Social Cost Assessment for Nuclear Fuel Cycle Options in the Republic of Korea

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1. Introduction

World energy consumption is constantly increasing in response to population growth and greater individual demands for energy consumption. Before deciding which energy supply systems to rely on for base line power, we have to assess the economics of each power supply system individually. This paper will investigate the vast array of economic factors to estimate the true cost of the nuclear power.

There are many studies addressing the external costs of energy production. However, it is only since the 1990s that the external costs of nuclear powered electricity production has been studied in detail [1]. Each investigation has identified their own set of external costs and developed formulas and models using a variety of statistical techniques. The objective of this research is to broaden the scope of the parameters currently consider by adding new areas and expanding on the types of situations considered. Previously the approach to evaluating the external cost of nuclear power did not include various fuel cycle options and influencing parameters.

Cost has always been a very important factor in decision-making, in particular for policy choices evaluating the alternative energy sources and electricity generation technologies [2]. Assessment of external costs in support of decision-making should reflect timely consideration of important country specific policy objective [2].

Thereby resulting in cost assessments that not only compare traditionally evaluated nuclear fuel cycle scenarios, but are expanded to include energy options that are on the horizon of ROK's nuclear energy program. This evaluation will not focus only on "cost" but will address all the factors associated with cost.

This paper defines the parameter for assessing social cost considering normal operation and accident situation. Based on the parameters defined as social cost and derived from fuel cycle model, the Multi-Criteria Decision Making (MCDM) method was used to evaluate various fuel cycle options.

2. Fuel Cycle Scenario [3]

In the Republic of Korea, four different scenarios of nuclear fuel cycle were analyzed to address the country's spent fuel management challenges.

1. **OT** - A once-through cycle
2. **FR-Pyro** - Recycling of nuclear materials in fast reactor after pyro-processing of spent fuel
3. **OT-Pyro** Direct disposal of high level waste after pyro-processing of spent fuel
4. **OT-ER** - Direct disposal of high level waste after electrolytic reduction of spent fuel without the separation of nuclear materials
5. **PWR-MOX** - Thermal recycling using MOX fuel in a PWR)

An equilibrium mass flow model by Li et al. [7] was used to obtain the Levelized Fuel Cycle Cost (LFCC). The code is based on Excel VBA including Python and FORTRAN code. The result includes [7]:

1. Uranium utilization
2. Repository size based on temperature and dose rate
3. High Level Waste (HLW) generation
4. Proliferation resistance
5. LFCC and total cost (construction cost + O&M + D&D)

3. Parameters of Social Cost

3.1 Definition of Parameters Related with Social Cost

First, we categorized the parameters of social cost based on two scenarios: normal operation and accident situation. The normal operation situation includes six categories: impacts on the environments, impacts on human beings, energy security, policy, 3S (Safety regulation, nuclear security, safeguards), and future generation costs. The accident scenario includes two categories: accident risk and national image.

❖ **Normal operation scenario**

A. Impacts on the environment from radiation emissions released by a nuclear power plant include: water pollution, earth disturbance, destruction of ecosystem, ground pollution, marine pollution, air pollution, soil change, injury of crops and forest, and climate change.

B. Impacts on human beings include impacts on human health such as general disease, occupational disease, general accident, and occupational accident. In addition, there are impacts from societal concerns including site conflict cost (conflict cost associated with siting nuclear-related facilities such as radioactive waste disposal sites and power transmission lines) and public acceptance (change in housing prices, positive and negative perception of nuclear facility, anti-nuclear movement, national tolerance index).

C. Energy security refers to the cost of achieving energy supply security.

D. Policy includes financial support for technology development, operation, and promotion of nuclear power generation.
E. 3S (Safety, Security, Safeguards) is comprised of additional costs resulting from reinforced safety regulations, nuclear security and safeguards.
F. Future generation refers to the opportunity cost resulting from the siting of a high-level radioactive waste disposal repository.

❖ **Accident scenario**

G. Accident risk includes the cost multiplied by risk of severe accident [10] and risk aversion cost [11].
H. National image includes import and export costs and impact on the tourist industry. For example, agricultural and marine products from Japan were denied by some countries after the Fukushima accident.

3.2 Assessment of each parameter

Each of the following major topics, an outline identifies the key items important to the previously identified items within the Normal scenario.

A. Impacts on the environment (A-IOE)

Scope of area:
- A limited region (- 30km)

A national region (30-300km)
Worldwide (over 300km)
- Figure 1. provides a general idea of how the regions can be defined in ROK.

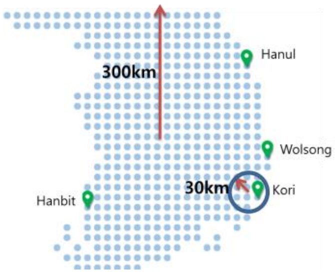

Figure 1. Scope of regions

Condition
- Territory of ROK
  (radius: 300km, area: 100,210km²)
- Emergency planning zone of a site
- (radius: 30km, area: 2826 ㎢) by KHNP

Scope of time:
- Short time: 1 yr
- Middle time: one life (100 yr)
- Long time: long term generation (1000 yr)

Method used: Impact Pathway Approach (IPA)

B. Impacts on human beings

➢ **Impacts on human health (B-HH)**
- Scope of area:
  - A limited region (within 30km),
  - A national region (30-300km),
  - Worldwide (over 300km)
- Scope of time:
  - Short time (1yr),
  - Middle time (100yr),
  - Long time (1000yr)
- Method used: Contingent Valuation Method (CVM)

➢ **Impacts of social problem**
- **Site conflict cost (B-SC)**

Conflict cost of the low and intermediate radioactive waste (LILW) disposal site (siting and development) was used as the surrogate variable for evaluating the cost of site conflicts (i.e. location of nuclear power plant). It is related to the amount of high-level waste followed metal mass unit flow [4-5].

Table 1. Conflict costs of a low and intermediate level radioactive waste disposal site

	COST
Unit cost of LILW disposal of ROK	65.52 (million Won/m^3)
Unit cost of LILW disposal of *other countries**	15.31 (million Won/m^3)
Difference between the unit costs	50.21 (million Won/m^3)
Accumulated amount of LILW	18,712 (m^3)
Total additional cost	939 (billion Won)

*U.S.A, France, UK, Sweden

- **Public acceptance (B-PA)**

Transmission line siting was also considered, and was calculated using data from KEPCO E&C [4]. The "Social Cohesion Index" will be used to calculate the cost of public acceptance as the surrogate variable.

C. Energy security (C-ES)

The cost of energy security is defined as the opportunity cost of insufficient energy supply. It means that this problem causes damage and incurs cost to the economic system of a country in terms of GDP loss [6].
- Equation: $G_i(t) = 549.075t$
- GDP (trillion KW) : 1464.2
- Disruption probability of Nuclear : 1.37E-03
- $CS_i = \pi i\{G_i(t)-R_i\}\cdot u[G_i(t)-R_i]$

where, $u[G_i(t)-R_i]=1$ for $G_i(t)-R_i > 0$,
$=0$ for $G_i(t)-R_i \leq 0$

Row 2 of Table 2 presents the R_i value calculated for each fuel cycle being investigated in this study.

Table 3. R_i value for each fuel cycle

	OT	FR-PYRO	OT-PYRO	OT-ER	PWR-MOX
Required U [tU]	20.444	12.342	20.448	20.448	17.921
R_i [trillion Won]	549.07	909.52	549.07	549.07	626.38

D. Policy (D-P)

It includes financial support for technology development, operation, and promotion of nuclear power generation (NPP) [4]. This paper will not specifically address this normal operation situation.

E. 3S (Safety, Security, Safeguard):

- **Safety regulation (E-SR)**

This parameter is related to the additional costs of meeting new regulatory requirements for ROK and is based on KHNP specific data [4]. It includes safety equipment reinforcement cost, the necessity for building new nuclear power plants, and new NPP design requirements.

- **Nuclear Security (E-NS)**

After 9.11, the risk of terrorism at nuclear facilities was much higher than before. This potential threat will be measured in terms of proliferation resistance [3]. The value is calculated using a fuzzy logic model based on the categorization of barriers.

- **Safeguards (E-SG)**

The safeguards aspect of the fuel cycle should be evaluated by comparing the cost differences between safeguards system. However, the evaluation methodology of safeguardability for fuel cycle will be developed in future studies.

F. Future generation (F-FG)

This is defined as a loss cost of future generation due to the siting of a high-level radioactive waste disposal facility. In terms of opportunity cost, future generations will lose the ability to use the property where the repository resides. As such, it can be calculated using the "Hedonic Price Function Model" from the area where the facility is proposed to be located, using their market price.

G. Accident risk:

- **Risk cost on severe accident (G-SA)**

There are three accident types related to nuclear power generation, such as, transportation accident, severe accident and critical accident. In this paper the cost of a severe accident will be calculated employing the "loss expectation" approach [4]. Each nuclear fuel cycle assumes that the operation time is calculated as 1TWh. [8] Applying the loss expectation method, the cost of loss and accident probability need to be calculated. There is a dataset addressing the cost of loss which will be used [9]. However, accident probability will be applied differently for each fuel cycle. In addition, there is no data addressing accident probability of SFR. But Tentner, et al. suggest it must be under 10^{-7} per year [10]. (See Table 3)

- Average severe accident cost in the world (2011, Fukushima accident): 4,993.6 billion yen or 73577.2 billion KW

Table 3. Accident probability and risk

Fuel cycle	Operation Time (h)	Accident probability (IAEA)	Accident risk cost (KW/kWh)
OT	PWR 1176	1.34E-06	9.88E-02
FR-Pyro	PWR 711 SFR 776	1.02E-06	7.49E-02
OT-Pyro	PWR 1176	1.34E-06	9.88E-02
OT-ER	PWR 1176	1.34E-06	9.88E-02
PWR-MOX	PWR 1176	1.34E-06	9.88E-02

- **Risk aversion cost (G-RA)**

This cost estimates the value of the statistical life for an NPP accident. CVM, which is a non-market valuation method that is widely used to estimate economic values for various types of ecosystems or environmental services, is used to elicit an individual's WTP for a specified mortality risk-reduction and to evaluate the VSL for an NPP accident by developing a plausible CV scenario for the NPP accident. There are models that use this development approach; the Willingness to pay estimation model (SBDC-CV with spike model), the Value of statistical life estimation model (life-cycle model). In addition to measuring the risk aversion to NPP accidents, there are also structural estimation methods for risk aversion is expected utility theory **[11]**.

C. National image (H-NI)

As mentioned earlier, this addresses a country's imports, exports and tourist industry. For example, the effect the Fukushima accident had on Japan's export of marine products. The National brand index will be used for this calculation [12, 13].

4. Social Cost Analysis

4.1 Quantifying the parameters

Some social cost factors have been assigned values in earlier research, while additional research is needed to quantify other factors. To assess the fuel cycle in a comprehensive way, it is important to include a variety of social cost parameters and evaluate them effectively. The values of the currently valuated parameters are listed in Table 4

Table 4. Result of parameter assessment

Parameter	OT	FR-Pyro	OT-Pyro	OT-ER	PWR-MOX	Unit
A-IOE	2.213	0.329	0.152	2.202	0.368	kgHM/GWh
B-HH	1	29.8	29.5	0.23	-	*
B-SC	2.079	0.309	0.143	2.068	0.346	Won/kWh
B-PA	Unknown					
C-ES	12	19	12	12	13	month
D-P	Unknown					

E-SR	Unknown					
E-NS	0.537 (H)	0.523 (H)	0.501 (H)	0.503 (H)	-	Proliferation resistance
E-SG	Unknown					
F-FG	Unknown					
G-SA	0.1	0.075	0.1	0.1	0.1	Won/kWh
G-RA	Difference is unknown (however, <0.5 Won/kWh)					
H-NI	Unknown					

* Ratio of total cumulative dose to humans per fully loaded HLW repository to the OT cycle case

The cost of implementing safety regulations and safeguards can be estimated relatively easily. However, these costs are mainly related to technical issue, which means the effect of social cost is limited. The value of ‘F-FG’ can be estimated using the cost, risk and operating time of a high-level waste repository. Then the most important factor is public acceptance and national images. These factors are usually estimated by surveys which require large budget and a sizable time commitment to complete.

4.2 Fuel cycle evaluation

The fuel cycle assessment can be performed by assigning a weight to each parameter and using multi-criteria decision-making (MCDM) methods. For example, Analytic Hierarchy Process (AHP) is one of the methods that can be successfully employed.

5. Conclusions

5.1 Comparison of the existing cost assessment

PWR-MOX and FR-Pyro are the best fuel cycle in parameter of environment impacts, but OT or OT-ER is proper than FR-Pyro in human beings. Using the OT fuel cycle is better than FR-Pyro to reduce the conflict cost. When energy supply is deficient, FR-Pyro fuel cycle stands longer than other fuel cycles. Proliferation resistance is shown as ‘high’ in all fuel cycles, so there are no difference between fuel cycles.

When the severe accident occurs, FR-Pyro cycle is economical than other OT based fuel cycles.

5.2 Future work

Additional costs associated with policy and safety regulations, which are currently included in O&M costs, need to be further investigated. In addition, the true cost of safeguards parameter must be understood in greater detail. Furthermore, cost parameter that currently lack values, such as X and Y must be evaluated and assigned values.

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