Estimating Peak Uranium Production in China - Based on a Stella Model[*]

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ABSTRACT

This paper uses the Logistic Curve and the STELLA Model to simulate the Hubbert Peak uranium production in China. We used three scenarios to estimate China's Peak uranium. And the results are quite robust. According to Scenario 3, the Hubbert Peak uranium production is expected to be reached in 2065 with 4605 tons per year. Before the peak, China's uranium demand will grow at the rate of about 7.69% per year, which is about three times the growth rate of production. China's uranium import dependence is estimated to continue to increase. In order to improve uranium resources security, the Chinese government needs to increase investment in uranium ore exploration, encourage private sector's investment in uranium production to promote competition, and improve cooperation with non-uranium mining enterprises for more efficient use of resources. To enhance the country's uranium security, China should establish development funds, accelerate acquisition of uranium enterprises abroad, increase R&D in the unconventional uranium resources such as phosphate mine, and take advantage of price downturn in uranium market to increase strategic reserves.

Key words: Uranium, Hubbert Peak, Logistic curve, STELLA model
JEL codes: Q47, C15, O13

1. Introduction

In face with growing environmental pollution, China’s coal-to-gas transition in energy use has led to increasing natural gas undersupply and soaring energy prices. The search for alternative energy source becomes imminent. Because of the emissions of traditional fossil energy sources and high costs of solar energy supply, China is forced to consider substituting nuclear energy for coal and using natural gas for heating and electricity generation. However, China is more dependent on imports for uranium ore, the major input of nuclear power plants, than for natural gas. China's uranium imports in 2017 accounted for 80.1% of the total demand (World Nuclear Association, 2018). Moreover, the source of China’s uranium imports is over concentrated on countries such as Australia, Canada, Kazakhstan, Uzbekistan and Namibia. Among these countries, Australia and Canada are traditional allies of the United States; Kazakhstan and Uzbekistan allies of Russia, and Namibia under the influence of France and suffering from political turmoil. Once in the event of war, geopolitical conflicts and other potential threats, China’s uranium imports are subject to high risk. Therefore, it is of great policy importance to study the gap between supply and demand of uranium in China and forecast the peak uranium.

To study Peak Uranium in China, we need to examine both flow variables and stock variables. In general, there are two ways to predict the supply of conventional and non-conventional uranium. One is to look at the geological exploration data. The other is to analyze the historical Hubbert curve and use these data to forecast the uranium supply. The use of historical trends to assess reserves and resources facilitates prediction of potential uranium supplies and provides reasonable parameter range for modeling. Discovery of exhaustible resources such as uranium has two fundamental effects on production: the information effect and the depletion effect (Uhler, 1976). By the information effect annual production of resources will be increased as new geological and technical information is gained with new resource being discovered continuously. By the depletion effect annual production and the probability of discovering new resources will decrease subject to the constraint of limited ultimate resource. The information effect and depletion effect jointly determine when peak production occurs.

In this paper, we use the Logistic curve and the STELLA model rather than the geologic forecasting to simulate the Hubbert curve to forecast the long-term prospects for uranium production in China and to determine how long the uranium production will last and when it peaks. This will provide a basis for prediction of future uranium price trend and formulating China's policy response to the uranium undersupply.

1.1. China Uranium Categories and Geographical Distribution Characteristics

There are various uranium deposit types in China. Uranium deposits mainly in small and medium-size form groups of ore fields. Ore quality is mainly medium and low grade, with the average grade of 0.1%-0.2% U and the quality of ore deposits in some parts of China can reach 0.5% U. Some volcanic rocks and granite deposits are in higher grade. In terms of uranium deposit types in China, the predominant type is hydrothermal (62.6%), the following one sedimentary (34.2%) and magmatic rocks about 3.2% (see Table 1). For subtypes, granite, volcanic and sandstone constitute the three major ones in China. The proportion of sandstone type has increased in recent years. But the deposits distribution is geographically uneven. The hydrothermal type is mainly located in the southeast and the sandstone type is concentrated in the northwest.

In recent years, China has made considerable progress in the exploration of sandstone-type uranium deposits. With financial support from national resources survey projects, the nuclear geology system has successively discovered many sandstone-type uranium deposits in numerous sizes in Xinjiang Yili Basin. Among them, China's first kiloton natural uranium production plant was built in July 2016 in the second phase of the Mengqiuer Uranium Project. CNNC (The China National Nuclear Corporation) explored the in-situ leaching process at this plant and this made China the second country in the world to master CO_2+O_2 underground uranium mining technology and industrial applications. The completion of Mengqiuer

Uranium Project marks a breakthrough in China’s large-scale, intensive and industrial exploitation of low-grade, low permeability, high carbonate and high salinity sandstone-type uranium resources. China accumulated experience in sandstone-type uranium exploration and mining.

As we can see from the geographical distribution of uranium deposits, there are currently seven production plants and they are in Inner Mongolia, Jiangxi, Xinjiang, Guangdong, Guangxi and Hunan provinces, specifically Fuzhou and Chongyi in Jiangxi Province in eastern China; Lam Tin in Shaanxi in central China; Benxi and Qinglong in Liaoning Province in northeastern China; Shaoguan in Guangdong Province in southern China; and Yining in Xinjiang in northwestern China. In addition, large-scale uranium deposits have also been discovered in Daying in Inner Mongolia, Tarim Basin, Ili Basin and Junggar Basin in Xinjiang and Songliao Basin in Northeast China.

In addition to exploration of domestic uranium ore, China is also actively engaged in foreign uranium mining. Both CNNC (The China National Nuclear Corporation) and CGN (China General Nuclear Power Group) have uranium mining and trading licences. Among them, CNNC also signed a strategic cooperation agreement with Sinosteel Corporation to jointly invest in overseas uranium resources. From Table 2, we can see that the main target countries of overseas holding by CNNC, CGN and Sinosteel include Namibia, Niger and Zimbabwe in Africa, Kazakhstan and Uzbekistan in Central Asia and other major uranium producing countries such as Canada, Australia and Mongolia.

[Insert Table 1 & Table 2 about here]

1.2. China’s Uranium Demand-Supply Gap

China’s demand for nuclear energy and uranium will increase over the medium- and long- term due to problems arising from its special energy structure. In 2016, the share of coal in China’s energy source is still as high as 61.8% (BP, 2017). This has led to the serious air pollution in China in recent years and the resulting environmental pollution and economic losses are tremendous. According to a World Bank (2016) report on air pollution costs, China reported a total of 1.6 million air-pollution-caused premature deaths in 2013. Central and local governments are forced to find clean energy to deal with the crisis. However, alternative sources of energy have their limitations, for example high costs of solar and wind power. The only clean energy available in the short term seems to be nuclear energy. But nuclear energy also has its inherent flaws. The first issue is nuclear power safety. The incident at Fukushima in Japan (2011) and the Chernobyl incident are examples. In addition, China is also faced with the risk in availability of uranium due to geopolitical conflicts. Despite these challenges, China’s vigorous nuclear power development is a second-best effort in response to the huge demand gap in clean energy resources.

China’s uranium demand has substantial room for growth. First, the share of nuclear power in primary energy consumption in China is low. As of December 2017, China’s nuclear power accounted for only 3.6%, well below the global average of 11% (Figure 1). In addition, the growth of nuclear power in China is by far the largest driver of the world’s nuclear power growth. From 2011 to 2017, China accounted for 59.5% of the global total of new connections to the electricity grid. China accounted for 23.7% of the world’s new constructions (Table 3). In 2016 alone, China made 5 new reactors connecting to the grid at Changjiang, Fangchenggang, Fuqing, Hongyanhe, and Ningde respectively, adding some 4.6GWe, accounting for about 50% of the year’s global nuclear capacity increase. In 2017, China has 20 of the world’s 57 nuclear power stations under construction, 35% of the total. The ambitious goal of China is to finish 40 nuclear power plants within the next five years and strive to reach a total of 58 GWe by 2020. By then China will account for 12.8% of global uranium demand. At present, China has purchased 95% of the uranium exports from Kazakhstan, Uzbekistan, Namibia and Australia.

[Insert Figure 1 about here]

[Insert Table 3 about here]

Compared with the demand, China’s uranium supply is quite limited. China has the eighth largest identified uranium deposits in the world. However, relative to the rapid development of nuclear power plants, the –supply of uranium falls short considerably. China’s uranium production only accounted for 2.8% of the world in 2017.As of January 2018, China’s installed capacity of nuclear power reached 8.8% of the world’s total. However, the increased capacity is overwhelmed by China’s ambition in developing nuclear power. NEA (Nuclear Energy Agency) and IAEA (International Atomic Energy Agency) predict that by 2035 China will account for 19.6% of the world’s reactor-related uranium demand. This does not include China’s uranium demand for strategic reserves and military applications. Figure 2 shows that China’s uranium supply and demand gap continues to rise. China’s dependence on foreign uranium climbed rapidly from 51% in 2007 to 80.1% in 2017. This gap will continue to rise in the coming decades. According to the data from the World Nuclear Association etc., in the near future, domestic production, imports, and overseas mining by Chinese companies account for 24%, 28% and 48% of China’s uranium demand respectively. In other words, domestic production accounts for one quarter of China’s uranium demand and the share of domestic production will continue to decline.

[Insert Figure 2 about here]

1.3. Hubbert Peak and Uranium Peak

The main purpose of this paper is to examine the historical trends of uranium production and reserves in China. As early as 1950, Hubbert proposed a model for extrapolating curves of depletable resources such as fossil fuels. The production rate is supposed to be zero at the beginning, and zero again once resources are fully depleted. Over this procedure, the production curve reaches one or more maximum values. The shape of the curve will vary with the reserve size of nonrenewable resources and it generally presents a bell curve. But Hubbert did not give any formal mathematical model. Hubbert (1974) proposed the Logistic curve based on the previous research and conducted further research along the line.

The Logistic curve and its derivatives are often referred to as Hubbert curves. Based on Hubbert curves, the term “peak oil” was thus proposed when Campbell and Laherrere founded the Association for the Study of Peak Oil (ASPO in 2002. Peak oil refers to the point in time at which a country or the world reaches the maximum possible production of oil per unit of time. After that, demand for oil starts to outstrip supply, oil supply never returns to its original level, and mining becomes increasingly difficult and expensive (Hubbert, 1956).

After Hubbert curve successfully predicted the peak oil production in the U.S. taking place in 1969-1971, it has been widely used for peak prediction for fossil fuels such as coal, natural gas and, particularly, oil. Although some (Greene 2010) think there is still plenty of oil, researchers increasingly believe Peak Oil has passed or is approaching soon (Kerr, 2011; Murray and King, 2012). Szkloet al. (2007) compare the forecasting differences in Brazilian oil production between Hubbert curve and Hotelling model. And they argue that the Hubbert curve implicitly emphasizes the effect of information and depletion on cumulative discoveries over time, and the positive impact of information on expanding reserves may exceed the negative effects of depletion. According to them, the Hubbert curve is better in predicting Brazil's oil production. Sorrell et al. (2009) conclude that the peak of the world’s conventional oil production may occur before 2030 and the increase in unconventional oil such as tar sands and shale oil is unlikely to make up for the shortfall caused by conventional oil. Other scholars examine unconventional oil spikes and believe that shale oil production reaches peak production rates much faster than conventional oil (Kerr 2011). Mohr and Evans (2010) discuss spike for unconventional oil production from heavy oil, natural bitumen (oil sands, tar sands) and oil shale and argue that it would be quite difficult for unconventional oil production to make up for conventional oil. They believe that even under the most optimistic scenario, unconventional oil production can only postpone the approaching of the world's peak oil by up to 25 years.

However, the traditional single-cycle Hubbert curve has its limitations. It does not consider multiple cycles. Changes in political, economic and technological factors can lead to multiple cycles in oil production. But Hubbert curve does not take this issue into consideration. If the traditional Hubbert model were used to predict resource production, prediction error might be large. To better predict oil production at world or country level, Reynolds (2014) and Saraiva et al., (2014) proposed Lambda Hubbert curve and multi-cycle Hubbert curve. In addition, some scholars compare the Hubbert curve with other resource depletion models in forecasting strength and weakness. Feng and Pang (2008) used the Hu-Chen-Zhang model and Hubbert curve to predict China's oil reserves and found the two models are quite different in prediction result. They think that the Hu-Chen-Zhang model is more in line with the reality in China. Wang et al. (2011) used Hubbert and generalized Weng models to predict the world's conventional oil production and concluded that with the ultimate recoverable reserves given, both models predict a global oil production peak of 30 billion barrels. On the basis of expatiating on the solving process of the two models, the author comparatively analyzes the intrinsic characteristics of the two models and considers that the generalized Weng model is an improvement on the multicyclic Hubbert model.

Some studies examine the application of the Hubbert curve to peak prediction for other depletable resources such as coal, natural gas, and uranium. Lin and Liu 2010 (Höök et al., 2010; Milici et al., 2013) use Hubbert curves and Gaussian curves to predict coal production in China, the United States and the world. Reynolds and Kolodziej (2009) examined the impact of institutions on the Hubbert curve for North American natural gas market. They concluded that the market follows Hubbert curve and that institutions are one of the important factors that lead to the inflection points in multi-period Hubbert curves. The authors believe that it is not appropriate to use a simple Hubbert curve which excludes the effects of institutions in predicting the supply of natural gas as a country can increase natural gas supplies by establishing good institutions. The Reynolds and Kolodziej argue that in the medium term, natural gas in North America may be in supply shortage, which may trigger a global energy crisis. Maggio and Cacciola (2012) used Multi-Hubbert Variant to examine the future production trend of world fossil fuel such as natural gas , coal and compared it with the results of Single-cycle Hubbert and Multi-cyclic Hubbert approach respectively. Hubbert (1956) had predicted in his classic paper that the ultimate reserve of high-grade uranium ores at the Colorado Plateau in the United States was in the range of 50,000 to 100,000 tons. However, using Hubbert model to predict a country's peak uranium is relatively rare. We first use Hubbert's (1959) Logistic curve method to forecast China's peak uranium, and then use the STELLA model to study the robustness and sensitivity of different variables on the year of peak uranium.

Uranium is a depletable fossil fuel. Peak uranium is the the point in time that maximum production rate is reached. After Peak production enters a decline phase. The concept of Peak uranium comes from the oil peak theory of M. King Hubbert. The concept of Peak uranium is similar to Peak oil. They differ only in extraction methods. Some countries such as South Africa and the United States have already entered the post Peak uranium phase. As a major uranium producing country in the world the 1950s to the 1980s, South Africa reached Peak uranium with a production rate of 6146 tons per year in 1980. The production declined to a rate of 490 tons in 2016, less than 1/10 of the peak (See Figure 3).

[Insert Figure 3 about here]

The production data for uranium in China used in this paper mainly come from The Red Book report series by the Nuclear Energy Agency and the International

Atomic Energy Agency. It contains production data from 1962 to 2016.

2. Methodology and Findings

2.1. The Logistic Curve

First, we use the Logistic function to estimate the Hubbert peak for China's Uranium. This method is proposed by Hubbert (1982). The Hubbert Curve as a linear function is derived from the Logistic curve. Hubbert linearization is based on using annual production and cumulative production data to estimate two key parameters of the Hubbert curve, namely Logistic growth rate and the quantity of ultimate recoverable resources. The method is mainly used to model the depletion of crude oil and finite mineral resources.

The first step in Hubbert linearization is to plot the P/Q and Q (see Figure 4). From Figure 4, we can see that except for early years, there is a linear relationship between the two variables. This linear relationship can be characterized by the Logistic difference equation:

$$\frac{dQ}{dt} = aQ(1 - Q/URR) \tag{1}$$

$$\text{Order, } P = \frac{dQ}{dt},\ m = a/URR \tag{2}$$

$$P/Q = a - mQ \tag{3}$$

Among them, P is the annual production, Q is the cumulative production. The above equation (3) shows that P/Q and Q are linear. Using the linear regression of historical data, we can estimate the slope and intercept of the line and derive the parameters of the Hubbert Curve. a is the intercept on the vertical axis. The URR and P_{max} can be calculated from the slope m of the line.

As China's uranium production has entered a new stage of rapid development after 2010, we have chosen the parameters of 2010 to 2016 for estimating the Hubbert peak. The correlation between the actual value and the fitted value reached 0.99 for

P/Q and Q after the cumulative production in 2010 reached 33,949 tons. By simple regression, we get the following linear equations:

$$P / Q = 0.045 - 1.56 \times 10^{-7} Q \tag{4}$$

$$(t, 189.839) \quad (t, -24.774) \tag{5}$$

$$R^2 = 0.994 \quad F = 613.757 \tag{6}$$

From the above equation (4) we can calculate URR and P_{max} .

$$URR = 0.045 / 1.56 \times 10^{-7} = 290197.588 \tag{7}$$

$$P_{max} = 0.045 \times 290197.588 / 4 = 3267.179 \tag{8}$$

[Insert Figure 4 about here]

Using a simple Logistic model, we can infer the Peak uranium production is 3267.2 tons and the quantity of ultimate recoverable resource is 290197.6 tons in China. To further understand the impact of different factors on the Peak uranium in China, we use the STELLA model to predict the Peak uranium production in China and analyze the sensitivity of the differences in the variables.

2.2. STELLA Model and China’s Peak Uranium Estimation

Using STELLA dynamic model to calculate the uranium peak has severalstrengths. First, the STELLA model is more flexible in terms of sensitivity and dynamic analysis. It is based on the theory of feedback control and is mainly used to study the structure, function and dynamic behavior of complex systems such as annual uranium production, cumulative production and ultimate recoverable reserves. It also examines dynamic changes in a system with different parameters. It is convenient for decision makers to observe different simulation results. Secondly, through special temporary "feedback loop" of STELLA tool, it is convenient to calculate the values of the relevant parameterssimutaneously. Third, the STELLA model helps to study social science experiments at low cost. In this paper, we use STELLA system dynamics model to calculate peak uranium and peak time etc.

We designed a feedback diagram of the variables for the Hubbert Peak uranium model. This includes two stock variables, four flow variables and six auxiliary variables (Figure 5). Using data for the three variables (annual production (P), reserves to production ratio (R/P) , and ultimate recoverable reserves (URR)) and the combination of the information effect represented by aQ and the depletion effect represented by $-aQ^2/URR$ in formula (1), we can reliably predict the time that Hubbert Peak is reached. Our empirical test results show that the model is robust.

[Insert Figure 5 about here]

First, we enter data such as annual production P and cumulative production, and then develop the equations for the relationship between the different variables (see appendix). We examine three different scenarios based on the same inverse decay time coefficient a, each with a different estimated ultimate reserve, obtained by calculating the recoverable reserves plus the reclaimed accumulated productions 43,099 tons (1962-2016).

1. Scenario 1 URR = 176,799 tons. We take data from Uranium 2016: Resources, Production and Demand. We obtain this result by adding up reasonably assured conventional resources of 53,400 tons, inferred conventional resources of 80,300 tons (production methods < USD 40/kgU), and cumulative production of 43,099 tons.

2. Scenario 2 URR=320,799 tons. We obtained the result by adding 128,800 tons of reasonably assured conventional resources, 148,900 tons of inferred conventional resources (production methods < USD 80/kgU), and cumulative production of 43,099 tons.

3. Scenario 3 URR = 409,299 tons. We obtained the result by adding 173300 tons of reasonably assured conventional resources, 192900 tons of inferred conventional

resources (production methods < USD 130/kgU), and cumulative production of 43,099 tons.

The main results of Scenario 3 (a = 0.045, URR = 409,299 tons) are shown in Figure 6 and Table 4. The results show that Hubbert Peak uranium production in China will be reached in 2065 with an annual production of 4,605 tons, 2.8 times of 2016's. According to the results of this scenario, China will reach annual production of 1960 tons in 2020. According to China's nuclear power development plan, China's annual demand will reach 12,000 tons by that time and its dependence on foreign uranium imports will reach 83.7%. The import volume of 21,390 tons will account for 14.1% of the global total of 81,465 tons. Looking forward into 2035, China will reach an annual production rate of 3069 tons and a demand of 20,500 tons. Its dependence on foreign uranium imports will reach 85%. Imports of 17431 tons will account for 26.7% of global production of 65,195 tons. This means that uranium imports by China and the United States combined will exceed half of the world.

The results for the three scenarios are shown in Figure 7 and Table 5. The smaller the URR is, the earlier the peak occurs with lower peak production. In other words, the depletion effect will lead to decline in annual production . The robustness test results show that the uranium peaks in three different scenarios range from 2042 to 2065, indicating strong robustness of the model. The maximum production can also be calculated using equation (1). The extreme value of the equation is taken at the apex, ie Q = R/2. At this value, the maximum value of P is P_{max}=aR/4. For example, if URR=409,299 tons (scenario 3), the maximum production is P_{max}=aR/4= 0.045×409299/4=4605 tons.

Except for three different scenarios with different ultimate recovery, we also examine the sensitivity of scenarios 3 with different inverse decay time coefficient a. The results are shown in Table 6. Our sensitivity analysis of the growth rate a shows that with larger a, the information effect leads to an increase in annual production, and the depletion effect leads to a decline in annual production. The combination of the two results in a higher peak uranium production and earlier peaks. A few important conclusions can be drawn from the above URR tests: Larger URRs produce more production if they extend the life span of the mine. An increase in the coefficient a also increases production and shortens the life span of the mine. Sensitivity analysis of different a values shows that the peak of uranium in China may occur between 2060 and 2070 and the highest production may be between 4093-5116 tons.

[Insert Figure 6 about here]

It can be seen from the results that in 2065, China’s uranium production from 2017 to peak uranium (scenario 3) is expected to increase at an average annual rate of 2.15%. In accordance with the “China’s medium and long-term energy plan (2030,2050) Development Strategy Study”, China’s nuclear power installed capacity will reach 400 Gwe in 2050. The average annual growth rate of China’s nuclear power for the next 30 years will reach 7.69%. This undoubtedly shows that China’s uranium supply-demand gap will continue to increase. China’s dependence on foreign uranium will continue to rise. China’s reliance on uranium imports and foreign mining may be much greater than most observers expect.

[Insert Table 4 about here]

[Insert Figure 7 about here]

[Insert Table 5 about here]

In the foreseeable future, China’s vigorous development of nuclear energy will lead to global booming in nuclear power. And China will become one of the most important players in the world market. According to the data of the World Nuclear Energy Association, the increase in China’s uranium demand in 2017 reached 2,951 tons, while the increase in uranium demand by the rest of the world was only 1,610 tons. China’s overseas uranium mining and M&A activities in Nigeria, Kazakhstan and other countries will change global uranium supply. In addition, China’s rising uranium demand will have considerable impacts on global uranium prices and energy prices. It is estimated that by 2035, China will surpass the United States as the world’s largest nuclear power country with an installed capacity of 23.2% of the world’s total. China’s huge uranium supply-demand gap will affect uranium futures and spot prices, despite currently the world having enough reserves to fill that gap. But it is noteworthy that, the entire process of uranium discovery to extraction may take up to 20 years. Opening a new uranium plant is not a simple or quick process. It takes time and effort. Therefore, China should make adequate preparations for the upcoming uranium price rise to ensure the security of uranium supply.

3. Conclusion and Policy Recommendations

In recent years, despite of the slow-down in economic growth in China, the high pollution and high emissions of traditional fossil fuels have led to a growth in China’s uranium demand. According to the IEA’s forecast, China will overtake the United States as the world’s largest nuclear power country by 2035, By then China’s reliance on uranium imports will further increase. Given the Peak uranium in China, China has far outweighed other countries in view of increasing dependence on nuclear energy. Therefore, it is very important to examine the trend in Peak uranium and the supply-demand gap in China.

In this paper, we use Logistic and Hubbert curves to predict the Peak uranium in China. We show that China’s largest uranium production is in between 1989 to 4605 tons. The timing of Peak uranium varies by different scenarios, but the results are more robust. Based on the most optimistic scenario, in scenario 3, China’s uranium peak will come in 2065. However, if in scenario 1, the peak would even come in 2042. The sharp decline in production thereafter will have a significant impact on the energy costs of China’s economy. According to the results of this study, China’s foreign dependence on uranium imports will reach 85% by 2035 and the import volume will account for 26.7% of the world’s total. By adjusting the sensitivity of growth rate coefficient a , the uranium peak in China will be reached between 2060 to 2070 and the maximum annual production is between 4093 and 5116 tons. By then, China's uranium import dependence will further rise, uranium security situation will be more severe.

To deal with the increasing shortage in uranium resources, China needs to strengthen both its domestic and foreign strategies. First of all, to support China's ambitious nuclear power plan, the central government should formulate a long-term strategic plan for developing uranium industry to minimize fluctuations in uranium exploration and mining. Second, the country should put additional efforts into uranium resources exploration, especially large and medium-sized sandstone-type uranium deposits in northwestern China, strengthen uranium exploration, and increase exploration depth so as to enrich uranium mineral resources. In addition, the central government should increase financial support to uranium industry by setting up a development fund to strengthen R & D in uranium theories and exploration technology and to improve training of uranium exploration technical staff. The government should encourage non-state capital to invest in uranium exploration and exploitation and establish a competitive and fair market environment to promote market participation in the uranium industry. Finally, coordination between the uranium industry and other metal mining industries through joint exploration and exploitation should be improved for a more efficient use of uranium resources.

For the foreign strategy, China needs to vigorously develop new overseas mineral importing sources, increase its level of effort in merger, acquisition, and shareholding in overseas mining industries, and set up a special council to implement and coordinate its foreign uranium strategy. Another viable option is to take advantage of China's "the Belt and Road" initiative to open up new sources of uranium resources in the along-route countries. In addition, the government needs to promote overseas uranium production and development through the establishment of overseas uranium development funds, as well as supportive policies such as financial investment, low-interest loans and tax incentives. In order to minimize potential concerns by foreign governments about China's overseas nuclear energy initiatives, the Chinese government should also ensure that the uranium mine is used for the purpose of generating electricity for civilian use rather than for military purposes. In order to increase the utilization rate of spent fuel and reduce the dependence on uranium imports, China should also strengthen its technical cooperation with nuclear technology leading countries such as France.

In addition, China should strengthen research and development on unconventional uranium resources such as phosphate ore to extract uranium from seawater and encourage active exploration and development of alternative nuclear fuel such as thorium. Moreover, to ensure uranium security, China should take advantage of the uranium market downturn to vigorously strengthen the country's uranium strategic reserve, and actively develop the fourth generation of nuclear power technology for a better utilization of fuel.

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Appendix: R codes

```
cumulative_prd(t) = cumulative_prd(t - dt) + (hubbert_prd) * dt
INIT cumulative_prd = 1
INFLOWS:
hubbert_prd=IF TIME<=2016 THEN actual_production ELSE
(1-cumulative_prd/ultimate_reserves) * cumulative_prd*a
Cumulative_proved_reserves(t)=Cumulative_proved_reserves(t-dt)+(annual_proved_
reserves_addition) *dt
INIT Cumulative_proved_reserves = 0
INFLOWS:
annual_proved_reserves_addition = hubbert_prd+delta_resv
UNATTACHED:
actual_production = prod
```

```
UNATTACHED:
proved_reserves = hubbert_prd*R_vs_P
a = 0.045
delta_resv = DERIVN(proved_reserves,1)
replacement_rate = annual_proved_reserves_addition/hubbert_prd
ultimate_reserves = 409299
prod = GRAPH(TIME)
(1962, 500), (1963, 500), (1964, 500), (1965, 500), (1966, 500), (1967, 500), (1968,
500), (1969, 500), (1970, 500), (1971, 500), (1972, 500), (1973, 500), (1974, 500),
(1975, 1450), (1976, 800), (1977, 800), (1978, 850), (1979, 850), (1980, 850), (1981,
850), (1982, 850), (1983, 850), (1984, 850), (1985, 800), (1986, 800), (1987, 800),
(1988, 344), (1989, 800), (1990, 800), (1991, 800), (1992, 955), (1993, 780), (1994,
480), (1995, 500), (1996, 560), (1997, 570), (1998, 590), (1999, 700), (2000, 700),
(2001, 700), (2002, 730), (2003, 730), (2004, 730), (2005, 750), (2006, 750), (2007,
710), (2008, 770), (2009, 1200), (2010, 1350), (2011, 1400), (2012, 1450), (2013,
1500), (2014, 1550), (2015, 1600), (2016, 1650)
R_vs_P = GRAPH(TIME)
(1962, 815), (1963, 815), (1964, 815), (1965, 815), (1966, 815), (1967, 815), (1968,
815), (1969, 815), (1970, 815), (1971, 815), (1972, 815), (1973, 815), (1974, 815),
(1975, 815), (1976, 510), (1977, 510), (1978, 480), (1979, 480), (1980, 480), (1981,
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