# External Cost Assessment of Nuclear Power Plant Accident considering Public Risk Aversion Behavior: the Korean Case

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## 1. Introduction

Since the Fukushima Daiichi nuclear power plant (NPP) accident, the internalization of the external cost of an NPP accident that arises from its external effects within the social cost of nuclear energy has obtained substantial attention [1]. One of the important external cost factors to be included in the internalization process is the public health effect from a NPP accident resulting in radioactive material release. The conventional approach for monetary valuation of NPP accident consequence consists of calculating the expected value of various accident scenarios [2]. However, the main criticism of the conventional approach is that there is a discrepancy between the social acceptability of the risk and the estimated expected value of NPP accident [3].

Therefore, an integrated framework for the estimation of the external cost associated with an NPP accident considering the public risk aversion behavior was proposed in this study based on the constructed theoretical framework for estimating both the value of statistical life (VSL) and the risk aversion coefficient associated with an NPP accident to take account of the accident cost into the unit electricity generation cost of NPP. To estimate both parameters, an individual-level survey was conducted on a sample of 1,364 participants in Korea. Based on the collected survey responses, both parameters were estimated based on the proposed framework and the external cost of NPP accident was estimated based on the consequence analysis and considering the direct cost factors for NPP accident.

## 2. Methods

To estimate the external cost of a NPP accident, an integrated framework is proposed in this study, which includes the following analysis: (1) assessment of the VSL, which is derived from the WTP for a decrease in mortality risks for hypothetical NPP accidents based on contingent valuation (CV) survey result, (2) estimation of the relative risk aversion (RRA) coefficient, as a measure of public risk aversion to NPP accident, based on the expected utility theory (EUT) by employing multiple price list (MPL) survey design, (3) derivation of the multiplication factor for estimating the external cost of an NPP accident considering various direct cost factors associated with the NPP accident consequences, and (4) internalization of the external cost related to NPP accident by reflecting the estimated external cost within the electricity cost of a NPP.

### *2.1 Estimation of the VSL for an NPP Accident*

In this study, a contingent valuation method (CVM) 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. In this section, the theoretical framework for estimating the respondents' WTPs based on an SBDC-spike model and deriving the VSL for an NPP accident based on the WTP for a given mortality risk reduction is described. The CV questions based on SBDC-spike model ask the respondents to accept or reject a suggested bid and ask the follow-up question for the zero payment for a given change in a certain risk situation. Each respondent is presented with one bid, and there are three possible outcomes, namely, "yes", "no-yes" and "no-no" responses such that:

$$\begin{cases} I_i^Y = \mathbf{1}\ (ith\ respondent's\ response\ is\ \text{"Yes"}) \\ I_i^{NY} = \mathbf{1}\ (ith\ respondent's\ response\ is\ \text{"No}-\text{Yes"}) \\ I_i^{NN} = \mathbf{1}\ (ith\ respondent's\ response\ is\ \text{"No}-\text{No"}) \end{cases} \tag{1}$$

where, $I_i^Y$, $I_i^{NY}$, and $I_i^{NN}$ are binary-valued indicator functions for the possible response paths for the main and follow-up questions. By formulating the CDF of a respondent's WTP as a logit model based on the utility difference model [4], the log-likelihood function for the SBDC-spike model can be derive as:

$$\ln L = \sum_{i=1}^{N} \{ I_i^Y \ln[1 - G_C(A_i)] + I_i^{NY} \ln[G_C(A_i) - G_C(0)] + I_i^{NN} \ln[G_C(0)] \} \tag{2}$$

where the CDF of a respondent's WTP and the mean WTP in the spike model can be defined as follows:

$$G_C(A) = \begin{cases} [1 + exp(a - bA)]^{-1} & if\ A > 0 \\ [1 + exp(a)]^{-1} & if\ A = 0 \\ 0 & if\ A < 0 \end{cases} \tag{3}$$

$$WTP_{mean} = ln[1 + exp(a)]/b \tag{4}$$

To estimate mean WTP with the constructed SBDC-spike model, the maximum likelihood estimation (MLE) procedure was used to estimate the parameters *a* and *b* using the log-likelihood function for the collected samples from the CV survey.

The relationship between a WTP and the VSL can be obtained from a life-cycle consumption model [5]. Based the model, a mean WTP for a small mortality risk reduction, $\Delta D$, elicited based on CVM approach is used to calculate the VSL as follows:

$$VSL = WTP/\Delta D \quad (5)$$

*2.2 Measuring the Risk Aversion for NPP accidents*

When evaluating risk situations for NPP accident, it was assumed that individuals replace the monetary values of their final wealth by the corresponding utility based on the expected utility criterion. The theoretical framework based on the EUT to estimate the relative risk aversion coefficient as a measure of risk attitude toward an NPP accident is described in this section.

Within the expected utility theory [6], the most frequently used class of utility functions for modeling risk-averse individuals is the constant relative risk aversion (CRRA) utility function defined as follows:

$$\mathrm{U(W)} = \frac{W^{1-\sigma}}{1-\sigma}, \text{ for } \sigma \neq 1 \quad (6)$$

where, σ is defined as the RRA coefficient. To estimate the RRA parameter, a cumulative normal distribution function was used to specify the probability of choosing the risk-safe option as the difference between the associated expected utility, $EU_A$, and the expected utility, $EU_B$, for risky alternatives following previous study as follows:

$$P(EU_j^A - EU_j^B > 0) = \Phi(\nabla EU_j) \quad (7)$$

Therefore, the conditional log-likelihood of the risk aversion responses, conditional on the EUT and CRRA specifications being true, can be defined as follows:

$$lnL(\sigma; y, S) = \sum_{i=1}^{N}\sum_{j=1}^{10}\left(\left(ln\left(\Phi(\nabla EU_j)\right)\middle|y_i^j = 1\right) + \left(ln\left(1-\Phi(\nabla EU_j)\right)\middle|\, y_i^j = -1\right)\right) \quad (8)$$

where $y_i^j$ = 1 (or –1) denotes the *i*-th individual's selection of option A (or B) for the *j*-th risk choice question. Based on the defined likelihood function, the MLE procedure was used to estimate the RRA coefficient.

## 3. Survey Design and Implementation

In this study, an individual-level survey was conducted to estimate the value of life and to derive relative risk aversion coefficient in case of NPP accident. The survey questionnaires consisted of four major components: 1) questions about the respondent's perception or attitude on the NPP operating in Korea; 2) hypothetical risk-choice questions based on MPL design that include both risk-safe and risky choices for each question to measure the degree of risk aversion of the respondents; 3) CV questions that elicit the respondents' WTP to reduce certain degree of mortality risk which results from an NPP accident; and 4) questions about the respondent's socio-economic status to investigate the heterogeneity in both estimated WTP and the degree of RRA and validate the estimate result.

## 4. Result

*4.1 Description of the Collected Survey Sample*

Table I provides statistical data for the sample of 1,364 respondents as well as for each demographic sub-sample. On average, the age of the respondents (40.32 years old) was similar to the national average value (40.30 years old). The average income of the respondents (4.51 million KRW) was similar to the national average (4.26 million KRW). In terms of the attitude towards NPPs operating in Korea, the percentage of the sample who agrees on the necessity of NPP operating in Korea (78.96%) was similar to the national average estimate (78.3%) [7]. Overall, the sample collected in the main survey was treated as a representative sample of the Korean population.

Table I: Statistics of Survey Respondents

| Demographics | | Observation |
|---|---|---|
| Gender | Male | 716 |
| | Female | 648 |
| Age Groups | 20-29 years old | 339 |
| | 30-39 years old | 315 |
| | 40-49 years old | 307 |
| | 50-59 years old | 285 |
| | 60-69 years old | 118 |
| Monthly household income | < 2 million | 203 |
| | 2 million – 4 million | 496 |
| | 2 million – 4 million | 381 |
| | 2 million – 4 million | 149 |
| | > 8 million | 135 |
| Average number of persons in household | | 3.18 |
| Percentage being supportive to the necessity of NPP | | 78.96 (%) |
| Total number of respondents | | 1,364 |

*4.2 Estimated Value of Statistical Life for NPP accident*

Table II presents the distribution of responses which indicates the number of respondents who stated that they would be willing to pay an additional income tax for reducing the mortality risk following an NPP accident for each initial bid amount. In this study, all zero responses are treated as true zero bids to conservatively estimate the VSL for an NPP accident.

Table II: Number of Responses by Bid Amount

| First Bid (KRW) | Sample Size | Number of Responses | | | | |
|---|---|---|---|---|---|---|
| | | YY | YN | NY | NNY | NNN |
| 5,000 | 267 | 69 | 61 | 5 | 58 | 74 |
| 10,000 | 291 | 67 | 66 | 19 | 94 | 45 |
| 20,000 | 265 | 43 | 71 | 14 | 72 | 65 |
| 40,000 | 269 | 24 | 46 | 25 | 114 | 60 |
| 80,000 | 272 | 11 | 34 | 15 | 155 | 57 |
| Total | 1364 | 214 | 278 | 78 | 453 | 301 |

Based on the respondents' elicitation, the spike model in Equation (4) was used to estimate the mean WTP. Table III describes the estimation results using the MLE method. All the parameters in the spike model were significant at the 1% level. Note that the coefficient for the bid amount was negative which supports the fact that the higher bid makes a "yes" response less likely.

Table III: Estimated WTP based on SBDC-spike model

| Variables | Coefficient |
|---|---|
| Constant (*a*) | 0.6593 (13.43) |
| Bid amount (*b*) | -0.0426 (-1027.78) |
| Log-likelihood | -2936.36 |
| Mean WTP[a] | KRW 25283.23 (33.24) |
| 95% confidence level of WTP | KRW 23792.29 – 26774.17 |

Notes: [a]The unit of the coefficient estimate of a bid amount is KRW 1000. [b]The numbers in parentheses below the coefficient estimates are t-values, and * indicate significance at the 1% level.

Based on the estimated mean WTP, the VSL was calculated as the estimated sample mean of yearly WTP divided by the mortality reduction rate described in the survey questionnaires, as shown in Table IV, using Equation (5). This method can be applied since a small mortality risk reduction rate was used in the survey; namely, respondents were asked to provide a monthly WTP for a yearly mortality reduction amount of 1E-04.

Table IV: Estimated VSL for a NPP accident

| Mean Yearly WTP | Yearly Mortality Risk Reduction | Mean VSL |
|---|---|---|
| KRW 303398.76 | 1E-04 | KRW 3.03 billion (USD 2.78 Million) |

### *4.3 Estimation Results for Risk Aversion Parameter*

Table V shows the distribution of switched rows for a consistent sample of 1,086 cases among total sample. Among the consistent sample, approximately 28% of the subjects always selected the risky choice, i.e., the subjects are willing to take the risk rather than pay a certain amount of money to avoid the risk. Furthermore, approximately 37% of the subjects always selected the risk-safe choice, indicating a more risk-averse behavior.

Table V: Distribution of Choices for the Consistent Sample

| Number of times the subject chooses a risk-safe option | Decision row in which the subject switches to a risky choice | Observations |
|---|---|---|
| 0 | Always the risky choice | 299 |
| 1 | 2 | 53 |
| 2 | 3 | 41 |
| 3 | 4 | 96 |
| 4 | 5 | 31 |
| 5 | 6 | 27 |
| 6 | 7 | 74 |
| 7 | 8 | 29 |
| 8 | 9 | 34 |
| 9 | Always the risk-safe choice | 402 |
| Total | | 1,086 |

In this study, only the consistent sample was used to estimate the RRA parameter, σ, without covariates following EUT specification, based on the survey results using Equation (6-8). In result, the RRA was estimated as 1.315 using MLE method for the collected sample response for risk choices.

### *4.4 Integration of risk aversion within the external cost calculation of an NPP accident*

Although the equivalent fatality from group accidents such as NPP accidents is not common and its risk is small compared to other accidents, individuals perceive group accidents differently from other accidents. This implies that there should be a multiplication factor when estimating the external cost for group accidents to reflect the risk aversion behavior of the public [8]. Therefore, the external cost can be estimated as the multiplication of the expected value of a NPP accident consequence, *EV*, and the multiplication factor, *M*, divided by the mean annual electricity production:

$$External\ cost\ of\ NPP\ accident\ (\$/kWh) = \frac{M * EV\ (\$)}{Mean\ annual\ electricity\ production\ (kWh)} \quad (9)$$

$$EV = \sum_{j=1}^{m}\left(N_j W_0\left(\sum_{i=1}^{n} p_{i,j} X_{i,j}\right)\right) \quad (10)$$

where $n$ is denoted as the number of states of the consequence, $m$ is the number of groups of the affected population, and the number of individuals in the $j$-th group is denoted as $N_j$. Here, the percentage for loss of wealth and the probability for the defined risk situation of an individual are defined as $X_{i,j}$ and $p_{i,j}$, respectively.

Based on Equations (9-10), the estimation of the external cost for NPP accidents requires considering the following factors: 1) the number of individuals affected by an NPP accident, 2) the states of risk situations for an individual, and 3) the various cost factors associated with the consequences of an NPP accident.

In this study, the number of individuals affected by a NPP accident was analyzed according to the definition of the emergency planning zone around the NPP, based on the result of previous study [9]. In addition, the risk situations for an individual as a consequence of an NPP accident were categorized based on the health effect status. In terms of the economic effects associated with the consequences of an NPP accident, the direct cost factors are only considered because of the limitation whereby indirect cost factors are difficult to quantify a priori. Regarding the direct cost factors associated with the consequences of an NPP accident, the cost estimates per affected individual are assumed based on reasonable assumptions. Table VI shows a summary of both the percentage of loss of wealth and the corresponding probability for each population sub-group, which were calculated based on the consequence analysis and the assumptions for direct cost factors.

Table VI: Description of Risk Status for Population Groups

| Sub-group | Risk situation | Percentage for loss of wealth ($X_{i,j}$) | Probability ($p_{i,j}$) |
|---|---|---|---|
| PAZ | Fatal health effect | 98.90 | 0 |
| | Non-fatal health effect | 2.03 | 0 |
| | No health effect | 1.79 | 1.43E-06 |
| | No accident | 0 | 9.99E-01 |
| UPZ, relocated | Fatal health effect | 98.90 | 1.08E-08 |
| | Non-fatal health effect | 2.03 | 2.33E-08 |
| | No health effect | 1.79 | 1.40E-06 |
| | No accident | 0 | 9.99E-01 |
| UPZ, not relocated | Fatal health effect | 97.17 | 3.09E-09 |
| | Non-fatal health effect | 0.30 | 7.13E-09 |
| | No health effect | 0.06 | 1.42E-06 |
| | No accident | 0 | 9.99E-01 |
| LPZ | Fatal health effect | 97.11 | 8.02E-10 |
| | Non-fatal health effect | 0.24 | 1.94E-10 |
| | No health effect | 0 | 1.43E-06 |
| | No accident | 0 | 9.99E-01 |

To evaluate the multiplication factor, a general risk situation characterized by various states of consequences was considered following Eeckhoudt et al. [10]. Note that the multiplication factor to be applied to the external cost of an NPP accident is obtained by considering the coefficients of risk aversion and risk neutrality, $M_{RA,j}$ and $M_{RN,j}$, which indicate the maximum percentages of the wealth of a risk-averse and risk-neutral individual in each population group, as follows:

$$M = \sum_{j=1}^{m} \frac{N_j M_{RA,j}}{N_j M_{RN,j}} = \sum_{j=1}^{m} \frac{N_j\{1 - [\sum_{i=1}^{n} p_{i,j}(1 - X_{i,j})^{1-\sigma}]^{\frac{1}{1-\sigma}}\}}{N_j[1 - \sum_{i=1}^{n} p_{i,j}(1 - X_{i,j})]} \quad (11)$$

Based on Table VI, a multiplication factor of 5.16 was obtained by substituting the values into Equation (11) and using the RRA estimates derived from the survey result. In result, the external cost of an NPP accident was obtained based on Equation (9-10), considering the mean annual electricity production of 5759.36 GWh by Korean NPPs in 2013 [11], which gives an external cost for an NPP accident of 4.39E-03 USD-cents/kWh.

## 5. Conclusion

Internalization of external costs into the comprehensive energy production cost has been considered as a potentially efficient policy instrument for a more sustainable energy supply and use. However, the internalization of externalities, such as public health damage, have raised a number of generic policy issues in a nuclear energy sector, with specific challenges resulting from the distinct characteristics of external cost estimation. Especially, the major challenge remained to address the public safety concerns regarding a nuclear accident, which can be specified as low-probability high-consequence accident, driven by the aspects of public risk aversion [12].

Therefore, an integrated framework for the estimation of the external cost associated with an NPP accident that considers the public risk aversion behavior was developed in this study by constructing a theoretical framework for estimating both the VSL and the risk aversion coefficient associated with an NPP accident to take account of the accident cost into the unit electricity generation cost of NPP. In terms of filling the gap between social acceptability of the risk and the external cost estimation, this study is expected to help energy policy decision-makers to internalize the external cost regarding NPP accident considering public risk aversion behavior and analyze the economic validity of NPP compared to other energy sources.

## ACKNOWLEDGEMENT

This work was supported by the ‘Valuation and Socioeconomic Validity Analysis of Nuclear Power Plants In Low Carbon Energy Development Era’ of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted by the Ministry of Trade, Industry & Energy of the Republic of Korea. 20131520000040.

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