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Economic potential of fuel recycling options: A lifecycle cost analysis of future nuclear system transition in China

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ABSTRACT

In today's profit-driven market, how best to pursue advanced nuclear fuel cycle technologies while maintaining the cost competitiveness of nuclear electricity is of crucial importance to determine the implementation of spent fuel reprocessing and recycling in China. In this study, a comprehensive techno-economic analysis is undertaken to evaluate the economic feasibility of ongoing national projects and the technical compatibility with China's future fuel cycle transition. We investigated the dynamic impacts of technical and economic uncertainties in the lifecycle of a nuclear system. The electricity generation costs associated with four potential fuel cycle transition scenarios were simulated by probabilistic and deterministic approaches and then compared in detail. The results showed that the total cost of a once-through system is lowest compared those of other advanced systems involving reprocessing and recycling. However, thanks to the consequential uncertainties caused by the further progress toward technology maturity, the economic potential of fuel recycling options was proven through a probabilistic uncertainty analysis. Furthermore, it is recommended that a compulsory executive of closed fuel cycle policy would pose some investment risk in the near term, though the execution of a series of R & D initiatives with a flexible roadmap would be valuable in the long run.

1. Introduction

The Fukushima accident unquestionably triggered global concerns about safety issues related to nuclear energy as well as a notable deceleration of nuclear energy expansion efforts in China (The State Council of the People's Republic of China, 2012; World Nuclear Association, 2016). Moreover, while in the midst of an obvious slowdown in their economic growth rate in 2015 (BBC News, 2015), China failed to accomplish its development target of an installed nuclear capacity of 40 GWe, as stated in the earlier (12th) five-year plan. As of the end of 2015, with 28 operating nuclear power plants (NPPs) (26 pressurized water reactors (PWRs) and two pressurized heavy water reactors (PHWRs)), more than 5000 tHM of spent nuclear fuel has accumulated in mainland China (China Committee of Nuclear Power Operators, 2016; World Nuclear Association, 2016). Most of the PWR spent fuel is temporarily stored in on-site water pools. Despite worldwide concern, the central government still optimistically reaffirmed its commitment to the development of nuclear power, i.e., with the goals of 58 GWe to be in operation and an additional 30 GWe to be under construction by 2020 (The State Council of the People's Republic of China, 2014).

Nuclear power has long been considered as a potential option to secure China's energy sustainability (Ye, 2015). However, great expectation does not mean an absence of challenges when attempting to double the nuclear installed capacity over the next five years. Furthermore, along with the rising demand for natural uranium as well as the storage difficulties associated with accumulated nuclear waste, China is in desperate need of the systematic optimization of the overall nuclear fuel cycle for its future transition based on the current once-through system. This optimization should not only conform to intrinsic multi-criteria decision-making but should also be in tune with the surrounding international environment. To address these issues, our previous work modeled the dynamic material flow of the nuclear fuel cycle in China through 2050 (Gao et al., 2015). However, the study focused mainly on a quantitative evaluation rather than a detailed economic analysis, primarily due to our conservative assumption regarding China's level of technology maturity of its R & D development by 2050. In any case, in today's profit-driven market, methods by which to pursue advanced nuclear fuel cycle technologies while maintaining the cost competitiveness of nuclear electricity are of crucial importance to determine the implementation of spent fuel reprocessing and recycling in China, especially with regard to the feasibility of China's

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closed fuel cycle policy. Thus, a real-time assessment of the economic feasibility of ongoing national projects concerning the degree of technical compatibility with the future fuel cycle transition has become one of the key determinants to push forward policies pertaining to national nuclear development while ensuring long-lasting energy stability and security (OECD/IEA, NEA, 2015).

Unfortunately, over the past few decades, while numerous studies around the world have debated the economics of diverse nuclear fuel cycle systems, a universal consensus remains elusive (Shropshire et al., 2009; Choi et al., 2014; Hamel, 2007; Machiels, 2009; Machiels and Sowder, 2010; Roo and Parsons, 2009; OECD/NEA, 2013; OECD/NEA, 2006; The Boston Consulting Group, 2006; Bunn et al., 2003; Zhou et al., 2014). Controversy has arisen given the different opinions about approaches most suitable for spent fuel management, i.e., whether to reprocess and recycle the spent fuel, conditional on each country's nuclear policy. In other words, there are considerable uncertainties underlying each cost element of nuclear electricity generation for specific nuclear energy systems as well as different assessment methodologies. For instance, most of the corresponding cost data can only be derived from the non-transparent engineering cost calculations and project valuations rather than from the actual expenses incurred through direct operations. Additionally, the widely used conventional deterministic analysis approach can only provide a rough estimation of the system cost (Kirchsteiger, 1999).

Therefore, in this study, we conducted a comparative analysis of four nuclear fuel cycle transition scenarios considering the consequential cost benefit and economic risk caused by the technical uncertainties in ongoing key R & D projects for recycling options through 2100. Section 2 demonstrates how the previous model of nuclear energy systems can be updated to advance toward a real long-term development strategy, also describing the relevant economic definitions, methods and parameters. In particular, we established a China-defined cost database and applied it to the Levelized Cost of Electricity (LCOE) calculation in which the material flow model was connected to all related system component costs. In Section 3, we adopted a probabilistic approach to analyze the consequential influences of the uncertainties in the LCOE by means of a Latin Hyper Cube Sampling (LHS) Monte Carlo Simulation. Moreover, a related uncertainty analysis was carried out and breakeven calculations were solved.

2. Methodology

2.1. Nuclear energy system transition scenarios

2.1.1. Nuclear power growth projection

According to national energy plans and academic studies of China's nuclear energy development published in recent years (The State Council of the People's Republic of China, 2014, 2016; CAE, 2011; National Bureau of Statistics of China, 2016), we developed a “three-phase” growth projection of electricity generation and nuclear power capacity through 2100. In this projection, phase 1 (1990–2020) begins with a summary of the historical data pertaining to China's nuclear electricity as of the end of 2015 (National Bureau of Statistics of China, 2016), and phase 2 (2021–2050) proceeds in this manner, following earlier work, up to 2050 (Gao et al., 2015). It is remarkable that phase 3 (2051–2100) is more unpredictable due to a lack of official guidelines for long-term energy development strategies. Hence, under rational expectations, we selected and adopted reference data from a report by the Energy Information Administration (EIA) (EIA, 2015) and from historical economic statistics of Organization for Economic Cooperation and Development (OECD) countries (OECD, 2015).

As shown in Fig. 1, in phase 1, China's nuclear electricity has experienced a series of development and reforms following successive five-year national plans since the start-up of the NPP of Daya Bay site in 1994 (The State Council of the People's Republic of China, 2016). Based on the latest Energy Development Strategic Action Plan (The

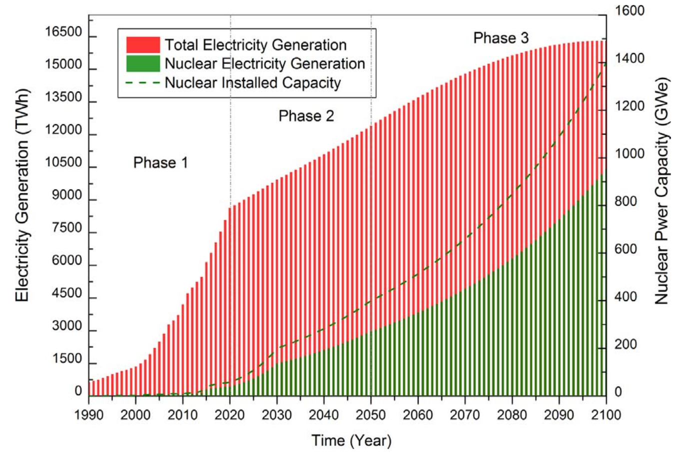

Fig. 1. Growth projection of electricity generation and nuclear power capacity.

State Council of the People's Republic of China, 2014), the total installed capacity of nuclear power in 2020 is projected to reach 58 GWe. In phase 2, nuclear power increases to 200 GWe in 2030 following the development assumptions devised by the Chinese Academy of Engineering (CAE) (CAE, 2011), with the target of 400 GWe finally achieved in 2050. For the same period, a transient surge in total electricity generation would occur in the first five years, with the growth rate gradually flattening, showing that the total electricity demand nearly reaches saturation by 2050. In phase 3 (2051–2100), nuclear power maintains a steady upward trend and increases exponentially. Finally, it reaches 1400 GWe, accounting for 64% of the total electricity generation in 2100. While the growth rate of total electricity demand has been dropping to zero, China will join the ranks of advanced developed countries at that point (EIA, 2015; OECD, 2015).

2.1.2. Future fuel cycle transition scenarios

According to the possibility of technical success, failures, and delays in ongoing projects regarding spent fuel management, we investigated the relevant consequences embodied in the future nuclear fuel cycle transition as well as the deployment of NPPs and supporting facilities. By means of a decision tree, four reference scenarios of the fuel cycle transition were identified and developed, as follows: 1) the direct disposal of PWR spent fuel without recycling, 2) the single-recycling of PWR spent fuel in PWRs fueled with mixed uranium-plutonium oxide (PWR-MOX) fuels, 3) the PWR-MOX followed by fast reactors (FRs), and 4) the direct recycling of PWR spent fuel through FRs, see Figs. 2 and 3.

Considering whether the first commercial-scale deployment of THORP can be completed in 2020 as planned, or not (The State Council of the People's Republic of China, 2016), the consequential fuel cycle transitions are reflected in scenarios 1 and 2, respectively. In scenario 1, it is assumed that all of the spent fuel will be directly sent to a geological repository for final disposal based on the current once-through system due to the permanent failure of the THORP project. In contrast, owing to the success of the THORP project being completed on time, the recovered plutonium from PWR spent fuel is refabricated into new MOX fuel and then reused one more time in PWR-MOXs, as shown in scenario 2. On the basis of scenario 2, in scenario 3, the spent MOX fuel discharged from PWR-MOXs is reprocessed and the resulting plutonium is repeatedly recycled in FRs given that the first FR starts up in 2040. Compared to scenario 3, plutonium separated from THORP will not be used for PWR-MOX but will be recycled directly and repeatedly in FRs from 2030 in scenario 4.

In terms of the operation status of NPPs in China (World Nuclear Association, 2016; China Committee of Nuclear Power Operators, 2016), the design specifications and parameters of the reference