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Cost Probability Analysis of China's Nuclear Fuel Cycle Transition

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1. Introduction

Considering that the specific and complex national energy system of China is extremely electricity-intensive relative to its rapidly expanding energy demand. Nuclear power is identified as relatively young but promising and competitive energy option in the huge open market of China. Although the Chinese government has already determined to develop the closed nuclear fuel cycle, its long-term roadmap of spent fuel management has not been decided yet. Currently, it seems that China's booming economy gives abundant financial assurance to develop nuclear programs in full play according to its near-term national plans. However, the viability and sustainability of nuclear power always depends critically on its economics. Therefore, it is necessary to conduct a well-focused cost-benefit and objective analysis of China's ongoing nuclear power programs with the future prospects. Additionally, this study also analyzed the economic divergences of potential nuclear fuel cycle transition, which is due to the large uncertainties underlying the unit cost variances of overall nuclear system.

2. Methods and Results

Based on the China's nuclear power growth profile and material flow study of nuclear fuel cycle transition scenarios by 2050 obtained by a dynamic model [1], we extended a systematic economic comparative analysis among these reference scenarios.

2.1 Nuclear Energy System Transition Scenarios

According to the current status of nuclear power and government plans of spent fuel management until 2050 [1], we predicted a decision tree of nuclear fuel cycle technology development in China, as shown in Fig. 1.

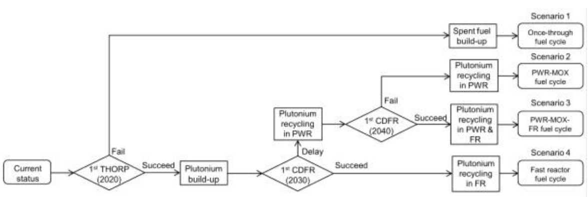

Fig. 1. Decision tree of nuclear fuel cycle transition scenarios in China.

It suggests four possible fuel cycle transition scenarios: the direct disposal of PWR spent fuel, the single-recycling of PWR spent fuel through PWR-MOX, the PWR-MOX followed by FR and the recycling of PWR spent fuel through FR.

2.2 Definition

Electricity generation cost of nuclear power mainly consists of two parts, which are reactor cost and nuclear fuel cycle cost. Reactor cost includes capital cost, operation and maintenance cost (O&M cost) and decontaminating & decommissioning (D&D) cost. Generally, previous studies focused on the reactor cost and nuclear fuel cycle cost separately to find the direct contributor to the partial electricity generation cost. Here, via a dynamic model, besides the consideration of the lead and lag time for each fuel cycle step combined with four reference nuclear transition scenarios, we also took account of the escalation and the discount rate while applied levelized cost of electricity (mills/kWh) to simulate a complete and actual economic performance of the overall nuclear energy system in China. Levelized Cost of Total Nuclear System (LCT) and Levelized Cost of Fuel Cycle (LCFC) are defined as the levelized cost of the overall nuclear system and the nuclear fuel cycle per unit of electricity generation, respectively. This paper simultaneously employs both costs to compare the economic competitiveness of four reference nuclear transition scenarios.

The LCOS is given by:

$$C_{levelized} = \frac{\sum_t \sum_i \frac{R_i(t)}{(1+r)^{t-t_b}} + \sum_t \sum_j \frac{F_j(t)}{(1+r)^{t-t_b}}}{\sum_t \frac{E(t)}{(1+r)^{t-t_b}}} \qquad (1)$$

where R_i is the component costs of i-th reactor at time t,

F_j is the component costs of j-th fuel cycle step at time t,

and E is the net electrical output at time t.

2.3 Breakdown of LCT

After calculation of LCT, the results of four reference scenarios are shown as follows: Scenario 1 is the cheapest as low as 62.688 mills/kWh while Scenario 4 is the most expensive as high as 66.775 mills/kWh.

Scenario 2 and Scenario 3 are 64.401 mills/kWh and 65.456 mills/kW, respectively. Fig. 2 shows the comparison of LCT components in four scenarios by 2050. As shown in Fig. 2, the largest cost component of LCT is reactor cost, which accounts for more than 82% of total electricity generation cost. However, compared with Scenario 1, the share of front-end fuel cycle cost could be reduced by 22%, 12% and 8% by reprocessing and recycling technologies in Scenarios 2-4, respectively.

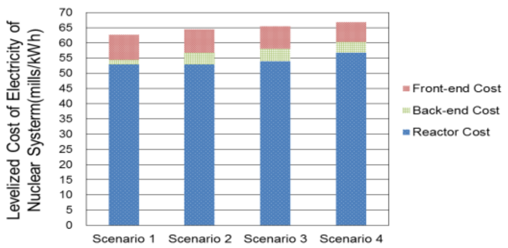

Fig. 2. LCT comparison in four scenarios until 2050.

2.4 Uncertainty Analysis of LCT

Fig. 3 shows the probability density of LCT in four scenarios by 2050 while considering unit cost data uncertainties. Compared to 50.16-77.36 mills/kWh of most-likely range in Scenario 1, the overlap of cost distribution in other three scenarios is about 90%, which means the real cost divergence in four scenarios is not obvious when we consider large uncertainty of unit cost data. However, to maintain LCT within above cost range, Scenario 4 could perform even better than Scenario 1. But it is almost impossible to reduce the LCT of Scenario 4 below the lower limit cost.

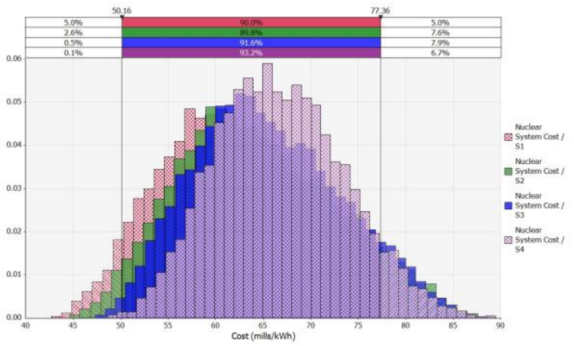

Fig. 3. Overlap of probabilistic distribution for LCT based on cost data uncertainties in four scenarios.

2.5 LCT Gap

Fig. 4 shows the cumulative probability of the LCT gap in Scenarios 2-4 compared with Scenario 1. The result shows that the LCT of Scenario 4 could be cheaper than that of Scenario 1 at a probability of 17.2% while cost 2 mills/kWh more at a probability of 67.2% based on the given cost data uncertainties. In contrast, the LCTs of Scenarios 2 and 3 are always higher than that of Scenario 1. As shown in Fig. 5, the LCT cost gap between Scenarios 1 and 4 is mainly influenced by reactor capital cost, which could make the cost gap change from -0.722 to 10.65 mills/kWh at given unit cost range. The other top ten sensitive steps are listed in Fig. 5.

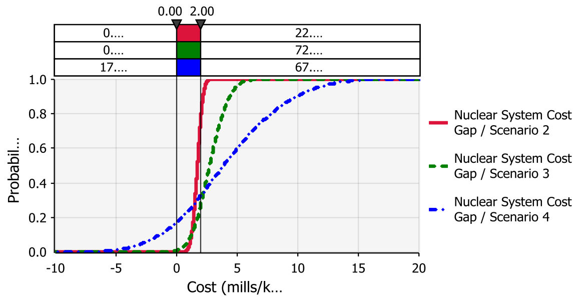

Fig. 4. Cumulative probability diagram for LCT gap compared with Scenario 1.

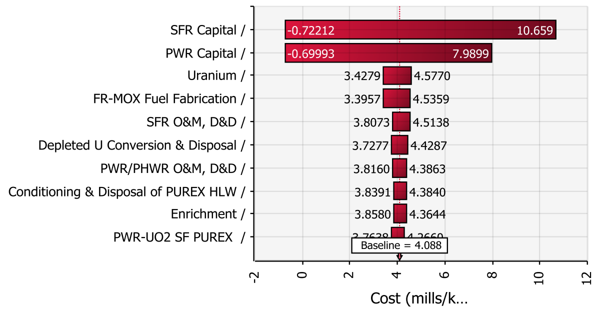

Fig. 5. Value tornado diagrams for the variation of LCT gap between Scenario 1 and 4 for each fuel cycle step.

3. Conclusions

In this study, we conduct a comparative analysis of electricity generation cost in four reference nuclear fuel cycle transition scenarios by 2050. Direct disposal is assumed to produce the cheapest LCT as low as 62.688 mills/kWh compared to the other options. However, after performing a relative uncertainty study, the results show that the capital cost of reactor is the key cost component which leads to the cost gap. In addition, when the unit cost is closed to the reference lower limit, the LCT of recycling the PWR spent fuel through FR is still comparative to the direct disposal without recycling.

REFERENCES

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