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Performance modeling and analysis of spent nuclear fuel recycling

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SUMMARY

The rapid expansion of nuclear energy in China has intensified concerns regarding spent fuel management. However, the consequences of failure or delay in developing approaches to managing spent fuel in China have not yet been explicitly analyzed. Thus, a dynamic analysis of transitions in nuclear fuel cycles in China to 2050 was conducted. This multidisciplinary study compares the environmental, security, and economic consequences of choices among ongoing technology development options for spent fuel management. Four transition scenarios were identified: the direct disposal of PWR (Pressurized Water Reactor) spent fuel, the recycling of PWR spent fuel through PWR-MOX (Mixed Oxides), the PWR-MOX followed by fast reactors, and the recycling of PWR spent fuel using fast reactors. Direct disposal would have the lowest cost of electricity generation under the current market conditions, while the reprocessing and recycling of PWR spent fuel would benefit the Chinese nuclear power program by reducing the generation of high level waste (67–82%), saving natural U resources (9–17%), and reducing Pu management risk (24–58%). Moreover, a fast reactor system would provide better performance than one-time recycling through PWR-MOX. The latter also poses high risks in managing the build-up of separated Pu.

KEY WORDS

spent nuclear fuel; nuclear fuel cycle; high level waste; economic analysis; security risk; fuel cycle transition

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1. INTRODUCTION

China, the world's largest energy consumer, depends greatly on electricity-intensive industries, a trend that will last for several more decades [1]. With this rapidly growing electricity demand, China is facing serious challenges to ensure a sustainable supply of inexpensive and reliable electricity [2]. Simultaneously, China has received international attention related to the reduction of greenhouse gas emissions and to the stabilization of the largest global market [3]. Regarding these issues, the Chinese government proposed an initial plan for the ambitious development of nuclear power in 2007 [4]. According to this plan, the installed capacity of nuclear power was supposed to increase from 7 GWe in 2007 to 40 GWe in 2020.

The rapid expansion of nuclear power will necessarily be accompanied by problems related to spent fuel management [5]. In 1987, China declared that a closed nuclear fuel cycle would be developed [6]; however, that decision was for enhancing U utilization [7,8]. In any case, the shortage of U resources is not likely to be a problem for the Chinese nuclear power program over the next 50 years [5,9]. Instead, after the Fukushima accident, the Chinese government began to consider the safe management of spent fuel seriously, and hence approved the 2012 Nuclear Safety Plan proposed by the National Nuclear Safety Administration [10]. As the largest player in the development of nuclear power today, the success of this Chinese plan is also significant globally, and most immediately, to all of East Asia [11].

Thus, it is necessary to assess whether the current Research and Development (R&D) programs can appropriately address spent fuel issues along with the rapid expansion of nuclear power. In addition, the assessment can reveal what the consequences of failure or delay in the back-end cycle programs might be and how much they matter. Such results are crucial for informed decision-making on spent fuel management. However, previous studies have not explicitly analyzed the consequences of failure and delay in making such provisions for the current R&D programs [12–17].

In this study, we analyzed multi-disciplinary factors of the Chinese nuclear energy systems by modeling the dynamic fuel cycle transitions and comparing the waste management performance of the four fuel cycle scenarios. Section 2 describes the current status of the nuclear power programs, and projects nuclear power growth up to 2050. In Section 3, we describe the four possible scenarios based on a decision tree, for which we consider the success, failure, or delay of the ongoing R&D activities. Section 4 describes mathematical methods and calculation parameters. In Section 5, we analyze and compare each scenario with the others, in terms of the required capacity of the reactor types deployed, the accumulation of spent fuel stored, the consumption of natural U, the build-up of Pu, and the levelized cost of electricity (LCOE) of the overall nuclear systems.

2. CURRENT STATUS OF NUCLEAR POWER PROGRAM IN CHINA

2.1. Current status of nuclear power plants

China has 20 Pressurized Water Reactors (PWRs) and two Pressurized Heavy Water Reactors (PHWRs) in operation. The total installed capacity of these reactors is 20.31 GWe, which provided 2.4% of the total electricity generation in 2014 [18]. China began its civilian nuclear power program in the 1980s [19], but has only recently been rapidly constructing nuclear power plants (NPPs). At present, an additional 26 NPPs (28.46 GWe) are under construction and 46 NPPs (53.3 GWe) are being planned. Tables I and II summarize the status of NPPs in operation and under construction as of the end of 2014.

2.2. Growth projection of nuclear power capacity

To develop a reference projection of nuclear power growth up to 2050, i.e. Figure 1, we collected reliable data from the Chinese government, the Chinese Academy of Engineering (CAE), and national research institutes. Every 5 years, the State Council develops a new national plan on economic, energy, and social development. The latest plan released in 2013 includes projections about national demand for electricity and nuclear power capacity by 2015 [22]. It planned for the total electricity consumption to reach 6150 TWh, while overall, 40 GWe of nuclear power capacity would be available in 2015, which is equivalent to 4.8% of total electricity generation. In the same year, the National Electric Power Planning and Research Center (EPPRC) released a national electricity demand and supply forecast for up to 2050 [23].

We considered three different phases of nuclear power growth. In Phase 1 (2015–2020), nuclear power keeps growing steadily to reach 58 GWe of total installed

Table I. Nuclear power plants in operation in China [18,20,21].

Site name	Unit number	Capacity (MWe)	Reactor type	Startup date
Qinshan I	1	310	PWR	1994-04
Qinshan II	1	650	PWR	2002-04
	2	650	PWR	2004-05
	3	660	PWR	2010-10
	4	660	PWR	2012-04
Qinshan III	1	728	PHWR	2002-12
	2	728	PHWR	2003-07
Daya Bay	1	984	PWR	1994-02
	2	984	PWR	1994-05
Tianwan	1	1060	PWR	2007-05
	2	1060	PWR	2007-08
Lingao	1	990	PWR	2002-05
	2	990	PWR	2003-01
	3	1086	PWR	2010-09
	4	1086	PWR	2011-08
Ningde	1	1089	PWR	2013-04
	2	1089	PWR	2014-05
Hongyanhe	1	1119	PWR	2013-06
	2	1119	PWR	2014-05
Yangjiang	1	1086	PWR	2014-03
Fuqing	1	1089	PWR	2014-11
Fangjiashan	1	1089	PWR	2014-12
Total	22	20 306		

Table II. Nuclear power plants under construction in China [18].

Site name	Unit number	Capacity (MWe)	Reactor type	Startup year
Fuqing	2	1087	PWR	2015
	3	1080	PWR	2015
	4	1080	PWR	2017
Ningde	3	1089	PWR	2015
	4	1089	PWR	2015
Hongyanhe	3	1119	PWR	2015
	4	1119	PWR	2015
Yangjiang	2	1087	PWR	2015
	3	1086	PWR	2015
	4	1086	PWR	2017
	5	1080	PWR	2018
	6	1080	PWR	2019
Haiyang	1	1250	PWR	2015
	2	1250	PWR	2016
Fangjiashan	2	1089	PWR	2015
Sanmen	1	1250	PWR	2015
	2	1250	PWR	2015
Fangchenggang	1	1080	PWR	2015
	2	1080	PWR	2016
Changjiang	1	650	PWR	2015
	2	650	PWR	2015
Taishan	1	1750	PWR	2016
	2	1750	PWR	2017
Tianwan	3	1060	PWR	2016
	4	1060	PWR	2017
Shidaowan	1	210	HTR[a]	2017
Total	26	28 461		

[a]HTR: high-temperature gas-cooled reactor.

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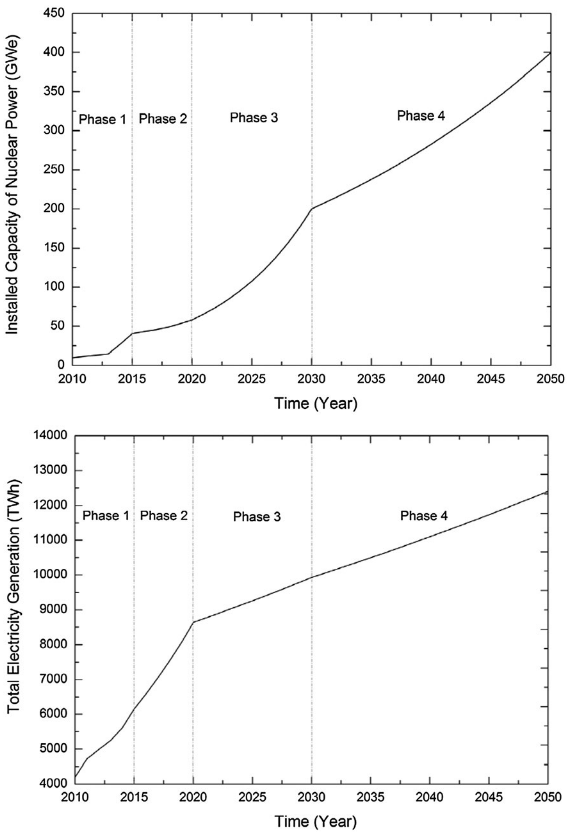

Figure 1. Growth profiles of nuclear power capacity and total electricity generation in China.

capacity [24]. The growth rate of total electricity demand will decrease slowly but still remain greater than 7% by 2020. The EPRC defined this phase as the transition to a primary developed economy [23].

In Phase 2 (2021–2030), the slope of the growth in nuclear power steadily increases while installed capacity grows to 200 GWe, which would then account for 15% of total electricity demand [25]. In contrast, the growth rate of total electricity demand is expected to decrease as the intermediate developed economy stage [23].

In Phase 3 (2031–2050), China's total electricity demand is projected to be saturated [23], and the annual growth rate is expected to decrease to about 1%. However, the rapid growth of nuclear power is maintained, reaching 400 GWe by 2050. In that year, nuclear power is projected to supply 24% of total electricity demand [25].

3. NUCLEAR FUEL CYCLE TRANSITION SCENARIOS

3.1. Current status of spent nuclear fuel management

According to the China National Nuclear Corporation (CNNC) [26], as of June 2013, about 4351 tHM of spent nuclear fuel has been accumulated, including 2241 tHM of PWR spent fuel and 2110 tHM of PHWR spent fuel. Most of the PWR spent fuel is temporarily stored in on-site water pools except for about 370 tHM shipped to interim storage with a capacity of 500 tHM in Gansu [27]. Moreover, 211 tHM of the PHWR spent fuel generated by Qinshan III is in dry storage. The dry storage began its operation in 2009 with a capacity of 48 000 bundles, which is planned to expand to its limit of 432 000 bundles [28]. In other words, the Chinese government is actively seeking ways to expand the capacity of spent fuel storage and to improve the transportation systems of spent fuel [29,30].

3.2. Future spent fuel management options

Since the early 2000s, China has developed spent fuel management approaches in cooperation with France and Russia [31]. The construction of a pilot-scale reprocessing plant (50 tons/yr) in Gansu was finished in 2005. In 2010, it completed its first hot test using Pu Reduction by Solvent Extraction (PUREX) technology [32]. In the same year, the China Experimental Fast Reactor (CEFR) was fueled with highly enriched U fuel and was connected to the electric grid successfully [33].

In November 2007, the CNNC signed a cooperative agreement on spent nuclear fuel reprocessing with AREVA Energy Company to introduce a commercial-scale Thermal Oxide Reprocessing Plant (THORP) with a capacity of 800 tHM/yr. The 12th Five Year Energy Technology Plan aims at implementing the first commercial reprocessing plant by 2020 [34]. In addition, the China Institute of Atomic Energy (CIAE) is planning to open a pilot-scale Mixed U-Pu Oxide (MOX) Fuel Fabrication Facility (MFFF, 0.5 tHM/yr) combined with the reprocessing plant [27].

According to the CIAE's report [25], the China Commercial-scale Demonstration Fast Reactor (CDFR) will be introduced in around 2030. In 2009, China decided to import two BN-800 units from Russia [35]. This reference CDFR is to be deployed in Phases 2–3 as the Fast Reactor (FR) technology development plan established by the CIAE (Table III). The CIAE plan also includes the development of China's own FR system, the so-called China Commercial-scale Fast Reactor (CCFR) project, by 2035 [36,37].

3.3. Future fuel cycle transition scenarios

Based on the plans for spent fuel management described in Section 3.2, we drew a decision tree of fuel cycle technology development in China (Figure 2). Four possible scenarios for fuel cycle transition were suggested. Figure 3 shows the overall flow of nuclear fuel cycle systems for each scenario. It should be noted that there will be no additional construction of PHWRs if the current two PHWRs are closed before 2043. This study also assumes for PHWR spent fuel to not be reprocessed.

In Scenario 1, Figure 3 (a), the PUREX project is assumed to have failed. After that, the Chinese government

Table III. Key projects of technology development for spent fuel management in China during 2015–2050.

Phase 1 2015–2020	Phase 2 2021–2030	Phase 3 2031–2050
- The first commercial-scale THORP using advanced PUREX technology (800 tHM/yr, CNNC-AREVA).	- The first two CDFRs (1600 MWe/yr, CNNC-Russia). - The second commercial-scale THORP (200–400 tHM/yr, CNNC).	- The first CCFR (1000–1200 MWe/yr, CIAE). - The first two commercial-scale FRPs (800 tHM/yr, CNNC).
- The pilot-scale MFFF (0.5 tHM/yr, CIAE).	- Two commercial-scale MFFFs (80 tHM/yr, CIAE). - The pilot-scale FRP (0.5 tHM/yr, CIAE).	

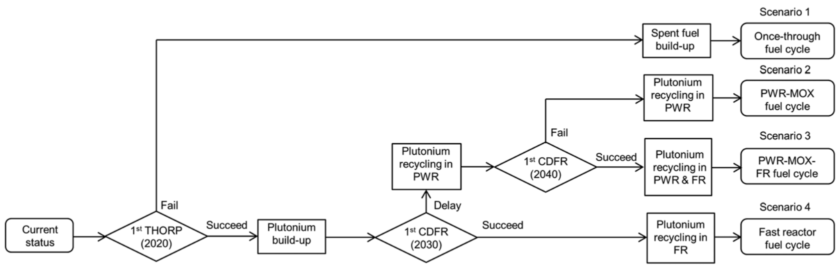

Figure 2. Decision tree of nuclear fuel cycle transition scenarios in China.

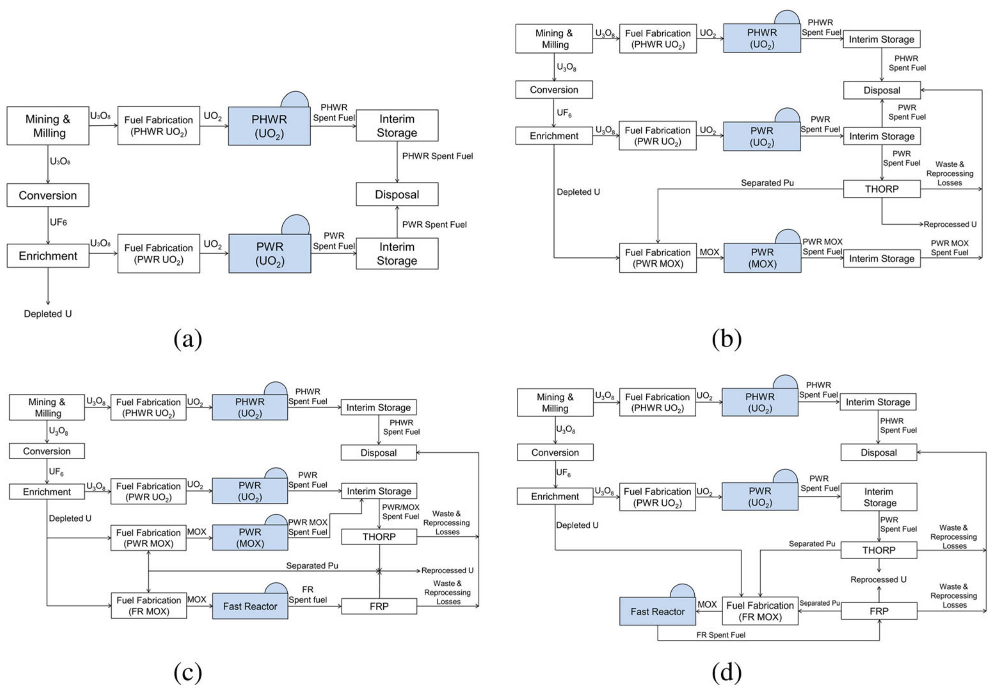

Figure 3. Flow diagrams of four scenarios for fuel cycle transition in China: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4.

may either fail to develop FR technology and the associated fuel cycle processes, or decide not to develop them. Hence, all spent fuels will be directly sent to a geological repository for permanent disposal without further processing after interim storage.

In Scenario 2, Figure 3 (b), China successfully develops the PUREX reprocessing technology in 2020. After that, it is assumed that the CDFR project will be delayed for 10 years and eventually fail. When we look back the previous experience of FR technology development in certain countries, the development schedule of commercial FRs can be delayed or fail. Under the pressure of expensive storage cost and the high security risk of separated Pu, it is feasible to reuse the Pu separated from PWR spent fuel one more time in PWRs fueled with MOX fuels (PWR-MOX) as some European countries have done [38,39].

We assumed that the same deployment rate of THORP is maintained as one new 800 tHM/yr unit starts up every 5 years. All spent MOX fuels will be sent for final disposal after interim storage.

In contrast to Scenario 2, in Scenario 3, the CDFR project is delayed for 10 years but eventually succeeds, as shown in Figure 3 (c). Here, the FR will receive MOX fuels containing Pu reprocessed from both PWR-UO_2 and PWR-MOX spent fuels. One new unit of advanced THORP processed PWR-MOX spent fuel (200 tHM/yr) will be deployed every five years from 2040. The spent MOX fuel discharged from the FR can also be reprocessed and recycled repeatedly. The FRP (Fast Reactor Fuel Reprocessing Plant) will be deployed in accordance with the available amount of FR spent fuel accumulated after cooling.

In Scenario 4, Figure 3 (d), the PUREX reprocessing project will be completed in 2020, and the CDFR project will succeed as planned in 2030. In this case, Pu from THORP will not be used for PWR-MOX, but will be stored for 10 years, waiting for the startup of the CDFR. Like Scenario 3, the spent MOX fuel discharged from the FR can be reprocessed in FRP and repeatedly recycled for use in the FR.

4. METHODS

4.1. Reactor and fuel cycle data

Table IV lists the design parameters of the reactors considered in this study. Table V summarizes the composition data of fresh and discharged fuels for each type of reactor.

4.2. Calculation

As shown in Figure 3, a fuel cycle system is divided into three parts: the front-end cycle, the irradiation within a reactor, and the back-end cycle. The front-end cycle includes mining and milling, conversion, enrichment, and fuel fabrication. The back-end cycle includes interim storage, reprocessing, fabrication of recycled fuel, and final waste disposal. This study modeled fuel cycle transition and analyzed the dynamic effects of the fuel cycle decisions. The detailed analysis includes the deployment of the reactors, the accumulation of high-level waste, the consumption of natural U, and the build-up of separated Pu by 2050.

The annual fuel fabrication is calculated as of the time when it is loaded into reactors. There are two different paths of fresh fuel demand: for the initial start-up of newly

Table IV. Design specifications and characteristics of reactors [5,40–43].

Reactor type	PWR Gen-II	PWR Gen-III	PHWR	FR (CR[a] = 1.0)	Unit
Model type	M310	CPR-1000	CANDU-6	BN-800	—
Power	1000	1250	728	870	MWe
Thermal efficiency	33	33	33	41.43	%
Capacity factor	85	85	85	85	%
Fuel types	UO_2	UO_2, MOX	UO_2	MOX	—
Discharge burnup	45 000	55 000	7500	100 000	MWd/tHM
Batch number	3	3	—	3–3.5[b]	—
Specific power	38.53	34.1	25.5	86.46	MW/tHM
Lifetime	40	60	40	60	Years
Related scenarios	1,2,3,4	1,2,3,4	1,2,3,4	3,4	—

[a]CR: conversion ratio.
[b]Half the radial blanket fuel assemblies have three refueling batches, the other half four refueling batches.

Table V. Composition of fresh and discharged fuels in reactors [40,41].

Fuel type		UO_2 fuel for PWR 1	UO_2 fuel for PWR 2	UO_2 fuel for PHWR	MOX fuel for PWR	MOX fuel for FR	Unit
U enrichment		4.45	4.95,	0.71	0.25	0.25	wt%
BOC[a]	U	100	100	100	92	88.63	wt%
	Pu	—	—	—	8	11.37	wt%
EOC[b]	U	94.2	92.95	98.89	88.36	84.04	wt%
	Pu	1.2	1.3	0.38	5.7	12	wt%
	MA[a]	0.1	0.1	0.003	0.53	0.1	wt%

[a]BOC: beginning of cycle.
[b]EOC: end of cycle.
[c]MAs: minor actinides.

commissioned reactors and for refueling reactors in operation. Once an order for fuel is received, the time required for fabrication is assumed to be one year. Hence, the annual fuel fabrication is calculated using

$$F(t) = \sum_{i}^{I}\sum_{j}^{J} F_{ij}^{O}(t-1) + F_{ij}^{S}(t-1) - \frac{F_{ij}^{S}(t-1)}{\lambda_{ij}} \quad (1)$$

where t is time, i and j indicate the types of reactors and fuels with total numbers of I and J, respectively, i.e. PWR-UO_2 ($i=1$), PHWR ($i=2$), PWR-MOX ($i=3$), and FR ($i=4$). F is the annual fuel fabrication, F_{ij}^{O} is the annual fuel order of refueling fuels for the i-th type reactor using the j-th type fuel, F_{ij}^{S} is the annual fuel order of start-up fuels for the i-th type reactor using the j-th type fuel, and λ_{ij} is the number of fuel batches. The last term fixes the double count of fuel orders because the newly started reactors are also included in reactors in operation at the startup year. Here, F_{ij}^{O} and F_{ij}^{S} are determined using

$$F_{ij}^{O}(t-1) = N_{ij}^{O}(t) \cdot \frac{P_{ij} \cdot 365 \cdot CF_{ij}}{\varepsilon_{ij} \cdot BU_{ij}} \quad (2)$$

$$F_{ij}^{S}(t-1) = \frac{P_{ij}}{\varepsilon_{ij} \cdot SP_{ij}} \cdot N_{ij}^{S}(t) \cdot \lambda_{ij} \quad (3)$$

where N_{ij}^{O} is the number of the i-th type reactor in operation using the j-th type fuel, N_{ij}^{S} is the number of newly started i-th type reactors using the j-th type fuel, P_{ij} is the power capacity (MWe), CF_{ij} is the capital factor, ε_{ij} is the thermal efficiency, SP_{ij} is the specific power (MWt/tHM), and BU_{ij} is the discharge burn-up (MWd/tHM).

The annually discharged spent fuel has two different generation paths: annually discharged fuel from reactors in operation and fuel discharged from the whole core removal of newly shutdown reactors. Hence, the annually discharged spent fuel is given by

$$D(t) = \sum_{i}^{I}\sum_{j}^{J}\left(N_{ij}^{O}(t) - N_{ij}^{D}(t)\right) \cdot \frac{P_{ij} \cdot 365 \cdot CF_{ij}}{\varepsilon_{ij} \cdot BU_{ij}} + F_{ij}^{D}(t-1) \quad (4)$$

where N_{ij}^{D} is the number of newly shutdown reactors, and F_{ij}^{D} is the annual fuel order of discharged fuel from the whole core removal of newly shutdown reactors. In Equation 4, F_{ij}^{D} can be written as

$$F_{ij}^{D}(t-1) = \frac{P_{ij}}{\varepsilon_{ij} \cdot SP_{ij}} \cdot N_{ij}^{D}(t) \cdot \lambda_{ij}\,. \quad (5)$$

The accumulated natural U consumption is calculated from

$$U(t) = U(t-1) + \sum_{j}^{J}\left(\left(F_{1j}(t-1)\right) \cdot \frac{e_{p_{1j}} - e_{t_{1j}}}{e_{f_{1j}} - e_{t_{1j}}} + F_{2j}^{O}(t-1) + F_{2j}^{S}(t-1)\right) \quad (6)$$

where $e_{p_{1j}}$ is the enrichment of ^{235}U of the j-type fuel loaded into PWR-UO_2 ($i=1$), $e_{f_{1j}}$ is its enrichment of natural U, and $e_{t_{1j}}$ is its enrichment of depleted U.

Then, the accumulated depleted U production is given by

$$DU(t) = DU(t-1) + \sum_{j}^{J}\left(\left(F_{1j}(t-1)\right) \cdot \frac{e_{f_{1j}} - e_{p_{1j}}}{e_{f_{1j}} - e_{t_{1j}}}\right) - \sum_{i=3,4}^{I}\sum_{j}^{J}\left(\left(F_{ij}^{O}(t-1) + F_{ij}^{S}(t-1)\right) \cdot X_{ij}^{DU}\right) \quad (7)$$

where X_{ij}^{DU} is the fraction of depleted U in fresh fuel.

The inventory of accumulated separated Pu is given by

$$Pu(t) = Pu(t-1) + \sum_{i}^{I}\sum_{j}^{J} R_{1j}(t-1) \cdot Y_{ij}^{Pu} \cdot \left(1 - l_{rp}\right) - \sum_{i=3,4}^{I}\sum_{j}^{J} \frac{\left(F_{ij}(t-1)\right) \cdot X_{ij}^{Pu}}{\left(1 - l_{fb}\right)} \quad (8)$$

where $R_{1j}(t-1)$ is the annual amount of spent fuel reprocessing, Y_{ij}^{Pu} is the fraction of Pu in spent fuel, X_{ij}^{Pu} is the fraction of Pu in fresh fuel, l_{rp} is the material loss factor in reprocessing, and l_{fb} is the material loss factor in fuel fabrication. The minimum cooling times of PWR and FR spent fuels before reprocessing are assumed to be 5 and 2 years after discharge, respectively.

5. RESULTS AND DISCUSSION

5.1. Deployment of reactors

Scenario 1 involves PWR and PHWR while the other scenarios involve the deployment of one or two more types of reactors for reusing fissile materials recovered from spent fuel. In Scenarios 2–4, the primary objective of the reactor deployment is to reduce the accumulation of high-level waste to be disposed of in the final repository. To meet this goal, the newly started PWR-UO_2 will be replaced by either PWR-MOX or FR using fissile materials separated from as much PWR spent fuel as possible. In other words, the highest deployment priority of the reactors is given to the advanced reactors reusing the separated fissile materials, which is limited by the deployment rate of spent fuel reprocessing plants.

As shown in Figure 4, in Scenario 1, PWR-UO_2 would supply all of the nuclear electricity demand from 2043, when the two currently operating PHWRs are closed. In Scenarios 2 and 3, PWR-MOX would provide 10.6% of nuclear electricity demand in 2050. In Scenarios 3 and 4, the capacity of the FRs would increase to 7.4% and 28.9% of the total nuclear power capacity, respectively.

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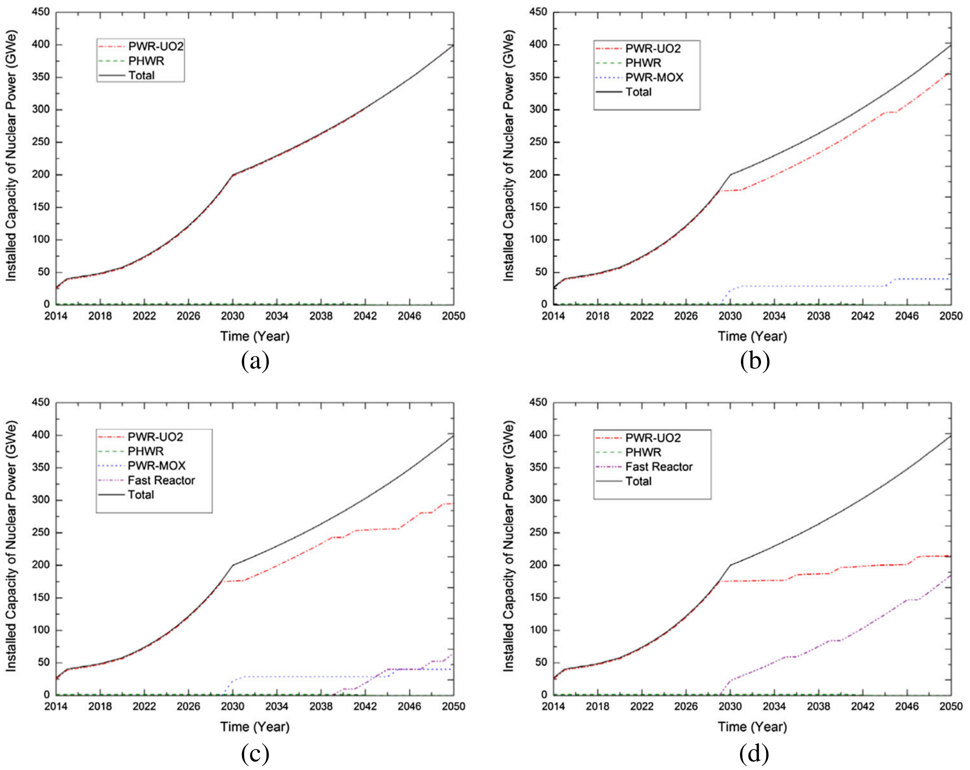

Figure 4. Installed capacity of nuclear power by types of reactors through 2050: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4.

Figure 5 shows the distribution of the reactors deployed in four scenarios by 2050. Regardless of the different transition scenarios, the PWR will remain the predominant type of reactor and will generate most of the nuclear electricity.

5.2. Generation of high level waste

High-level waste is generated from different sources, as listed in Table VI. In all scenarios, PHWR spent fuel is treated as high-level waste. By 2050, about 7.3 ktHM of

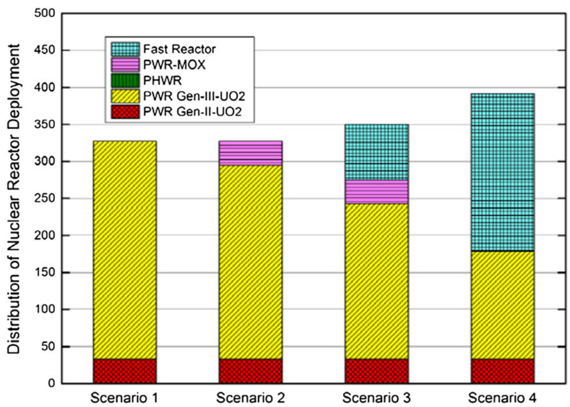

Figure 5. Number and distribution of nuclear reactors deployed by 2050.

PHWR spent fuel would be generated and await final disposal without recycling. In Scenarios 2–4, the amount of PWR spent fuel accumulated decreases as it is reprocessed, while generating a small amount of high-level waste from reprocessing and fuel fabrication. In Scenario 2, PWR-MOX spent fuel is high-level waste, but most of it is reprocessed and recycled in Scenario 3.

Figure 6 shows the amount of PWR spent fuel accumulated in all scenarios. In Scenario 1, the growth rate of PWR spent fuel accumulation will increase sharply because of the dramatic expansion of nuclear power. As a result, 140.9 ktHM of PWR spent fuel would be accumulated by 2050. However, in the other scenarios, the accumulation of PWR spent fuel can be greatly reduced through reprocessing. In Scenario 2, the reduction would be about 75% compared with Scenario 1. In Scenarios 3 and 4, the reductions would be 77% and 82%, respectively.

Figure 7 shows the accumulation of high-level waste including PWR-MOX spent fuel and reprocessing loss. Although, a considerable amount of PWR spent fuel is reprocessed in Scenario 2, a relatively large amount of high-level waste (up to 11.6 ktHM) still remains in 2050 because of the accumulation of PWR-MOX spent fuel. In Scenario 3, PWR-MOX spent fuel would accumulate to 4.4 ktHM through 2039, and its stockpile would then accumulate slower as it is reprocessed for new refueling fuels in the FR. In contrast, the accumulation of high-level waste would be less than 0.7 ktHM in Scenario 4 by 2050.

Table VI. High level waste (HLW) sources in four scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PHWR spent fuels	HLW	HLW	HLW	HLW
PWR-UO_2 spent fuels	HLW	Recycled	Recycled	Recycled
PWR-MOX spent fuels	Not produced	HLW	Recycled	Not produced
PWR spent fuel losses (during reprocessing and fabrication)	Not produced	HLW	HLW	HLW
FR spent fuel losses (during reprocessing and fabrication)	Not produced	Not produced	HLW	HLW

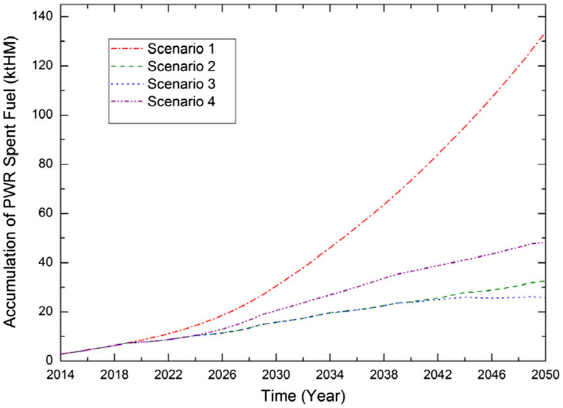

Figure 6. Accumulation of PWR spent fuel through 2050.

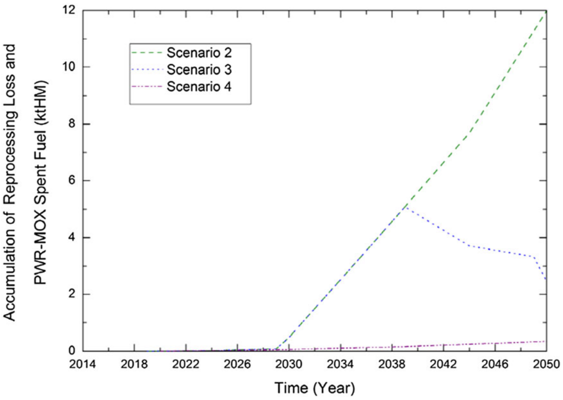

Figure 7. Accumulated reprocessing loss and PWR-MOX spent fuel through 2050.

5.3. Consumption of natural U resources

Figure 8 shows the accumulated depleted U. Thanks to the rapid integration of FRs into the electric grid, the accumulation of depleted U could be reduced by 18% through 2050 in Scenario 4. However, the accumulation of depleted U in Scenarios 2 and 3 would be more difficult to reduce because of the offset by depleted U gains during enrichment. In all scenarios, PWRs using enriched U fuels would still dominate the market, as shown in Figures 4 and 5.

Figure 9 compares the accumulated consumption for natural U in the four scenarios. The reduction of natural U consumption can enhance the energy security because China

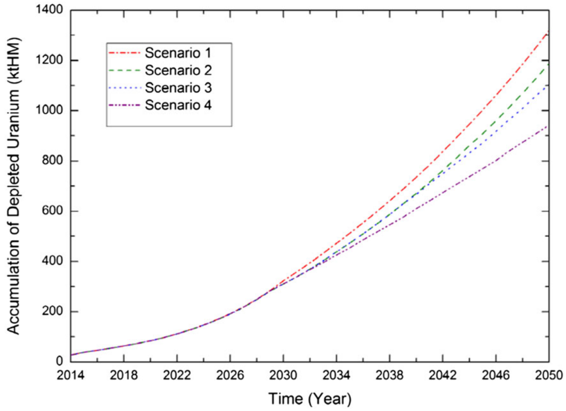

Figure 8. Accumulation of depleted U through 2050.

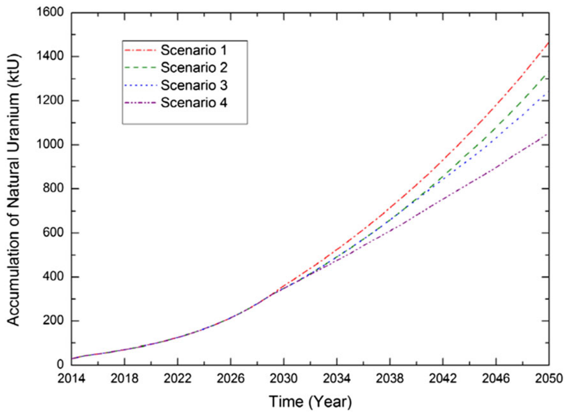

Figure 9. Accumulated requirement for natural U through 2050.

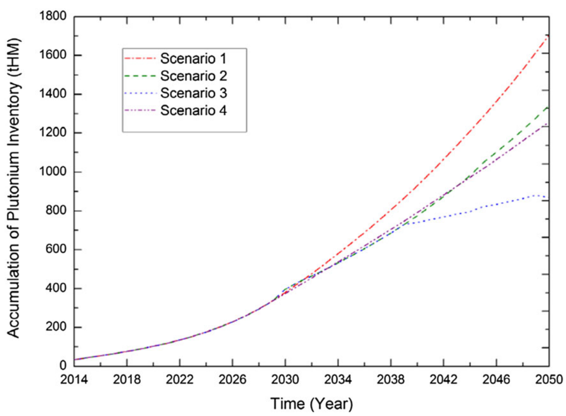

Figure 10. Pu inventory in overall nuclear systems through 2050.

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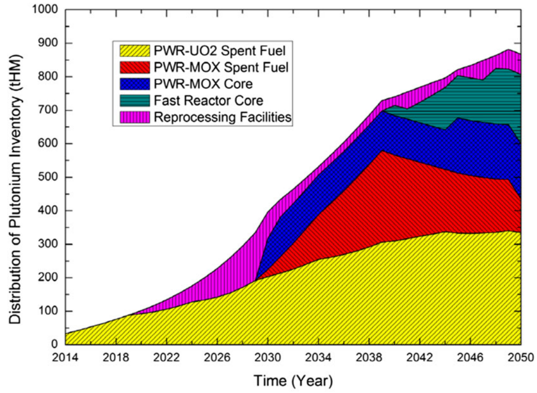
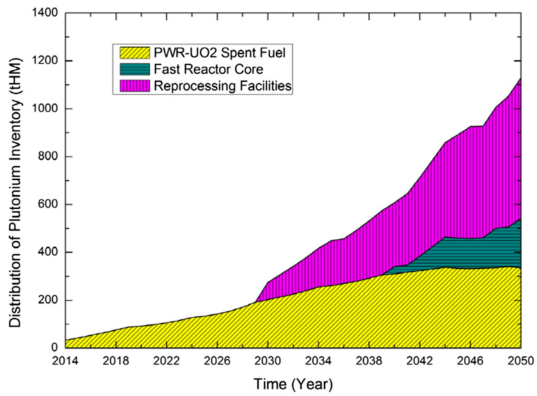
still imports about 80% of the U ore from abroad [18]. Similar to the case of depleted U, Scenario 4 depends least on natural U imports because of the rapid deployment of FRs instead of PWR-UO_2. Scenarios 2 and 3 can reduce natural U consumption by 8.6% and 11.4%, respectively.



(a)



(b)

Figure 11. Distribution of Pu inventory in the overall nuclear system: (a) Scenario 3 and (b) Scenario 4.

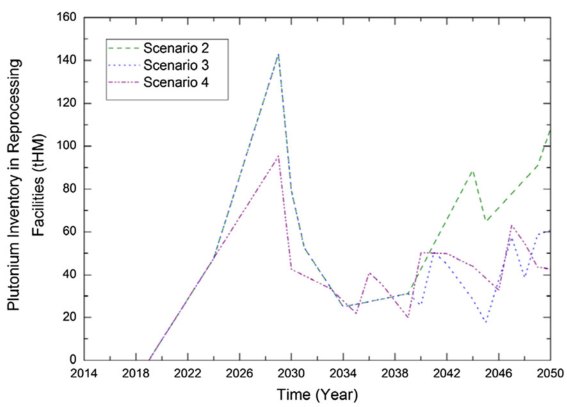


Figure 12. Inventory of separated pure Pu temporarily stored in reprocessing plants through 2050.

5.4. Accumulation of separated Pu inventory

The accumulation of separated Pu inventory matters greatly because of the nuclear security risk imposed by management of this pure fissile material. Scenarios 3 and 4 can eliminate long-term concerns about potential Pu mines in a geological repository compared to the other scenarios, but they will produce a new near-term management risk caused by the temporary storage of separated Pu. Excluding Pu in the reactor core, the Pu inventory in the overall nuclear energy system exists in three different forms: residual Pu in all spent fuel, Pu included in MOX fuels, and separated Pu temporarily stored in reprocessing plants.

Starting from Pu within 2.2 ktHM of PWR spent fuel in 2013, the residual Pu in PWR spent fuel would gradually increase to about 1706.5 tHM by 2050 in Scenario 1 (Figure 10). In Scenario 1, there is no Pu residue in MOX fuels or separated Pu in the reprocessing plants. In

Table VII. Unit costs for nuclear system components [44–47].

Step	Unit cost (2014 USD)	Unit
Reactor unit cost		
PWR capital	4219	\$/kWe
FR capital	4976	\$/kWe
PWR O&M[a] and D&D[b]	71	\$/kWe
PHWR O&M and D&D	71	\$/kWe
FR O&M and D&D	76	\$/kWe
Front-end fuel cycle unit cost		
Natural U	101	\$/kg U
Conversion	11	\$ kg U
Enrichment	119	\$/SWU
PWR UO_2 fuel fabrication	270	\$/kg HM
PHWR UO_2 fuel fabrication	146	\$/kg HM
Back-end fuel cycle unit cost		
Interim storage of PWR-UO_2 spent fuel	130	\$/kg HM
Interim storage of PHWR spent fuel	130	\$/kg HM
Interim storage of PWR-MOX spent fuel	130	\$/kg HM
PUREX reprocessing for PWR-UO_2 spent fuel	1111	\$/kg HM
PUREX reprocessing for PWR-MOX spent fuel	1389	\$/kg HM
Advanced PUREX reprocessing for FR spent fuel	2778	\$/kg HM
PWR-MOX fuel fabrication	2667	\$/kg HM
FR fuel fabrication	3056	\$/kg HM
Temporary storage of reprocessed Pu	2812	\$/kg HM
Conversion and storage of depleted U	12	\$/kg U
Conditioning and storage of PUREX HLW	7031	\$/kg HM

[a]O&M: operation and maintenance.
[b]D&D: decontamination and decommission.

Scenario 2, the total Pu inventory can be reduced by 23.6% by reusing Pu in the PWR spent fuel. Most of the remaining Pu is still contained in un-reprocessed PWR spent fuel.

Figure 11 shows the Pu distribution in the overall nuclear systems for Scenarios 3 and 4. Scenario 4 is more effective at reducing the total Pu inventory in the overall system and would reduce it by 58%, compared with 35% in Scenario 3.

However, Scenarios 3 tends to have a lower security risk in on-site Pu management than Scenarios 2 and 4 because there would be less separated pure Pu stored in reprocessing plants. As shown in Figure 12, the stockpile of Pu in the reprocessing plants may be used faster in Scenario 3 owing to a higher consumption from both PWR-MOX and FR. In Scenarios 2–4, spent fuel recycling can maintain low peaks of Pu build-up (less than 100 tHM after 2030).

Compared to the FRs, PWR-MOX needs almost twice the amount of Pu for the initial cores. Additionally, before the newly start-up FRs become self-sustaining through reprocessing and recycling their own spent fuel, each FR requires refueling for an extra 3 years with external Pu sources: 2 years for the initially discharged fuel to cool down and 1 more year for it to be reprocessed and refabricated into a new MOX fuel.

5.5. Economic analysis

Based on the growth and material flow of the nuclear power program provided in the previous sections, we conducted relevant dynamic economic analyses of four nuclear fuel cycle transition scenarios, considering the LCOE of the overall nuclear energy system at a discount rate of 5%. In Table VII, the unit cost data for nuclear energy system components in this study are summarized. Because the final disposal of high level waste in a deep geological repository is expected to be operated after 2050 [28,48], we did not consider the final disposal cost of high-level waste in this study. The breakdown of the calculated cost results for nuclear system components in the four scenarios is provided in Table VIII.

Figure 13 shows the LCOE of the overall nuclear system in the four scenarios until 2050. Compared to the other scenarios, Scenario 1 is the cheapest (as low as 56.391 mills/kWh), but its front-end cost is up to 12.1% of the total, which is higher than in Scenarios 2–4. In contrast, the LCOE of Scenario 4 is the most expensive (up to 59.464 mills/kWh) while its front-end fuel cycle cost could be reduced by 13.7%. In Scenarios 2 and 3, their LCOE are 3.2% and 3.8% higher than that of Scenario 1, respectively.

Table VIII. Summarized results of LCOE for nuclear system components (Unit: mills/kWe based on 2014 USD).

Step	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Reactor cost				
PWR capital	39.126	38.126	37.650	31.481
FR capital	0	0	1.741	9.017
PWR O&M[a] and D&D[b]	9.508	9.508	9.374	8.323
PHWR O&M and D&D	0.087	0.087	0.087	0.087
FR O&M and D&D	0	0	0.143	1.269
Reactor cost subtotal	48.722	48.722	48.996	50.177
Front-end fuel cycle cost				
Natural U	3.105	2.864	2.808	2.669
Conversion	0.327	0.302	0.296	0.282
Enrichment	2.610	2.413	2.368	2.254
PWR UO_2 fuel fabrication	0.774	0.715	0.702	0.671
PHWR UO_2 fuel fabrication	0.022	0.022	0.022	0.022
Front-end fuel cycle cost subtotal	6.838	6.316	6.197	5.897
Back-end fuel cycle cost				
Interim storage of PWR-UO_2 spent fuel	0.425	0.042	0.051	0.042
Interim storage of PHWR spent fuel	0.017	0.017	0.017	0.017
Interim storage of PWR-MOX spent fuel	0	0.019	0.010	0
PUREX reprocessing for PWR-UO_2 spent fuel	0	1.668	1.668	1.659
PUREX reprocessing for PWR-MOX spent fuel	0	0	0.056	0
Advanced PUREX reprocessing for FR spent fuel	0	0	0.034	0.356
PWR-MOX fuel fabrication	0	0.582	0.582	0
FR fuel fabrication	0	0	0.087	0.488
Temporary storage of reprocessed Pu	0	0.095	0.079	0.098
Conversion and storage depleted U	0.389	0.352	0.341	0.319
Conditioning and storage of PUREX HLW	0	0.388	0.394	0.411
Back-end fuel cycle cost subtotal	0.831	3.162	3.320	3.389
Total nuclear energy system cost	56.391	58.200	58.512	59.464

[a]O&M: operation and maintenance.
[b]D&D: decontamination and decommission.

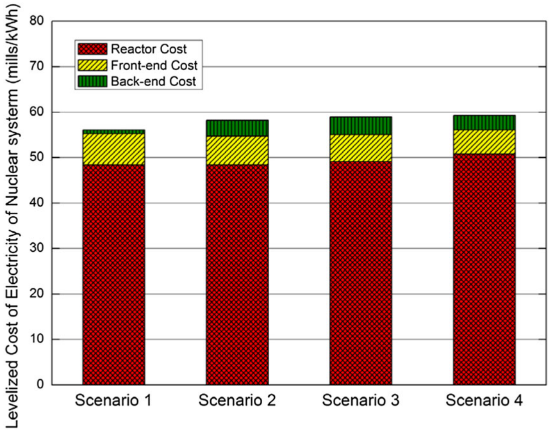


Figure 13. Levelized cost of electricity of overall nuclear system through 2050.

However, the reactor share of the total system cost for the four scenarios is more than 83%.

Moreover, in Scenario 3, China would need to develop and deploy three types of reprocessing plants and reactors separately. Undoubtedly, this would make it more complex and costly to meet its safety and security standards for reprocessing plants and reactors as well as for robust systems for transportation and storage.

6. CONCLUSIONS

We analyzed and compared the environmental, security, and economic consequences of ongoing approaches to spent fuel management in China. We developed four possible scenarios of nuclear fuel cycle transition through 2050 based on current ongoing R&D projects and plans. The four transition scenarios include the direct disposal of PWR spent fuel, the single recycling of PWR spent fuel through PWR-MOX, the PWR-MOX followed by the FR, and the recycling of PWR spent fuel through the FR.

The recycling of PWR spent fuel can benefit the nuclear power program by reducing the generation of high level waste, saving natural U resources, and reducing Pu management risk in the long-term. The first benefit can decrease potential concerns over finding several appropriate geological repositories for high-level waste, while the second will enhance the energy security by reducing natural U imports. Scenario 2 provides very limited advantages compared to Scenarios 3 and 4, and remains a greater Pu inventory in the overall nuclear system than Scenarios 3 and 4. Meanwhile, Scenario 3 requires a more complex and costly management system to meet the safety and security standards related to different kinds of storage facilities, reprocessing plants, and reactors. However, Scenario 1 shows the cheapest LCOE (as low as 56.391 mills/kWh) compared to Scenarios 2–4.

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