Energy Strategy Reviews 9 (2016) 50–61

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.ees.elsevier.com/esr

CASE STUDY

Uranium demand and economic analysis of different nuclear fuel cycles in China

Jian-ping Zhang [a], Zhi-rong Liu [a,b,*], Lin Wang [a]

[a] East China University of Technology, School of Nuclear Engineering and Geophysics, Nanchang City, Jiangxi 330013, China
[b] Key Laboratory of Nuclear Resources and Environment, Ministry of Education, East China University of Technology, Nanchang City, Jiangxi 330013, China

ARTICLE INFO

Article history:
Received 16 May 2015
Received in revised form
9 August 2015
Accepted 2 December 2015
Available online 29 December 2015

Keywords:
Uranium needed
Economics
Nuclear fuel cycle
Energy strategy
Uncertainty analysis

ABSTRACT

The demand of natural uranium of two different cycle options of China's PWRs were calculated in this paper, the once-through cycle route (OTC) is 197.2 t/8.702 TWh and the partial recycling in PWR route (PRR) is 131.0 t/8.702 TWh. The fuel cycle component ($LCOE_{Total\ fuel\ cycle}$) of the levelised cost electricity (LCOE) for NPPS under different capacity, different cycle routes and different discount rate was calculated. In addition, the sensitivity analysis was made to identify the most influential parameters in the final price. Also, the breakeven price of uranium was calculated to be 130 $/kgU (59 $/lb) for PRR fuel cycle with a fleet generating 100 TWh/year at 4% discount rate and 74 $/kgU (34 $/lb) at 2% discount rate with reference to the OTC option. Then, the uncertainty analysis was made by EXCEL&Crystal software.

1. Introduction

Since reform and opening up, the rapid economic development of China results in an increase of energy demands. Electricity consumption in 2012 rose 5.5% to 4.9 trillion kWh, and it rose 7.5% to 5.3 trillion kWh in 2013. In 2014 it rose 3.8% to 5.5 trillion kWh (76.5% from thermal power, 17.8% from hydropower, 2.8% from wind power and 2.4% from nuclear power), according to the National Energy Administration of China and China Electricity Council (CEC). Rapid growth of energy demand has given rise to power shortages, and the reliance on fossil fuels has caused much air pollution. Official measurements of fine particles in the air measuring less than 2.5 μm, which pose the greatest health risk, rose to a record 993 μg per cubic meter in Beijing on 12 January 2013, compared with World Health Organization guidelines of no higher than 25. The impetus for increasing nuclear power share in China is increasingly due to air pollution from coal-fired plants. Fig. 1 shows the new incremental nuclear power installed capacity from 2009 to 2014. In China, it currently has 23 operating nuclear reactors and 23 more on the way. China plans to increase the nation's nuclear capacity to about 20 GWe by 2020, 200 GWe by 2030 and 400 GWe by 2050.

Different countries may treat spent fuels in different ways. Sweden and Finland have definitively adopted the open cycle route. While some countries have reprocessing facilities which used for spent fuels recirculation; for example, France, Russia, the United Kingdom, Japan, India, Pakistan and recently, China [1]. China's policy is closed fuel cycle that was first articulated in the 1980s. China's main rationale for a closed fuel, mainly because the techniques of uranium mining are not so advanced and the cost of it is relatively high. On the basis of understanding China's need to separate plutonium to conserve its limited uranium resource for its growing nuclear power program, China has planned to adopt a closed fuel cycle strategy to reprocess the resulting civilian spent fuel. The economy of nuclear fuel cycle plays, with no doubt, a significant role for policy makers.

In this paper, two main options of nuclear fuel cycle were considered – the once-through cycle route (OTC option) and the partial recycling in PWR route (PRR option). Over the last decade, several assessments [2–6] have been developed in order to compare the two main spent fuel options. Ko's group [7] considered that the PRR option was more favorable based on the economics analysis on different cycle routes. Because there was a negligibly small difference in the case of total cost and the PRR option needed lesser natural uranium than the OTC option. While economics analysis was also conducted by Matthew Bunn's group [8] in Harvard University, and J.M. Deutch's group [9] in Massachusetts Institute of Technology, arrived at their conclusions that the OTC option was more economic than the PRR option.

* Corresponding author. East China University of Technology, School of Nuclear Engineering and Geophysics, Nanchang City, Jiangxi 330013, China.
E-mail address: zhrliu@ecit.cn (Z.-r. Liu).

http://dx.doi.org/10.1016/j.esr.2015.12.001
2211-467X/

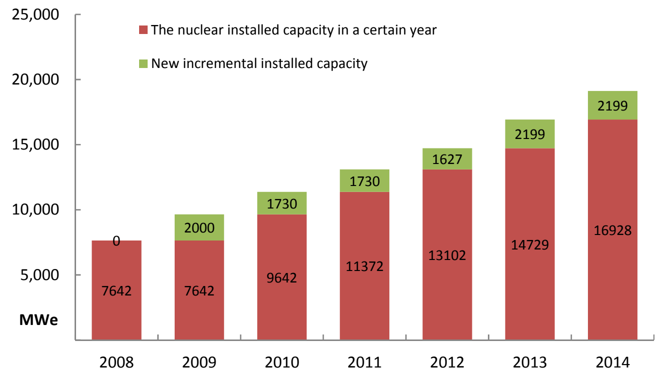

Fig. 1. New incremental installed capacity.

In order to make use of uranium resources adequately and make nuclear power be used economically and sustainably, the suitable nuclear fuel cycle option should be analyzed by means of economic calculations. In order to intuitively present the necessity of recovering and recycling spent nuclear fuel, the demand of nature uranium and accumulated natural uranium of China by the end of 2014 were calculated in this paper. A typical PWR (CPR-1000) was used to calculate the equilibrium material flows in two different nuclear fuel cycle options. We collected different unit cost data from various sources and calculated the fuel cycle component $LCOE_{Total\ fuel\ cycle}$ of the levelised cost electricity (LCOE) for NPPs, including both the front-end cost and the back-end cost that corresponds to the management of the SNF. The definition and advantages of LCOE will be elaborated in chapter five. The Monte Carlo simulation was used for uncertainty analysis, and the sensitivity analysis on the uranium breakeven price and a suitable cycle plan in current China were discussed. This paper also introduced China's spent nuclear fuel management included current practices and future strategies.

2. The natural uranium needed in China for nuclear power plants

2.1. Model and calculations

By the end of 2014, there are 23 operating reactors in China that connected to the grid with a combined generating capacity of 19,127 MW [10]. More than 80 percent of the nuclear reactors (20 of 23) are PWRs and it is mainly CPR-1000 reactor which belongs to Generation II + reactor. It is reasonable to assume a simplified model for a typical PWR (CPR-1000) for each cycle option. The annual requirement of the fuels (M, tHM/year) was calculated based on the parameters of the typical PWR as Eq. (1).

$$M = Q/B_d = \frac{P_e \times CF \times 365}{\varepsilon \times B_d} \quad (1)$$

Where Q, B_d, P_e, CF, ε are the annual reactor heat (GWd/a), discharge burn up (GWd/tHM), electrical power (GWe) of a PWR, capacity factor (%) and thermal efficiency (%), respectively. After figuring out M, the mass of nature uranium (M_{nat}, tHM/year) converted to M can be modeled as Eq. (2).

$$M_{nat} = F\frac{1}{r} = P\frac{X_p - X_t}{X_{nat} - X_t}\frac{1}{r} = M\frac{X_p - X_t}{X_{nat} - X_t}\frac{1}{r^3} \quad (2)$$

Where F, P, X_p, X_{nat}, X_t, r are the natural uranium mass during the enrichment process, the mass of enrichment uranium production, ^{235}U in enrichment uranium production, ^{235}U in natural uranium, ^{235}U in tail assay and uranium recovery ratio of both conversion and fuel fabrication process, respectively. The parameters of these references were listed in Table 1.

2.2. Total natural uranium needed for 2014

Given the number of reactors that were due to be commercial in the period up to 2014 in China, the uranium accumulation and annual needed model is given as Eqs. (3) and (4).

$$U_a = \sum_{i=1}^{n} U_k \quad (3)$$

Where U_a is the uranium accumulation; U_k represents the uranium needed in a certain year, respectively. U_k is defined as Eq. (4).

$$U_k = (C_n - C_{n-1}) \times 600 + C_{n-1} \times A + 238 \quad (4)$$

Where C_n is the total installed capacity in n_{th} year; C_{n-1} is the total installed capacity in n_{th-1} year; A[1] is the natural uranium needed for a CPR-1000 reactor per year and it can be replaced in different burn-up, respectively. The glossary of above terms was shown in Table A3. About 600 tons of natural uranium could be required for a 1 GW PWR to fabricate the fuel assembly for its initial core.

[1] A is the natural uranium needed for a 1 GW reactor in a year, which has been calculated 205.49 tons (Generation II), 181.41 tons (Generation II+), respectively.

Table 1
Characteristics of the reactors and the model [11].

Parameters	Value	
	Generation II	Generation II+
	M310 VVER CNP-600	CPRC-1000
B_d (GWd/tHM)	33	50
CF (%)[a]	88.4	92.35
ε (%)	34	38
X_p (%)	3.2	4.45
X_{nat} (%)	0.712	0.712
X_t (%)	0.3	0.3
r (%)	99.5	99.5

[a] The average capacity factor (CF), which is the most common measure of power plant performance that is used, comparing the actual generation to the maximum possible generation, amounted to 88.4% and 92.35%, respectively, from 2009 to 2013 in China.

About the Qinshan III (Canadian CANDU-6) reactor, the average fuel bundle discharge burn-up was about 7.5 GWd/t, and the design average capacity factor was 92.9%. The corresponding natural uranium consumption for the CANDU-6 reactors was about 170 tons per GW electrical. The total natural uranium consumption of Qinshan III with 2 × 728 MW capacity installed was approximately 238 tons per year.

According to Eqs. (3) and (4), we could calculate the annual and accumulated natural uranium that were showed in Fig. 2. Fig. 2 shows the amount of accumulated Uranium is increasing rapidly which from 9618.79t (2010) to 27,734.26t (2014), and is growing by an average of 4529 tU a year. So, it is so necessary to reuse and recycle the uranium and plutonium for saving natural uranium.

3. Scenarios considered and equilibrium material flows

There are two major nuclear fuel cycle options in the world: the once-though cycle (OTC) option and the closed fuel cycle (CFC) option [11]. While there are no China Commercial Fast Reactors[2] (CCFR) currently in operation, and it is exploring. So, nuclear fuel cycle options in current China mainly are OTC and the partial recycling in PWR route (PRR) which is considered in this article.

3.1. Once-though cycle route

In this scenario it is considered that the spent fuel, after being irradiated in the

[2] CCFR's estimated startup is 2030–2035 according to Xu Mi.'s article (Fast reactor development strategy targets study in China).