficiency of uranium resource, rapid development will pose a great challenge to the safety of uranium supply. Import dependence will be 60.49% by 2015, which is lower than earlier estimates of 65%, because nuclear installed-capacity fails to perform as expected. But the dependence will reach its peak at 97.32% in 2019, and remain at around 80% since 2021. Thus China should build an efficient uranium reserve system early to respond the changing supply situation, and strengthen the cooperation with those resource-rich countries simultaneously.
4) Coal consumption controlling is an available mean to accelerate nuclear power development, which can increase installed capacity as well as generation. But there is still a long way to go before China gets rid of its high reliance on coal resource.

In conclusion, China's nuclear power faces both opportunities and challenges after the restart of new project approval. As a clean and efficient energy, nuclear power will play an irreplaceable important role at the aspects of ensuring energy supply security and eliminating air-pollution emission. On the other hand, China should focus on uranium supply security and nuclear safety to realize the rapid and healthy development of nuclear power.

Acknowledgments

Project supported by the Fundamental Research Funds for the Central Universities of China (No. MS201439).

References

[1] Sun C, Zhu X. Evaluating the public perceptions of nuclear power in China: evidence from a contingent valuation survey. Energy Policy 2014;69:397–405.
[2] Tang L, Yu L, He K. A novel data-characteristic-driven modeling methodology for nuclear energy consumption forecasting. Appl Energy 2014;128:1–14.
[3] Zhou Y. Why is China going nuclear? Energy Policy 2010;38:3755–62.
[4] Li A, Lin B. Comparing climate policies to reduce carbon emissions in China. Energy Policy 2013;60:667–74.
[5] Shi H, Song H. Applying the real option approach on nuclear power project decision making. Energy Procedia 2013;39:193–8.
[6] Yan Q, Wang A, Wang G, Yu W, Chen Q. Nuclear power development in China and uranium demand forecast: based on analysis of global current situation. Prog Nucl Energy 2014;53:742–7.
[7] Nathaniel G, Matthew K. The political economy of China's energy and climate paradox. Energy Res Soc Sci 2014;4:135–8.
[8] Guizhen H, Arthur PM, Zhang L, Lu Y. Public participation and trust in nuclear power development in China. Renew Sustain Energy Rev 2013;23:1–11.
[9] Wang Y, Li N, Li J. Media coverage and government policy of nuclear power in the People's Republic of China. Prog Nucl Energy 2014;77:214–23.
[10] Zhao X, Thomas PL, Cui S. Lurching towards markets for power: China's electricity policy 1985–2007. Appl Energy 2012;94:148–55.
[11] Peggy M, Kenneth BK. Modelling tools to evaluate China's future energy system – a review of the Chinese perspective. Energy 2014;69:132–43.
[12] Wang D, Lu Y. Roles and prospect of nuclear power in China's energy supply strategy. Nucl Eng Des 2002;218:3–12.
[13] Wang Q. China needing a cautious approach to nuclear power strategy. Energy Policy 2009;37:2487–91.
[14] Cai L, Guo J, Zhu L. China's future power structure analysis based on LEAP. Energy Sources Part A: Recovery Util Environ Effects 2013;35:2113–22.
[15] Fang D, Li H. Clean development mechanism and nuclear energy in China. Prog Nucl Energy 2000;37:107–11.
[16] Zhou Y, Christhian R, Chen P, Jonathan H. Is China ready for its nuclear expansion? Energy Policy 2011;39:771–81.
[17] Zhou S, Zhang X. Nuclear energy development in China: a study of opportunities and challenges. Energy 2010;35:4282–8.
[18] Chen J, Wei M, Liu X, Wang J. Back-end of nuclear fuel cycle in China. Prog Nucl Energy 2012;54:46–8.
[19] Xu Y. The struggle for safe nuclear expansion in China. Energy Policy 2014;73:21–9.
[20] Wang Q, Chen X. Regulatory transparency—how China can learn from Japan's nuclear regulatory failures? Renew Sustain Energy Rev 2012;16:3574–8.
[21] Mu R, Zuo J, Yuan X. China's approach to nuclear safety—from the perspective of policy and institutional system. Energy Policy 2015;76:161–72.
[22] Özer Betül, Görgün Erdem, Incecik Selahattin. The scenario analysis on CO_2 emission mitigation potential in the Turkish electricity sector: 2006–2030. Energy 2013;49:395–403.
[23] SheikhiFini A, Parsa Moghaddam M, Sheikh-El-Eslami MK. A dynamic model for distributed energy resource expansion planning considering multi-resource support schemes. Electr Power Energy Syst 2014;60:357–66.

[24] Zhu H, Huang G. Dynamic stochastic fractional programming for sustainable management of electric power systems. Electr Power Energy Syst 2013;53:553–63.

[25] Salman A, Razman bin MT. Using system dynamics to evaluate renewable electricity development in Malaysia. Renew Electr Dev 2013;43:24–39.

[26] Li L, Sun Z. Dynamic energy control for energy efficiency improvement of sustainable manufacturing systems using Markov decision process. IEEE Trans Syst Man Cybern—Syst 2013;43:1195–205.

[27] Garcia E, Mohanty A, Lin W, Cherry S. Dynamic analysis of hybrid energy systems under flexible operation and variable renewable generation—Part II: dynamic cost analysis. Energy 2013;52:17–26.

[28] Santiago M, Luis JM, Felipe B. A system dynamics approach for the photovoltaic energy market in Spain. Energy Policy 2013;60:142–54.

[29] Liu L, Zong H, Zhao E, Chen C, Wang J. Can China realize its carbon emission reduction goal in 2020: from the perspective of thermal power development. Appl Energy 2014;124:199–212.

[30] Zhao X, Ma Q, Yang R. Factors influencing CO_2 emissions in China's power industry: co-integration analysis. Energy Policy 2013;57:89–98.

[31] Ali K, Mustafa H. Exploring the options for carbon dioxide mitigation in Turkish electric power industry: system dynamics approach. Energy Policy 2013;60:675–86.

[32] Feng Y, Chen S, Zhang L. System dynamics modeling for urban energy consumption and CO_2 emissions: a case study of Beijing, China. Ecol Model 2013;252:44–52.

[33] Li F, Dong S, Li Z, Li Y, Wan Y. The improvement of CO_2 emission reduction policies based on system dynamics method in traditional industrial region with large CO_2 emission. Energy Policy 2012;51:683–95.

[34] Nastaran A, Abbas S. A system dynamics model for analyzing energy consumption and CO_2 emission in Iranian cement industry under various production and export scenarios. Energy Policy 2013;58:75–89.

[35] Zheng M, Zhang K, Dong J. Overall review of China's wind power industry: status quo, existing problems and perspective for future development. Renew Sustain Energy Rev 2013;24:379–86.