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Economic Analysis of Several Nuclear Fuel Cycles

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1. Introduction

Economics is one of the essential criteria to be considered for the future deployment of the nuclear power. With regard to the competitive power market, the cost of electricity from nuclear power plants is somewhat highly competitive with those from the other electricity generations, averaging lower in cost than fossil fuels, wind, or solar. However, a closer look at the nuclear power production brings an insight that the cost varies within a wide range, highly depending on a nuclear fuel cycle option. The option of nuclear fuel cycle is a key determinant in the economics, and therefrom, a comprehensive comparison among the proposed fuel cycle options necessitates an economic analysis for thirteen promising options based on the material flow analysis obtained by an equilibrium model as specified in the first article (Modeling and System Analysis of Different Fuel Cycle Options for Nuclear Power Sustainability (I): Uranium Consumption and Waste Generation). The objective of the article is to provide a systematic cost comparison among these nuclear fuel cycles.

The generation cost (GC) generally consists of a capital cost, an operation and maintenance cost (O&M cost), a fuel cycle cost (FCC), and a decontaminating & decommissioning (D&D) cost. FCC includes a front-end cost and a back-end cost, as well as costs associated with fuel recycling in the cases of semi-closed and closed cycle options. As a part of GC, the economic analysis on FCC mainly focuses on the cost differences among fuel cycle options considered and therefore efficiently avoids the large uncertainties of the Generation-IV reactor capital costs and the advanced reprocessing costs. However, the GC provides a more comprehensive result covering all the associated costs, and therefrom, both GC and FCC have been analyzed, respectively [1].

As a widely applied tool, the levelized cost (mills/KWh) proves to be a fundamental calculation principle in the energy and power industry [2][3], which is particularly appropriate for an estimate on the costs of energy given the various technologies. Levelized fuel cycle cost (LFCC) and levelized generation cost (LGC) have offered effective indicators for economic comparison among nuclear fuel cycles and were adopted to compare the fuel cycle options considered in this study [4][5][6].

The unpredictable change of the unit costs of several key components due to the uncertainties can lead to considerable differences in levelized costs among the fuel cycle alternatives. To take these unavoidable uncertainties into account, a wide scale was applied to each unit cost and a distribution of levelized cost was also obtained.

2. Methods

2.1 Model Setup

One is equilibrium model and the other is dynamic model. Equilibrium model focus on the batch study with the assumptions that the whole system is in a steady state and mass flow as well as the electricity production all through the fuel cycle is in equilibrium state, which calculates the electricity production within a certain period and associated material flow to obtain several criteria for assessment of the sustainability of nuclear power, e.g., resource utilization, waste generation, environment affects. Dynamic model takes the time factor into consideration to simulate the actual cases. Compared with the dynamic analysis model, the outcome of equilibrium model is more theoretical which may offer relatively clear and direct comparisons, especially with regard to the large uncertainty of the development of the pyro-technology evaluated. In this study equilibrium model was built to calculate the material flow on a batch basis.

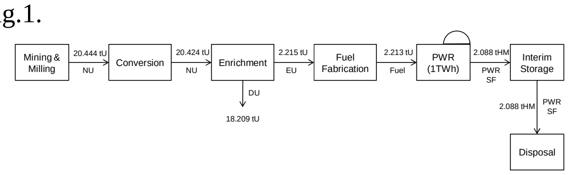
2.2 Fuel Cycle Cost

Cost of each fuel cycle component	Cost calculation methods	
Uranium	$F_U = M_f \cdot f_U \cdot P_U \cdot (1+r)^{t_U}$	(1)
	where, $M_f = M_p \cdot [(e_p - e_t)/(e_f - e_t)]$	(2)
	$f_U = (1+l_C)(1+l_E)(1+l_F)$	(3)
Conversion	$F_C = M_f \cdot f_C \cdot P_C \cdot (1+r)^{t_C}$	(4)
	where, $f_C = (1+l_C)(1+l_E)(1+l_F)$	(5)
Enrichment	$F_E = SWU \cdot f_E \cdot P_E \cdot (1+r)^{t_E}$	(6)
	$SWU = M_p \cdot V_p + M_t \cdot V_t - M_f \cdot V_f$	(7)
	$M_t = M_f - M_p$	(8)
	$V_x = (2e_x - 1)\ln[e_x/(1-e_x)]$	(9)
	$f_E = (1+l_E)(1+l_F)$	(10)
Fabrication	$F_F = M_p \cdot f_F \cdot P_F \cdot (1+r)^{t_F}$	(11)

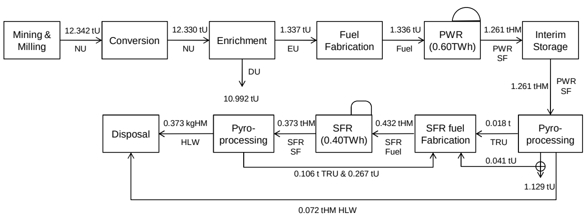
	where, $f_F = (1+l_F)$	(12)
Transport & storage	$F_{TS} = M_{TS} \cdot f_{TS} \cdot P_{TS} \cdot (1+r)^{t_{TS}}$	(13)
	where, $f_{TS} = (1+l_{TS})$	(14)
Disposal	$F_D = M_D \cdot f_D \cdot P_D \cdot (1+r)^{t_D}$	(15)
	where, $f_D = (1+l_D)$	(16)

2.3 Main components of nuclear fuel cycle

The breakdown structure of the nuclear fuel cycle scheme is specified by the series of components (or steps) included in the four fuel cycle options of this study. Typical OT and Pyro-SFR main components are shown in Fig.1. Material flow data are also specified in Fig.1.



(a) Once-through (OT) Cycle



(b) Pyro-SFR Recycling

Fig.1. Main components in the nuclear fuel cycle

3. Results and Discussion

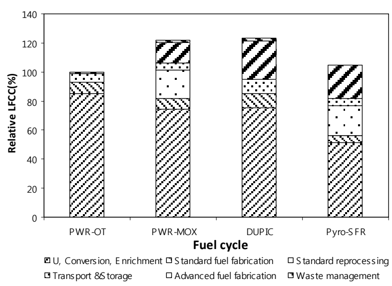


Fig. 2. Relative LFCC of four fuel cycles

The calculation results of LFCC concerning these four fuel cycle scenarios show: OT 7.35 mills/kWh, DUPIC 9.06 mills/kWh, PUREX-MOX 8.94 mills/kWh, and Pyro-SFR 7.70 mills/kWh. The relative total costs of the fuel cycle options are presented by a bar chart in Fig. 2. It shows that DUPIC is 23%, PWR-MOX is 22%, and Pyro-SFR is 5% higher than OT option, respectively.

Fig. 2 shows that uranium price is the key cost component of LFCC in all these four nuclear fuel cycles. With the current uranium price, OT is the most economical option and Pyro-SFR is the second due to the low uranium consumption. In the Pyro-SFR scenario, the uranium consumption decreases because of the utilization of the metal fuel made from reprocessed TRU. Pyro-Metal-Fab., however, make up for the difference in uranium costs between the Pyro-SFR and OT scenarios. In PWR-MOX scenario, the uranium consumption is still high, meanwhile reprocessing, however, is costly. The relative high cost of DUPIC scenario is because the low uranium utilization efficiency due to the low burn-up and the high fabrication cost to make PWR SF into CANDU fuel.

4. Conclusions

An economic analysis has been performed to compare four nuclear fuel cycle options, once-through cycle (OT), DUPIC recycling, thermal recycling by using MOX fuel in pressurized water reactor (PWR-MOX) and sodium fast reactor recycling employing pyroprocessing (Pyro-SFR), to suggest an economic competitive fuel cycle for Republic of Korea. The fuel cycle cost (FCC) has been calculated based on the equilibrium material flows integrated with the unit cost of fuel cycle components. The levelized fuel cycle costs (LFCC) have been derived in terms of mills/kWh for a fair comparison among the FCCs, and the results are as follows: OT 7.35 mills/kWh, DUPIC 9.06 mills/kWh, PUREX-MOX 8.94 mills/kWh, and Pyro-SFR 7.70 mills/kWh. Due to the unavoidable uncertainties, a cost range has been applied to each unit cost and an uncertainty study has been performed accordingly. A sensitivity analysis has also been carried out to obtain the breakeven uranium price (215$/kgU) for Pyro-SFR against OT, which demonstrates that the deployment of Pyro-SFR may be economical in a foreseeable future. The influence of pyro-techniques on LFCC has also been studied to determine at which level the potential advantages of Pyro-SFR could be realized.

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