Investigation of economics of back-end nuclear fuel cycle options in the Republic of Korea based on Once-through

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1. Introduction

Although nuclear power has made significant contributions to the economic success of the Republic of Korea (ROK), its back-end fuel cycle policy remains uncertain with the “sit and watch” strategy. A number of investigations have been made to suggest how the back-end fuel cycle should be developed in the ROK. These investigations are mostly focused on capacity estimation of the fuel storage facilities. However, there are still remaining questions surrounding the back-end fuel cycle development in the ROK. These questions are related to licensed operation period extension, use of nuclear power vis-à-vis the reunification of the Korean peninsula and the need for construction of second fuel storage facilities. The purpose of this study is to examine these questions and perform economic evaluations of various cases of Once-through back-end fuel cycles in the ROK. Therefore, the study is to support decision making in terms of how the long term spent nuclear fuel (SNF) management strategy should be developed. A spreadsheet model was developed to plan reactor construction, the interim storage and the HLW repository construction within engineered constraints, based on the estimation of the spent fuel flow and the energy supply of the nuclear power program. The model computes the back-end levelized costs for various fuel cycle choices. The scenarios assumed in the model include (1) 0year/10year/20year of licensed operation period extension; (2) the phase-out of NPP program and the continuous use including the reunification of Korean peninsula; (3) reactor decommissioning and construction lead times – 10 years and 5 years respectively in this study; (4) geological constraints of siting for a new reactor – 38 for without the reunification and 70 for with the reunification; (5) the first initiation of reactor decommissioning and operation of HLW repository – assumed to be 2020 and 2050; and (6) capacity factor of reactor operation and the on-site wet storage pool capacity – 0.85 and 0.498 MTHM per MWe which is equivalent with APR1400. The capacity factor for PHWR reactors was assumed at 0.85 and the plan for PHWR was fixed as phase-out. The spreadsheet model conducts computation for annual expenditures of the back-end fuel cycle and calculates the levelized costs.

The supporting cost data was developed from the reports from Nirex, U.K. (2005) and EPRI, U.S. (2009) and the Korean Ministry of Knowledge and Economy (2012).

2. SNF generation and screening

The scenario of SNF generation is based on the 5th energy supply demand plan of the ROK. Table 1 presents the list of NPP in the ROK and their operation history.

Table 1: NPP operation history in the ROK

Rx	Capacity (MWe)	Start year	End year	Licensed operation period (yr)
Kori 1	608	1977	2017*	30
Wolsung 1	700	1982	2022*	30
Kori 2	676	1983	2023	40
Kori 3	1042	1985	2025	40
Kori 4	1041	1985	2025	40
Hanbit 1	996	1986	2026	40
Hanbit 2	993	1986	2026	40
Hanul 1	1003	1988	2028	40
Hanul 2	1008	1989	2029	40
Hanbit 3	1050	1994	2034	40
Hanbit 4	1049	1995	2035	40
Wolsung 2	700	1997	2037	40
Wolsung 3	700	1998	2038	40
Hanul 3	1050	1998	2038	40
Hanul 4	1053	1998	2038	40
Wolsung 4	700	1999	2039	40
Hanbit 5	1053	2001	2041	40
Hanbit 6	1052	2002	2042	40
Hanul 5	1051	2003	2043	40
Hanul 6	1051	2005	2045	40
S.Kori 1	1048	2010	2050	40
S.Kori 2	1045	2012	2052	40
S.Wolsung 1	1043	2012	2052	40
S.Wolsung 2	1000	2015	2055	40
S.Kori 3	1455	2015	2075	60
S.Kori 4	1455	2016	2076	60

The reactor construction plan in the model includes 12 additional new reactors, all assumed to be APR1400 with 60 years of licensed operation period. The rate of increase in nuclear electricity demand is set to be 1.7% following the projection based on the reunification scenario [1]. To compute the spent nuclear fuel flow from the reactors, the average discharge burn-up was assumed to be 44.6 MWd/kg. Spent fuel accumulation was calculated by Eq. (1), (2).

$$F(y) = \frac{P \cdot 365 \cdot CF \cdot N}{BU \cdot eff} \tag{1}$$

$$\sum_{n=1}^{n} F_n = \sum_{n=1}^{n} P_n \cdot SF + \sum_{n=i}^{n} I_n + \sum_{n=g}^{n} H_n \tag{2}$$

Where P = installed NPP capacity at n year
CF = NPP capacity factor
N = number of NPP
BU = average discharge burn-up value
SF = on-site spent fuel storage per kWe
I = spent fuel flow to the interim storage
i = initiation year of the interim storage
H = spent fuel flow to the HLW repository
g = initiation year of the HLW repository

2.1 Effect of licensed operation period extension

The licensed operation period of Kori 1 and Wolsung 1 was extended for 10 years. In the case of the U.S, license renewals for 10 or 20 years were commonly accepted [2]. It is assumed that the remaining reactors in the ROK are likely to follow the case of U.S., therefore, the capacities of the facilities for SNF might also be increased. Fig.1 shows the anticipated trend of nuclear energy use in the future in the ROK with licensed operation period extension for 0 year, 10 year and 20 year.

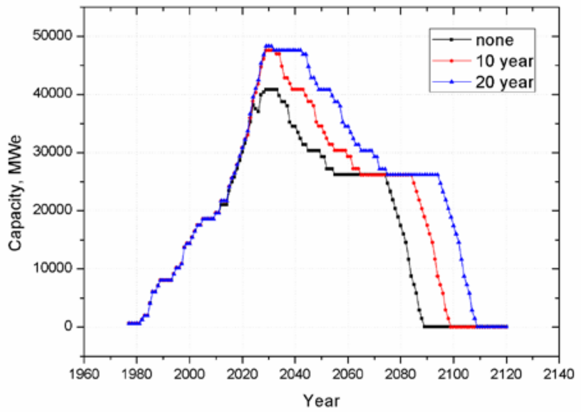

Fig. 1. NPP installed capacity for the cases of licensed operation period extension

Fig 2 presents the effect of the extended operation years of nuclear power plants on cumulative spent fuel generation that corresponds to the needed capacity of HLW repository. With the extended use of on-site spent fuel storage, the needed capacity of the interim storage did not increase a lot.

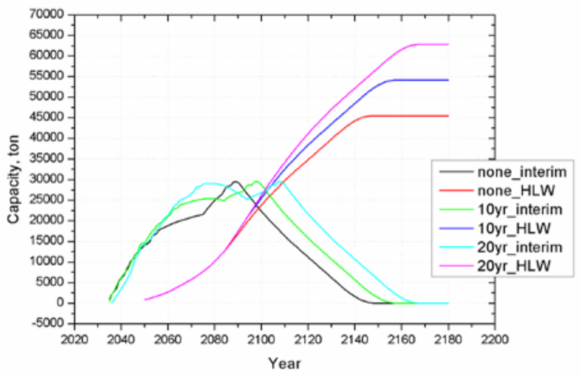

Fig. 2. Needed capacities of the interim storage and HLW repository for the cases of licensed operation period extension

2.2 Comparison between nuclear Phase-out and continuous use

The ROK has not decided which reactor decommissioning strategy it will deploy. Entombment is a method of reactor dismantling encasing radioactive contaminants in a long-lived material (e.g. concrete) till the radioactivity reduces below the regulated level. Entombment enables late deployment of final dismantling of the reactor which ensures making more funds available upon discount rate. Immediate dismantling of a reactor allows the facility to be removed from regulatory control and the site to be used for alternative purposes. In this study, assuming the public acceptance is no longer inclined to additional siting of new reactor constructions, the current reactor sites are reused for new builds after immediate dismantling. The decommissioning and construction lead time of a reactor are assumed to be 10 years and 5 years respectively. Fig 3 and Fig 4 show the nuclear energy supply trend and the corresponding cumulative spent fuel generation for the nuclear phase-out and the continuous use case.

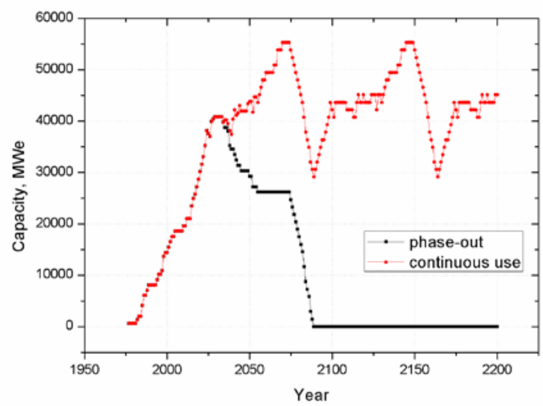

Fig. 3. NPP installed capacity for the cases of the phase-out and continuous use options

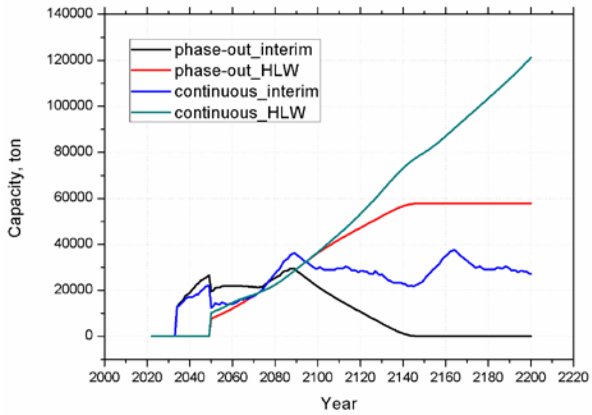

Fig. 4. Needed capacities of the interim storage and HLW repository for the cases of the phase-out and continuous use options

Under the continuous use scenario, licensed operation periods of the interim storage and HLW repository are assumed to last until dismantling.

2.3 Reunification of the Korean peninsular

The major obstacle for the continuous use of nuclear energy in the ROK is the low public acceptance and lack of suitable sites for new builds. However, the reunification of the Korean peninsula opens new possibilities. To study the reunification scenario, DSGE (Dynamic Stochastic General Equilibrium) model from KINU (Korea Institute for National Unification) was used. The reunification scenario assumed in the study is as follows: 1) Reunification occurs in year 2030, 2) GDP increases at rate of 2.2 ~ 3.8% after the reunification, 3) North Korea benefits a large amount of investment and financial support for infrastructure development from the South [1]. Under this scenario, the continuous use of nuclear energy has better prospects. In this study, it was assumed that the reunification option opens a large number of new reactor sites up to 70 and that the increase rate of nuclear energy demand is proportional to that of GDP. Fig 5 and Fig 6 show the future trend of nuclear energy supply and cumulative generation of spent fuel under the once-through option.

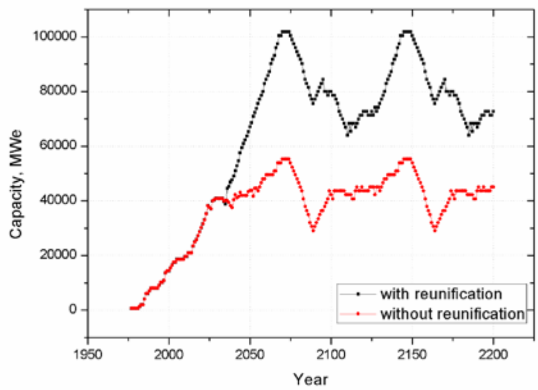

Fig. 5. NPP installed capacity with and without the reunification

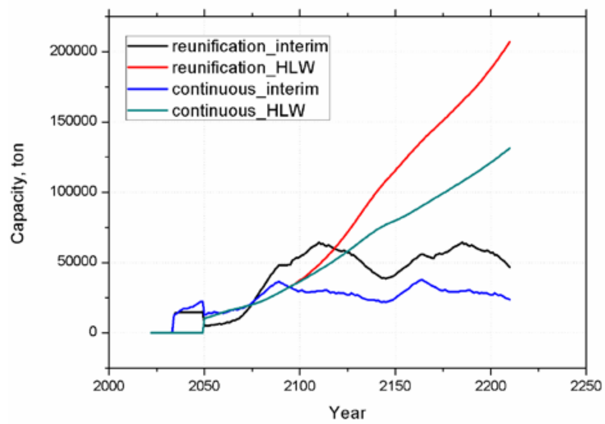

Fig. 6. Needed capacities of the interim storage and HLW repository with and without the reunification

3. Levelized Cost computation

3.1 Benchmark cost data

The cost of the back-end fuel cycle in the ROK consists of reactor dismantling cost, spent fuel interim storage cost and geological disposal cost. This is given in Eq. (3).

$$\sum_{n=1}^{n}\frac{D\cdot E_n}{(1+r)^n}=\sum_{n=1}^{n}\frac{Rx_n}{(1+r)^n}+\sum_{n=1}^{n}\frac{I_n}{(1+r)^n}+\sum_{n=1}^{n}\frac{H_n}{(1+r)^n}\quad(3)$$

Where D = levelised cost of the back-end fuel cycle
E_n = electricity production at n^{th} year
Rx_n = reactor decommissioning cost at n^{th} year
I_n = costs for the interim storage at n^{th} year
H_n = costs for the HLW repository at n^{th} year

The reactor dismantling cost was benchmarked against the case of Maine Yankee for PWR (immediate dismantling) and against the case of Darlington, Canada (deferred dismantling) for PHWR [3].

Table 2: Decommissioning cost estimates

	PWR (immediate dismantling)	PHWR (deferred dismantling)
USD(2001)/kWe	421	345

The cost for interim storage and geological repository was developed from the EPRI report (2009) [4] and the Korean Ministry of Knowledge Economy (2012) [5] and the Nirex report (2005) [6]. The cost was also a function of the capacity, following Eq. (4) [7].

$$\mathrm{OVC}(capacity1)=\mathrm{OVC}(capacity2)\left(\frac{capacity1}{capacity2}\right)^{0.6}\quad(4)$$

Table 3 and Table 4 list the estimated cost breakdown for the facilities.

Table 3: Referenced estimated cost breakdown for the interim storage (capacity : 39547MTHM)

Description	Cost (PWR)	Cost (PHWR)	Currency
Interim storage construction cost	840.2	827.4	BKRW (2012)
Interim storage operation(annual)	50.7	13.53	BKRW (2012)
Interim storage operation (per canister/module)	2.9	6.2	BKRW (2012)
Decommissioning cost	1141.9	36.1	BKRW (2012)

*BKRW : Billion won

Table 4: Referenced estimated cost breakdown for the HLW repository (capacity : 17000MTHM)

Description	Cost	Currency
Repository construction to first emplacement	1081	£m (2004)
Repository construction post first emplacement	499	£m (2004)
Repository operation(annual)	25.57	£m (2004)
Repository operation (per canister)*	65000	£ (2004)
Sealing and closure	279	£m (2004)

*canister cost of 0.465 bKRW not included

3.2 Levelized cost computation of the back-end fuel cycle

The effect of licensed operation period extension on the levelized costs is shown in Fig 7. In this comparison, 1.5% of discount rate was assumed.

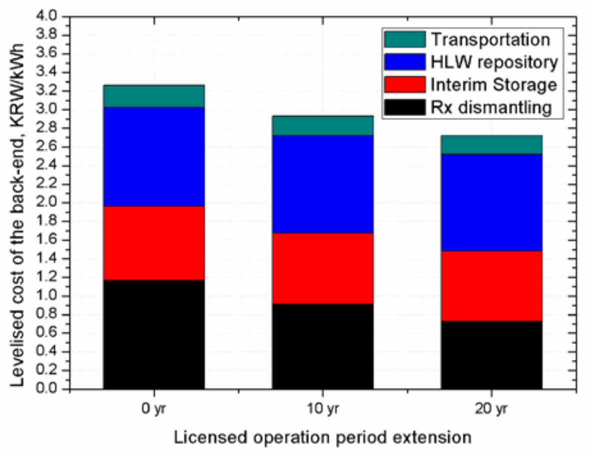

Fig. 7. Back-end fuel cycle cost breakdown of different licensed operation period extension options (phase-out) at 1.5% discount rate

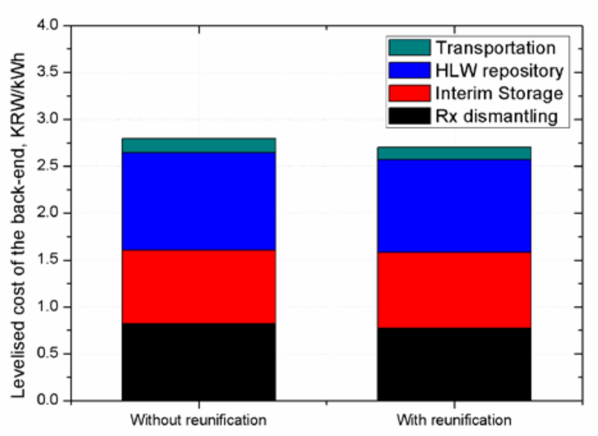

Fig. 8. Back-end fuel cycle cost comparison to the reunification scenario(continuous use) at 1.5% discount rate

Fig. 8 shows the comparison of levelised fuel cycle cost for the case of continuous use between unification and no-unification.

In this continuous use calculation, the size efficiency of the back end fuel cycle facilities results the lower cost of reunification scenario with 1.5 percent of discount rate. In the estimation in the reunification scenario, we may not have found a significant difference in cost. However, compared to the current cost of roughly 9KRW/kWh for funding of the back-end fuel cycle in the ROK, it appears to include a large portion of social cost. Therefore, with low social cost expected at the development phase in the reunification, the difference of the back-end fuel cycle cost is likely much greater.

4. Conclusions

Based on a spreadsheet model to estimate the levelised cost, various back-end fuel cycles were analyzed under Once-through scenario. It is shown that the cost decreases with licensed operation period extension and the size of the fuel cycle system. In the case of the continuous use option, the levelised cost in the reunification scenario is slightly lower than no-reunification.

Licensed operation period extension enhances not only economic efficiency, stable energy supply, but also reduces burden of siting for a new reactor and waste disposal. And regardless the reunification, continuous use of nuclear energy lowers the back-end fuel cycle cost. With projection that a large portion of social cost is included in the current back-end fuel cycle cost, nuclear energy likely has more competency in economy in the reunification scenario. Time delay of the deployment of HLW repository may be another factor that affects the cost of the back-end fuel cycle since it is related to the storage of SNF from decommissioned reactors.

Through this study, we could examine factors that affect fuel cycle economy and confirm that nuclear energy in the ROK will still likely be competitive in the future. Timely policy making for the back-end fuel cycle program is needed to utilize nuclear energy continuously in the future in terms of energy economics and preparedness to the reunification.

REFERENCES

[1] G. R. Kim, The Attraction of Korean Unification: Inter-Korean and International Costs and Benefits, Korea Institute for National Unification, p. 27, 2013

[2] Per. F. Peterson, Will the United States Need a Second Geologic Repository?, the Bridge liking engineering and society, Fall 2003

[3] Decommissioning Nuclear Power Plants, OECD/NEA, p.59-61, 2003

[4] J. Kessler, Cost Estimate for an Away-From-Reactor Generic Interim Storage Facility(GISF) for Spent Nuclear Fuel, EPRI, p.1-4, 2009.

[5] 2012 년 방사성폐기물관리비용 산정 최종보고서, 지식경제부 방사성폐기물 관리비용산정위원회, p.24, 2012.

[6] Cost Estimate for a Reference Repository Concept for UK High-level Waste/Spent Nuclear Fuel, Nirex, 2005

[7] The Economics of the Back End of the Nuclear Fuel Cycle, OECD/NEA, p.81, 2013