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Integrated framework for the external cost assessment of nuclear power plant accident considering risk aversion: The Korean case

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HIGHLIGHTS

- External cost assessment framework for NPP is proposed considering risk aversion.
- VSL was derived from WTP for mortality risk reduction from hypothetical NPP accident.
- RRA was derived to integrate public risk aversion into external cost of NPP accident.
- Individual-level survey was conducted to derive WTP and RRA for NPP accident risk.
- The external cost was estimated considering the direct cost factors of NPP accident.

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ABSTRACT

Recently, the estimation of accident costs within the social costs of nuclear power plants (NPPs) has garnered substantial interest. In particular, the risk aversion behavior of the public toward an NPP accident is considered an important factor when integrating risk aversion into NPP accident cost. In this study, an integrated framework for the external cost assessment of NPP accident that measures the value of statistical life (VSL) and the relative risk aversion (RRA) coefficient for NPP accident based on an individual-level survey is proposed. To derive the willingness to pay and the RRA coefficient for NPP accident risks, a survey was conducted on a sample of 1550 individuals in Korea. The estimation obtained a mean VSL of USD 2.78 million and an RRA coefficient of 1.315. Based on the estimation results in which various cost factors were considered, a multiplication factor of 5.16 and an external cost of NPP accidents of 4.39E−03 USD-cents/kW h were estimated. This study is expected to provide insight to energy policy decision-makers on analyzing the economic validity of NPP compared to other energy sources by reflecting the estimated external cost of NPP accident into the unit electricity generation cost of NPP.

1. Introduction

1.1. Research background

Since the Fukushima Daiichi nuclear power plant (NPP) accident, the estimation of the external cost of an NPP accident within the social cost of nuclear energy has obtained substantial attention. A related issue that arises from environmental damages and its external effects is the internalization of such externalities (Bickel et al., 2005). Electricity generation, especially nuclear energy generation, like other industries is not free from health and environmental impacts. Several of these impacts, where their costs are imposed on society and environment, have traditionally not been accounted for in the market price, in particular the price of electricity.

One of the important external cost to be included in the internalization process is the public health effect from a NPP accident resulting in radioactive material release (OECD/NEA, 2003). The calculations of the economic consequences of a NPP accident requires a series of analysis, including the accident consequence analysis based on a NPP accident scenario and associated probabilities. The conventional approach consists of calculating the expected value of various accident scenarios, calculated as the sum of the accident scenario probabilities multiplied by their

Abbreviations: CDF, Cumulative Distribution Function; CRRA, Constant Relative Risk Aversion; CV, Contingent Valuation; CVM, Contingent Valuation Method; DB, Double-Bounded; DBDC, Double-Bounded Dichotomous Choice; DC-CV, Dichotomous Choice-Contingent Valuation; EUT, Expected Utility Theory; LPZ, Long-Term Planning Zone; MACCS2, MELCOR Accident Consequence Code System 2; MLE, Maximum Likelihood Estimation; MPL, Multiple Price List; PAZ, Precautionary Action Zone; NPP, Nuclear Power Plant; RRA, Relative Risk Aversion; SBDC, Single-bounded Dichotomous Choice; UPZ, Urgent Protective Action Planning Zone; VSL, Value of Statistical Life; WTP, Willingness to Pay

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associated monetary consequences (Markandya et al., 1998; European Commission, 2005; Kim and Kang, 2008; Jang et al., 2011).

However, the main criticism of this approach is that there is a discrepancy between the social acceptability of the risk and the estimated expected value of NPP accident (Nuclear Energy Agency, 2002). Beyond the quantification of the physical impacts on mankind and the environment, some issues regarding the integration of economic indicators such as the monetary value of statistical life (VSL), or risk aversion premium with the expected value of NPP accident consequence have been suggested to be reflected in the estimation of the external costs of the nuclear fuel cycle. Therefore, various valuation methods for the external cost assessment of a NPP accident, including the use of rule of thumbs model and the estimation of risk aversion coefficient based on the risk averse behavior of investors, have been proposed. However, more analytical work on external cost estimation, including monetary valuation of life and the consideration for the public risk perception are needed to support a comprehensive internalization of externalities in the decision making-process for the economic agents or policy makers (European Commission, 2005; Laes et al., 2011).

Therefore, an integrated framework for the external cost estimation of a NPP accident to estimate the value of life for the equivalent fatality following a NPP accident by investigating the willingness to pay (WTP) for a given mortality reduction rate for a hypothetical NPP accident and to quantify risk aversion coefficient based on the structural estimation method is proposed in this study. The main objective of this study are the following: (1) to assess the VSL, is derived from the WTP for a decrease in mortality risks in hypothetical NPP accidents based on the contingent valuation (CV) survey result, (2) to analytically estimate 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) to derive multiplication factor for estimating the external cost of an NPP accident considering various direct cost factors associated with the NPP accident consequences, and (4) to support decision making processes towards the internalization of the external cost related to NPP accident by reflecting the estimated external cost within the electricity cost of a NPP.

1.2. Literature review

1.2.1. External cost assessment of NPP accident

The externalities of energy refer to the social effects, such as health and environmental impacts, arising from the process of producing the energy, but that are not reflected in the market price of the energy. Especially for the nuclear-generated electricity, the evaluation of the consequences of a NPP accident plays an important role in the reliability and credibility of the overall external costs of nuclear-generated electricity (Nuclear Energy Agency, 2002).

The conventional methodology used to evaluate the impacts of accidental releases is based on analyzing the expected damages caused by NPP accident (Markandya et al., 1998; European Commission, 2005). The estimate is calculated as the summation of the probability of the occurrence of possible accident scenarios multiplied by the corresponding consequences resulting from the accident. In the nuclear energy sector, probabilistic safety assessment (PSA) has served a basis to evaluate the potential causes of the accident, the possible probabilities of occurrence, and the corresponding expected environmental releases. A number of PSA studies have been carried out for different types of reactors in various countries to estimate the external cost of NPP accident based on the expected-value approach. Especially, previous studies in external cost assessment of NPP accident included top-down approach where the cost was estimated based on the historical experience of NPP accident, such as Chernobyl reactor accident (Laes et al., 2011; Hohmeyer, 1988; Ottinger et al., 1990; Rabl and Rabl, 2013), bottom-up approach where the weight of NPP accident risk and consequence calculation was given based on the simplified PSA analysis (Masuhr and Oczipka, 1994; Burgherr and Hirschberg, 2008) or the plant-specific PSA analysis (Hirschberg and Cazzoli, 1994; Wheeler and Hewison, 1994).

An economic analysis of severe accidents in energy sectors often involves assigning monetary values to human lives, which is of particular concern in the case of the nuclear energy because humans may be significantly affected by exposure to radioactive fission products may be released into the environment and may pose a radiation hazard to the local population (Lewis et al., 1979). However, although the risk of fatality resulting from a NPP accident can be identified in physical terms, it is difficult to directly convert the risk of fatality into the health effect cost of the accident because there are no direct market prices for the value of life regarding the equivalent fatality resulting from an accident (Weil, 2001). While there are a number of studies on estimating VSL, the value of the estimated VSL differs on the country, the level of wealth, risk categories, and others (Biausque, 2010; Viscusi and Aldy., 2003). Therefore, a proper method which can estimate the VSL regarding a NPP accident considering the risk characteristics or the risk perception of a specific group of population is needed.

The economic assessment based on expected-value approach as presented above have been challenged by civil society in their inability to reflect risk perception (Markandya, 1994; O'Riordan and Cameron, 1994). It has been recognized that there is a discrepancy between the social acceptability of the risk and the average monetary value which corresponds in principle to the compensation of the consequences, or the cost of expected health impacts, for each individual of the population affected by the accident (Nuclear Energy Agency, 2002). In particular, the expected-value approach has been criticized for ignoring risk aversion and the perceived probability of an accident (Pearce, 2000). Therefore, recent studies have tried to integrate the public risk perception toward NPP accident in the external cost; thus, several methods have been proposed for this purpose.

1.2.2. Public risk aversion towards NPP accident

It has been widely known that the perceived risks are much greater than the expert estimates in the nuclear context (Roth et al., 1990). This phenomena suggests that people do not value risks of group accidents, in which tens or hundreds of deaths occur because of a single accident, in the same way as they value individual deaths although the equivalent fatality from the group accidents are not common and its risk is small compared to other accidents. Especially in the case of NPP accident, previous study found the insignificant relationship between the probability of a disaster and the choice of individuals; that is, the individuals process their perceived risk on the basis of conditional losses from an NPP accident, rather than the probability of an accident (Itaoka et al., 2006). However, it is less obvious how the public risk aversion toward NPP accident can be quantitatively accounted for and reflected into the external cost assessment.

Therefore, there have been various studies which explored the relationship between the risk aversion and the expected value of a NPP accident consequence and proposed a method to take account of risk aversion in the external cost estimation. Early studies have suggested the rules of thumb models for valuing group deaths by considering the probability of an accident and the number of persons affected and derived an implied risk premium based on the proposed rules of thumb model (Ferguson, 1992; Rocard and Smets, 1992; Ascari and Bernasconi, 1997). However, the estimated risk premium for different rules of thumb models differs several orders of magnitude; therefore, it has been suggested that there is little empirical basis or theory for such rules of thumb models (Biausque, 2010).

Recent studies have therefore tried to incorporate risk perception by the addition of a risk aversion coefficient based on expected utility approach (Krupnick et al., 1993; Eeckhoudt et al., 2000). In the expected-utility approach, a risk aversion coefficient takes into account of the fact that the disutility of a potential loss of wealth experienced by an individual is higher than the expected value of the loss calculated based on the expected-value approach; hence, the external cost of the risk will be higher. A representative method using expected-utility approach in evaluating the external cost of a NPP accident was proposed where the RRA coefficient was chosen based on the analysis of financial risks in stock markets and the reference French scenario of a hypothetical NPP accident (Eeckhoudt et al., 2000). However, the use of the financial risk aversion coefficient for NPP accidents was considered inappropriate because financial risks and NPP accident risks have different nature (Lee and Lee, 2006). That is, the risk situation faced by an individual for the case of a NPP accident can be described as a “low-probability with a high-consequence” situation compared to the case of a general risk situation in economic markets, in which the potential gains or losses for an individual are smaller. Therefore, the risk aversion coefficient which can incorporate the public risk aversion toward a NPP accident within the external cost assessment must be assessed considering the distinct risk characteristics of NPP accident.

2. Methods

2.1. Estimation of the value of statistical life for an NPP accident

In this study, the value of life for the equivalent fatality due to an NPP accident is measured by estimating an individual's WTP for a given mortality risk reduction in the case of a hypothetical NPP accident. There are two approaches to empirically estimating an individual's WTP for mortality risk reduction: the revealed preference approach, which is based on a compensating wage or consumer behavior data, and the stated preference approach such as the contingent valuation method (CVM) (Krupnick et al., 2002). The advantage of the CVM over the revealed preference approach is that it can be flexibly designed by assuming a hypothetical market situation when no similar markets exist. This feature of the CVM approach is especially important when estimating the economic cost of an NPP accident because the actual risk of NPP accidents is very small; thus, there is no direct market price for the value of life for an equivalent fatality due to a severe NPP accident. Additionally, CVM studies have the advantage of increased flexibility when studying a population and a specific type of risk because they use surveys to ask individuals to directly state their WTPs for a reduction in the risk of their premature fatality in the case of a hypothetical incident (Alberini and Chiabai, 2007).

In this study, a 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. In this section, the theoretical framework for estimating the respondents’ WTPs based on an SBDC-spike model and for deriving the VSL for an NPP accident based on the WTP for a given mortality risk reduction is described.

2.1.1. Willingness to pay estimation model: SBDC-CV with spike model

In this study, the single-bounded dichotomous choice (SBDC) model is combined with a spike model is used to estimate the WTP of the respondents for a certain value of mortality risk reduction in the case of an NPP accident. Here, the utility difference model applied by Hanemann for dichotomous choice-contingent valuation (DC-CV) provides an approach for developing a theoretical foundation for deriving the Hicksian compensating and equivalent surplus measures from DC-CV data (Hanemann, 1984; Hanemann, 1987).

The SBDC-CV questions ask the respondents to accept or reject a suggested bid for a given change in the risk situation. Each respondent is presented with one bid, and there are two possible outcomes, namely, “yes” and “no” responses such that

$$\begin{cases} I_i^Y = 1\,(i\ th\ respondent\text{'}s\ response\ is\ \text{“}Yes\text{”}) \\ I_i^N = 1\,(i\ th\ respondent\text{'}s\ response\ is\ \text{“}No\text{”}) \end{cases}, \tag{1}$$

where I_i^Y and I_i^N are binary-valued indicator functions for the possible response paths of “yes” and “no”, respectively, and whose values are one if the argument is true and zero otherwise. Given the assumption of utility-maximizing respondents in a sample size of N respondents, the log-likelihood function of the WTP of a respondent, which can be treated as a random variable having a cumulative distribution function (CDF) $G_C(A_i)$, can be derived as

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

where A_i is the suggested bid for a given change in the risk situation. Following the general practice of former studies, $1 - G_C(A_i)$ is formulated as a logistic CDF, which yields the mean WTP as follows:

$$G_C(A) = \frac{1}{1 + e^{a - bA}} \tag{3}$$

$$WTP_{mean} = \int_0^{\infty} \left[1 - G_C(A)\right] dA - \int_{-\infty}^{0} G_C(A)\, dA = \frac{a}{b} \tag{4}$$

where a and b are parameters that determine the location and scale of the logistic CDF.

Considering the situation of paying additional money to reduce the mortality risk due to an NPP accident, a zero WTP may be expressed by those who do not consider the public interest that arises from the decrease in the mortality risk related to an NPP accident. In other words, not every public effect is a net benefit to every affected person; however, the variety of reasons for zero or negative valuations is anticipated in CV studies (Yoo et al., 2001). To address the zero WTP response, the spike model suggested by Kristrom is used to allow a spike at zero. This spike is the truncation at zero of the negative part of the WTP distribution, which considers the fact that some respondents would not be willing to incur such a cost (Kriström, 1997).

To adopt the spike model, additional survey questionnaires were designed for the respondents who responded “no” to the initial question with a follow-up question: Is the respondent willing to pay anything at all for the improvement of a risk situation. When designing the follow-up question, the binary-valued indicator variables of each respondent, i.e., I_i^N in Eq. (1), can be divided into I_i^{NY} and I_i^{NN} such that

$$\begin{cases} I_i^{NY} = 1\,(i\ th\ respondent\text{'}s\ response\ is\ \text{“}No-Yes\text{”}) \\ I_i^{NN} = 1\,(i\ th\ respondent\text{'}s\ response\ is\ \text{“}No-No\text{”}) \end{cases} \tag{5}$$

By formulating the CDF of a respondent's WTP as a logit model, the log-likelihood function for the SBDC-spike model is given by

$$\ln L = \sum_{i=1}^{N}\left\{ I_i^{Y}\ln\left[1-G_C(A_i)\right] + I_i^{NY}\ln\left[G_C(A_i)-G_C(0)\right] + I_i^{NN}\ln\left[G_C(0)\right]\right\}, \tag{6}$$

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

$$G_C(A)=\begin{cases}[1+exp(a-bA)]^{-1} & ifA>0\\ [1+exp(a)]^{-1} & ifA=0,\\ 0 & ifA<0\end{cases} \tag{7}$$

$$WTP_{mean}=ln[1+exp(a)]/b, \tag{8}$$

To estimate the 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 defined likelihood function for each observation. Then, the mean WTP for the mortality risk reduction in the case of an NPP accident was derived using Eq. (8).

2.1.2. Value of statistical life estimation model: life-cycle model

The relationship between a WTP for mortality risk reduction and the VSL can be obtained from a life-cycle consumption model (Shepard and Zeckhauser, 1982; Cropper and Sussman, 1990). In such a model, a person of age j receives an expected utility of V_j over the remainder of his lifetime, which is a maximized objective function that is subject to a person's initial wealth and their borrowing and lending opportunities. Based on the life-cycle model, the maximal quantity of initial wealth, W_j, that an individual would surrender to decrease D_j, which is the probability of an individual dying within a given period, can be determined. The rate of substitution between D_j and W_j while the expected utility, V_j, remains constant corresponds to the VSL of a person of age j, i.e., VSL_j, which is the marginal value of a risk change. This is defined as

$$VSL_j=(dV_j/dD_j)/(dV_j/dW_j) = dW_j/dD_j \tag{9}$$

where dW_j corresponds to the individual's WTP for the mortality risk reduction in dD_j. Using the CVM approach, a mean WTP for a small risk reduction in ΔD_j can be elicited. If the proposed risk reduction is small, the VSL_j can be calculated as the estimated sample mean of the WTP divided by the mortality reduction rate described in the survey questionnaires:

$$VSL_j=WTP_j/\Delta D_j \tag{10}$$

2.2. Measuring the risk aversion for NPP accidents

Based on the expected value approach, the external cost of an NPP accident can be derived as the expected monetary values required for compensating individuals affected by the accident and is simply calculated as the product of the monetary consequences of the accident and the corresponding probabilities. However, the external cost estimation based on the expected value approach might lead to an underestimation of the social cost because it does not consider the risk perception of individuals (OECD/NEA. Comparing Nuclear Accident Risks With Those From Other Energy Sources, 2010).

Therefore, when evaluating risk situations such as NPP accidents, it is assumed that individuals replace the monetary values of their final wealth by the corresponding utility based on the expected utility criterion (Myerson, 2005). Because an individual's utility function characterizes his attitude toward risk, the theoretical framework based on the EUT to estimate the RRA coefficient as a measure of risk attitude toward an NPP accident is described in this section.

2.2.1. Structural estimation method for risk aversion: expected utility theory

Within the EUT, the utility function for an individual with a risk-averse attitude is described by a concave function (Holt and Laury, 2002). The most frequently used class of utility functions for modeling risk-averse individuals is the constant relative risk aversion (CRRA) utility function, or the power utility function, which has the functional form

$$U(W)=\frac{W^{1-\sigma}}{1-\sigma},\quad \text{for } \sigma\neq 1, \tag{11}$$

where σ is a RRA coefficient (Hansen and Singleton, 1983). In this specification, the risk aversion is determined by the curvature of the utility function, with $\sigma=0$ denoting risk neutrality, $\sigma>0$ indicating risk aversion, and $\sigma<0$ denoting risk loving.

Following previous studies, it is assumed that the risk-safe choices over risky alternatives follow the EUT and that the utility function of a risk-averse individual follows the functional form of the CRRA utility function (Andersen et al., 2008; Harrison and Rutström, 2008). Based on the CRRA utility function, the expected utility can be expressed by the probability-weighted utility of each outcome for each option in lottery questions. Assuming K possible outcomes of each decision, the expected utility for the jth decision choice question, EU_j, is

$$EU_j=\sum_{k=1}^{K}[p_k U_k], \tag{12}$$

where p_k is the probability associated with the utility outcome of U_k. To describe the likelihood function for the choices that the respondents made and to jointly estimate the RRA coefficient σ, a cumulative normal distribution function is 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 as follows (Andersen et al., 2010):

$$P(EU_j^A-EU_j^B>0) = \Phi(\nabla EU_j), \tag{13}$$

$$\nabla EU_j=EU_j^A-EU_j^B \tag{14}$$

Therefore, the likelihood of the risk aversion responses, conditional on the EUT and CRRA specifications being true, depends on the estimates of σ and on the observed choices. If the responses that reflect indifference are not considered, the conditional log-likelihood function can be defined as follows:

$$\ln L(\sigma; y, S) = \sum_{i=1}^{N}\sum_{j=1}^{10}\left(\left(ln\left(\Phi(\nabla EU_j)\right)\middle|y_i^j=1\right)+\left(ln\left(1-\Phi(\nabla EU_j)\right)\middle|y_i^j=-1\right)\right), \tag{15}$$

where $y_i^j=1$ (or -1) denotes the i-th individual's selection of option A (or B) for the j-th lottery question.

Based on the defined likelihood function, the MLE procedure was used to estimate the RRA coefficient as a measure of the degree of risk aversion to the NPP accident.

3. Survey structure and implementation

In this study, an individual-level survey was conducted to estimate the value of life for the NPP accident by eliciting the respondents' WTP to reduce mortality risk resulting from NPP accident and to derive RRA coefficient based on the respondents' choice for the risk-safe choice and risky choice in the low-probability with a high-consequence situation.

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 lottery-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 respondents' WTP and the degree of RRA and validate the estimate result.

In the first section of the survey, the questions concerning the respondent's general perception of NPPs operating in Korea were designed to capture the WTP of the respondent according to their observable attributes using a 7-point scale for each question. The questions concerned the following: (1) the individual's preference among various energy options, e.g., NPPs and coal power plants; (2) the individual's political stance on expanding the energy share of NPPs or on supporting NPP operations in Korea; and (3) the individual's perception of the safety of NPPs currently operating in Korea.

In the second section, the respondents were informed of a hypothetical government policy that suggests preparing countermeasures for minimizing the radiological consequences in response to an NPP accident. By employing MPL design, the respondents were asked to select whether they would pay a certain amount of income tax, which corresponds to a risk-safe choice for which a sure loss of wealth is defined, or if they would like to take the risky choice, as shown in Table 1.

Table 1 shows ten paired lottery-choice questions, and two hypothetical options for loss of wealth are assumed in each question. Each question includes a certain individual loss: a risk-safe choice with a relatively small loss of wealth (option A) and a very low-probability for a high loss of wealth as the risky choice (option B). The logic behind the survey questionnaires is that the expected value of option A is higher than that of option B in the first decision problem; thus, only an extreme risk seeker would choose option B, in contrast to the case of the last decision problem, in which extremely risk-averse individuals choose option A.

The third section of the survey includes questions eliciting the respondent's WTP regarding a reduction in the mortality risk due to an NPP accident. The challenges in using the CV method to estimate the VSL based on the WTP concern, for example, the design of the questionnaire and the choice of the elicitation method. Although the WTP approach based on CVM is recommended for monetary valuation regarding the risk of fatalities by various regulatory bodies (U.S. Office of Management and Budget, 1996; Fisher et al., 1989), it has been subject to the risks or uncertainties in the CV survey due to biases that can occur when applying CVM. A particular challenge arises from the potential biases such as vehicle bias, starting point bias, and self-selection bias (Morrison et al., 2000; Herriges and Shogren, 1996).

Therefore, to eliminate such potential biases in the CV survey, the respondent sample for the survey was carefully selected and the survey questionnaires were designed in a prudent manner by conducting pilot survey. As a payment vehicle, an income tax was selected in a closed-ended questionnaire to elicit the WTP and the respondents were told that they would have to pay an additional income tax to support the hypothetical government policy to reduce the mortality risk due to NPP accidents to manage vehicle bias, following the payment vehicle practiced in the previous studies (Itaoka et al., 2006; Smith and Desvousges., 1986). In addition, a pilot survey was conducted to determine an initial bid amount for the main survey and the dichotomous choice method, which is considered less subject to the starting point bias compared to other methods, such as iterative bidding or payment card techniques, was selected to manage starting point bias (Arrow et al., 1993; Freeman, 1993). For the self-selection bias, the respondent sample for the main survey was selected carefully to represent the general Korean population's risk attitude towards the NPP as well as the general demographic characteristic of Korean population (Whitehead, 1991). In addition, the respondents were given general background information on the operational status of NPPs in Korea and on the hypothetical mortality risk due to an NPP accident before the WTP questions were asked.

In this study, double-bounded (DB) questions were employed, as shown in Fig. 1. The DB questions present each respondent with a sequence of two bids and asks for a “yes” or “no” response as to whether the respondent's WTP equals or exceeds each bid. The second bid was designed to be conditional on the respondent's response to the first bid; the second bid is twice the first bid if the respondent's response to the first bid is “yes” and half the first bid if the response is “no”. Table 2 shows the amounts of the initial and second bid used in this study, which were derived as the quartile boundary values of the WTP based on the results of the pilot survey. The determined initial and second bid amount derived from the pilot survey corresponded to the bid amount used in other studies conducted in Korea regarding the mortality risk reduction in various sectors including nuclear energy (Lee and Lee, 2006; Rhee, 2013). In terms of the baseline risk used in the survey questionnaire, a generic value of equivalent fatalities resulting from NPP accident was used based on the PSA analysis result reported for the conventional NPPs (Burgherr and Hirschberg, 2014). The double-bounded dichotomous choice (DBDC) question was followed by an open-ended question for which the respondents who answered yes–yes or no–no provide their WTP as a subjective response.

The final section of the survey is composed of various socio-economic questions to ascertain information about the respondent such as gender, age, education level, and income. In the analysis of the mean WTP for the mortality risk reduction RRA coefficient for an NPP accident, each factor was assumed to be an independent variable.

According to the testing protocol of the NOAA panel, which states that a total sample size of at least 1000 respondents is required for a CVM study (Arrow et al., 1993), the main survey was

Table 1
Ten paired hypothetical lottery-choice questions.

Question number	Option A (risk-safe choice)	Option B (risky choice)
1	A sure loss of 0.1 million KRW	A possibility of 5/100 of losing 0.1 billion KRW
2	A sure loss of 0.1 million KRW	A possibility of 2/100 of losing 0.1 billion KRW
3	A sure loss of 0.1 million KRW	A possibility of 1/100 of losing 0.1 billion KRW
4	A sure loss of 0.1 million KRW	A possibility of 5/1000 of losing 0.1 billion KRW
5	A sure loss of 0.1 million KRW	A possibility of 2/1000 of losing 0.1 billion KRW
6	A sure loss of 0.1 million KRW	A possibility of 1/1000 of losing 0.1 billion KRW
7	A sure loss of 0.1 million KRW	A possibility of 5/10000 of losing 0.1 billion KRW
8	A sure loss of 0.1 million KRW	A possibility of 2/10000 of losing 0.1 billion KRW
9	A sure loss of 0.1 million KRW	A possibility of 1/10000 of losing 0.1 billion KRW
10	A sure loss of 0.1 million KRW	A possibility of 0 of losing 0.1 billion KRW

The government would like to propose a policy to reduce the yearly mortality risk by 1/10000 by preparing both beforehand and ex-post countermeasures for the NPP accident. Would you be willing to pay additional income tax of 5,000 KRW to support this policy?	
☐ Yes If yes, would you be willing to pay up to 10,000 KRW to reduce the mortality risk by 1/10000? ☐ Yes ☐ No If yes, what is the maximum income tax you would be willing to pay? ____________ KRW	☐ No If no, would you be willing to pay up to 5,000 KRW to reduce the mortality risk by 1/10000? ☐ Yes ☐ No If no, how much income tax would you be willing to pay? ____________ KRW

Fig. 1. An example of double-bounded dichotomous choice questions used in the survey.

conducted by trained interviewers with 1550 participants in Korea from March 12th to 23rd, 2015. Respondents who have a regular income and thus pay income tax every month were selected as the target sample.

4. Results

4.1. General description of the collected survey sample

Among a total of 1550 collected survey samples, 186 were rated by the enumerators as being of poor quality due to a misunderstanding of the questions or improper responses to certain questions and were therefore removed from the sample. Table 3 provides statistical data for the remaining sample of 1364 respondents as well as for each demographic sub-sample. In the final sample, 47.51% of the respondents were female, which is less than the national average of 50.32%. On average, the age of the respondents (40.32 years old) was similar to the national average value (40.30 years old). The collected sample included respondents with more members per family (3.18 persons) than the national average (2.7 persons), and 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%); thus, evidence of self-selection bias was considered to be negligible (Whitehead, 1991). Overall, it can be inferred that the sample collected in the main survey can be treated as a representative sample of the Korean population.

4.2. Estimated willingness to pay of an individual

4.2.1. Distribution of WTP responses

Table 4 presents the distribution of responses to the valuation questions and indicates the total number of respondents who stated that they would be willing to pay an additional income tax for the hypothetical government policy aimed at reducing the mortality risk following an NPP accident for each initial bid amount. Note that the number of 'yes' responses to the first bid amount decreases as the initial bid increases. It can be inferred that the percentage of the 'yes' responses for the initial bid amount is the sum of the YY and YN column; 26.42% of the respondents were willing to pay the initial bid of KRW 5000, whereas only 9.15% of the respondents were willing to pay the initial bid of KRW 80,000.

The number of respondents who did not want to pay any amount of money was 301 (22% of the sample). One of the considerations when estimating the WTP of a respondent through the CVM is how to interpret the zero value response and address the differences between true zero bids and protest zeros. A true zero response is consistent with an economic behavior and is a true reflection of preferences, indicating that the respondent derived no benefits from the good or faced income constraints (Pyo et al., 2000). In this study, all zero responses are treated as true zero bids to conservatively estimate the VSL in the case of an NPP accident.

Table 2
Bid amounts for the willingness to pay used in the five survey types.

Survey type	First bid (KRW)	Second bid (KRW)	
		If the response of the first bid is "yes"	If the response of the first bid is "no"
1	5000	10,000	2500
2	10,000	20,000	5000
3	20,000	40,000	10,000
4	40,000	80,000	20,000
5	80,000	160,000	40,000

Table 3
Statistics of survey respondents.

Demographics		Observations	National average
Gender	Male	716	–
	Female	648	–
	Percentage being female (%)	47.51	50.32 (Statistics Korea, 2015)
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	–
	Average age (years)	40.32	40.30 (Statistics Korea, 2015)
Monthly household income	~2 million KRW	203	–
	2 million KRW–4 million KRW	496	–
	4 million KRW–6 million KRW	381	–
	6 million KRW–8 million KRW	149	–
	> 8 million KRW	135	–
	Average (million KRW)	4.51	4.26 (Statistics Korea, 2015)
Average number of persons in household		3.18	2.7 (Statistics Korea, 2015)
Percentage being supportive to the necessity of NPP (%)		78.96	78.3 (Korea Nuclear Enegy Agency, 2013)
Total number of respondents		1364	–

4.2.2. Estimation results of the mean willingness to pay

The conventional model in Eq. (2) and the spike model in Eq. (6) were used to estimate the mean WTP with the MLE method. The estimates of the conventional model were calculated by

Table 4
Number of responses by bid amount.

First, Bid (KRW)	Sample Size	Number of responses[a]				
		YY	YN	NY	NNY	NNN
5000	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

Notes: YY, YN, NY, NNY, and NNN indicate 'yes–yes', 'yes–no', 'no–yes', 'no–no–yes', and 'no–no–no' answers, respectively.

[a] The second bid is twice the first bid if the respondent's response to the first bid is 'yes' and half the first bid if the response is 'no'.

assuming that the additional follow-up question had not been answered. Table 5 describes the estimation results. All the parameters in both models were significant at the 1% level, whereas the constant term in the conventional model was not. The coefficient for the bid amount was negative. This supports the fact that the higher bid makes a "yes" response less likely, as previously discussed.

The conventional model gives an estimated mean of KRW −2337 and an estimated *t*-value of −0.64. However, the mean WTP in the spike model, computed as KRW 25283, is highly significant, as evidenced by the estimated *t*-value of 33.24. Moreover, the confidence interval of the mean in the spike model is narrow, whereas that in the conventional model is wide. Consequently, it can be concluded that the information at zero drastically decreases the standard error of the mean and renders the confidence interval fairly narrow in this study, which supports the application of the spike model when estimating the WTP.

Based on the spike model, the demographics of the respondents, which affect the likelihood that they are willing to pay for the policy for reducing the mortality risk following an NPP accident, were examined. It is common to test for internal consistency or theoretical validity in CV studies by estimating the model with covariates. When the model is estimated with covariates, a in Eq. (8) is simply replaced by the following expression:

$$a = a_0 + \sum_{i=1}^{n} a_i x_i \tag{16}$$

where n is the number of covariates, a_0 is the constant term, x_i is a vector of covariates, and a_i is a vector of the coefficient for the corresponding covariates.

In this study, the seven variables that were investigated in the survey were used as covariates in the spike model. A detailed description of the variables used in this study is presented in Table 6. Table 7 shows the estimation results of the spike model that includes the covariates. All the coefficient estimates for the variables were significant at the 1% level except for the dummy variables of KNOWLEDGE and POLITICAL STANCE. As in the model without covariates, the coefficient for the bid amount is negative and significantly different from zero.

Table 7 shows that the respondents who reported a high risk perception of the safety of operating NPPs and who have a negative political stance against NPPs were less likely to pay for a decrease in mortality risk in the case of an NPP accident. This can be interpreted by the fact that people who have a negative attitude toward NPPs regard a policy for decreasing mortality rates that are caused by NPP accidents with skepticism and prefer alternative energy sources, such as renewable energy sources, as replacements to NPPs. Female respondents were more willing to pay than male respondents. The older the respondent, the lower the likelihood of being willing to pay. In addition, the respondent's education level has a negative effect on the likelihood of voting "yes" for a given bid. These effects of demographics on the WTP are consistent with those reported by other studies (Kwak et al., 2013; Yoo and Kwak, 2009).

Table 5
Estimation results of the conventional model and the spike model.

Variables	Conventional model[a]	Spike model[a]
Constant	0.052 (0.61)	0.6593 (13.43)***
Bid amount[b]	−0.022 (−8.96)***	−0.0426 (−1027.78)***
Log-likelihood	−844.70	−2936.36
Mean WTP[c]	−2337.20 (−0.64)	25283.23 (33.24)***
95% confidence interval of WTP[c]	−9498.04 – 4823.65	23792.29 – 26774.17
Number of observations	1364	1364

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

[a] The numbers in parentheses below the coefficient estimates are *t*-values.

[b] The unit of the coefficient estimate of a bid amount is KRW 1000.

[c] The unit of the WTP is KRW.

4.2.3. *Expanding the willingness to pay to the value of statistical life*

The individual estimates of the mean WTP for reducing the mortality risks in the case of an NPP accident can be used to estimate the VSL for NPP accidents. Based on Eqs. (9) and (10), the VSL was simply calculated as the estimated sample mean of yearly WTP divided by the mortality reduction rate described in the survey questionnaires in this study. This method of conceptualizing the WTP as a change in the risk of mortality can be applied because a small risk of mortality was used in the survey; namely, respondents were asked to provide a monthly WTP value for a yearly mortality reduction amount of 1E−04 (Dockins et al., 2004). The sample WTP estimate for the model without covariates was expanded to estimate the VSL for NPP accidents, and the estimation results are shown in Table 8.

4.3. *Estimation results for risk aversion parameter*

4.3.1. *Distribution of the hypothetical lottery question responses*

To acquire a sense of the distribution of the risk preferences for the collected sample, the probability of risk-safe choices, which is calculated as the average of the number of risk-safe choices to the number of total choices, was analyzed, as shown in Table 9. The probability of choosing risk-safe options increases for the female group, lower education group, and lower income group. The patterns in risk attitudes across demographic groups are consistent with those reported by other studies (Harrison and Rutström, 2008; Dave et al., 2010).

An issue with the MPL design is that certain subjects tend to continuously switch between lotteries as they move down the decision rows (Andersen et al., 2008). To examine the respondents' choices, the subjects are divided into consistent and inconsistent sub-samples. Table 10 shows the distribution of switched rows for the case of a consistent sample of 1086 cases (80% of the 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.

4.3.2. *Risk aversion parameter estimation result*

In this study, only the consistent sample was used to estimate the risk aversion parameter, and the RRA parameter σ (without and with covariates), which is described as a function of individual

Table 6
Definitions and sample statistics of the covariates used in the analysis.

Variables	Definitions
GENDER	Dummy for the gender of the respondent (1=Male, 2=Female)
AGE	Dummy for the age group of the respondent (From 1=20–29 years old to 5=60–69 years old)
KNOWLEDGE	Dummy for the respondent's knowledge on NPPs (From 1=Very little to 7=Very much)
INTEREST	Dummy for the respondent's interest in issues related to NPPs (From 1=Very little to 7=Very much)
POLITICAL STANCE	Dummy for the respondent's stance on the NPP expansion policy (From 1=Very objective to 7=Very supportive)
RISK PERCEPTION	Dummy for the respondent's degree on the safety of operating NPPs (From 1=Very unsafe to 7=Very safe)
ALTERNATIVES	Dummy for the respondent's degree on replacing NPPs with renewable energy sources (From 1=Very little to 7=Very much)
EDUCATION	Dummy for the education level of the respondent (1=below college graduates, 2=college graduates)
INCOME	Dummy for the monthly household total income (From 1=~2 million KRW to 5=8 million KRW~)

Table 7
Estimation results of the spike models with covariates.

Variables	Sample mean	Spike model[a]
Constant		0.130 (0.23)
GENDER	1.475 (0.500)	0.282 (2.71)***
AGE	2.654 (1.289)	−0.148 (−2.38)**
KNOWLEDGE	4.159 (1.272)	0.023 (0.46)
INTEREST	4.740 (1.299)	0.082 (1.61)*
RISK PERCEPTION	3.212 (1.503)	−0.198 (−2.60)***
POLITICAL STANCE	3.600 (1.510)	0.062 (0.52)
ALTERNATIVES	5.554 (1.144)	0.076 (1.59)*
EDUCATION	1.585 (0.493)	−0.204 (−2.17)**
INCOME	2.646 (1.157)	0.148 (3.26)***
Bid amount[b]		−0.043 (−540.81)
Wald statistic (p-value)[c]		38.33 (0.0000)
Mean WTP		23591.34 (8.09)***
95% confidence interval of WTP		17874.25–29308.43
Number of observations		1364

Notes:
***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.
[a] The numbers in parentheses below the coefficient estimates are t-values.
[b] The unit of the coefficient estimate of the bid amount is KRW 1000.
[c] The hypothesis is that all the parameters are jointly zero, and the corresponding p-values are reported in the parentheses.

Table 8
Estimation results for the value of statistical life for an NPP accident.

Mean yearly WTP	Value of statistical life	
	Mean	95% confidence interval[a]
KRW 303398.76	KRW 3.03 billion (USD 2.78 million)	KRW 2.86–3.21 billion (USD 2.62–2.94 million)

[a] The confidence intervals are based on the estimation results of the WTP for reducing the mortality risk due to an NPP accident.

Table 9
Probability of risk-safe choices based on individual characteristics.

Demographics		Probability of risk-safe choice[a]	Observations
Gender	Male	0.464 (0.359)	716
	Female	0.486 (0.355)	648
Age groups	20–35 years old	0.522 (0.353)	339
	35–50 years old	0.423 (0.359)	315
	50–69 years old	0.459 (0.352)	307
Education level	Less than high school graduate	0.475 (0.350)	32
	High school graduate	0.489 (0.349)	534
	College graduate	0.465 (0.363)	798
Monthly household income	–2 million KRW	0.436 (0.379)	203
	2 million KRW–4 million KRW	0.483 (0.349)	496
	4 million KRW–6 million KRW	0.471 (0.354)	381
	6 million KRW–8 million KRW	0.499 (0.369)	149
	>8 million KRW	0.483 (0.352)	135
Total Respondents		0.474 (0.357)	1364

[a] The probability of risk-safe choice refers to the ratio of the average number of risk-safe choices to the number of total choices, and the standard deviations are reported in parentheses.

Table 10
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	Percentage
0	Always the risky choice	299	27.53
1	2	53	4.88
2	3	41	3.78
3	4	96	8.84
4	5	31	2.85
5	6	27	2.49
6	7	74	6.81
7	8	29	2.67
8	9	34	3.13
9	Always the risk-safe choice	402	37.02
Total		1086	

characteristics following the EU theory specifications, is estimated based on the survey results, as shown in Table 11. Column 1 presents the results when the RRA is not allowed to vary across individual characteristics, and column 2 presents the estimates of the RRA with covariates.

When heterogeneity in the risk aversion parameter was allowed, the parameters GENDER, AGE, INTEREST, RISK PERCEPTION, and EDU showed a significant effect on the risk aversion parameter. The estimation results showed that older, more educated, and female respondents showed an increased risk aversion. This result is in agreement with the results of other studies, which found that subjects who are female, older, and more educated are more risk averse (Halek and Eisenhauer, 2001). In agreement with the results of previous studies, the risk aversion parameter has no significant correlation with risk attitudes and wealth or income across all sub-samples (Binswanger, 1980; Mosley and Verschoor, 2005).

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

4.4.1. A case study: calculation of the external cost of an NPP accident

Although deaths from group accidents such as NPP accidents are not common and the risk is small compared to other accidents, individuals perceive group accidents differently from other accidents. This group accident phenomenon implies that there should

Table 11
Maximum likelihood estimation results of the risk parameter.

Variables	Risk parameter[a]	
	(1)	(2)
Constant	1.315 (128.91)***	−0.311 (−0.01)
GENDER		0.016 (3.38)***
AGE		0.010 (3.25)***
KNOWLEDGE		0.004 (1.58)
INTEREST		−0.012 (−4.87)***
RISK PERCEPTION		−0.007 (4.41)**
POLITICAL STANCE		0.007 (1.34)
WILLINGNESS[b]		1.474 (0.03)
ALTERNATIVE		0.003 (1.48)
EDU		0.011 (3.11)***
INCOME		0.002 (1.15)
Log-likelihood	−6752.4726	−6361.0092
Wald statistic (*p*-value)[c]		63.67 (0.0000)
Number of observations	1086	1086

Note:
***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

[a] The numbers in parentheses below the coefficient estimates are *t*-values.

[b] WILLINGNESS denotes the dummy for the willingness to pay of the respondent (1 = payment, 0 = no payment).

[c] The hypothesis is that all the parameters are jointly zero, and the corresponding *p*-values are reported in the parentheses.

be a multiplication factor when estimating the external cost for group accidents in the energy sector to reflect the risk aversion behavior of the public (Krupnick et al., 1993). Therefore, the external cost can be estimated as the multiplication of the expected value of a consequence due to an NPP accident, EV, and the multiplication factor, M, divided by the mean annual electricity production as follows:

$$\text{External cost of NPP accident (\$/kWh)} = \frac{M*EV\,(\$)}{\text{Mean annual electricity production (kWh)}}, \tag{17}$$

$$EV = \sum_{j=1}^{m}\left(N_j W_0\left(\sum_{i=1}^{n} p_{i,j} X_{i,j}\right)\right), \tag{18}$$

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.

Based on Eqs. (17) and (18), the estimation of the expected value for NPP accidents requires considering the following factors: (1) the number of individuals affected by the NPP accident, (2) the states of lotteries for an individual, and (3) the economic effects based on various cost factors, which are associated with the consequences of an NPP accident.

Based on the defined evacuation planning zone, the number of individuals affected by a NPP accident was determined according to the definition of the emergency planning zone around the NPP, which includes a precautionary action zone (PAZ) with a radius of up to 5 km, an urgent protective action planning zone (UPZ) with a radius of up to 30 km, and a long-term planning zone (LPZ) with a radius of up to 80 km from the NPP site (Thorne, 2013; Collins et al., 1978). In this study, a population density of 485.6 residents/km^2 with a uniform population distribution, adopted from the average population density estimate of Korea for the year 2010, was assumed in the calculation of the total number of individuals inside each planning zone (Statistics Korea, 2015).

The states of lotteries for an individual as a consequence of an NPP accident can be categorized based on the health effect status, which includes (1) no health effects, (2) non-fatal health effects, and (3) fatal health effects. For offsite consequences following an NPP accident, the effects of the release of radioactive material from the NPP site are described by the number of early fatalities and latent cancer fatalities. Following a previous study, the number of equivalent fatalities for both early and latent cancers was estimated as a fatal and non-fatal health effect, respectively, using the MELCOR Accident Consequence Code System 2 (MACCS2) developed by Sandia National Laboratories, as shown in Table 12 (Lee and Kang, 2015; Chanin et al., 1997).

In terms of the economic effects associated with the consequences of an NPP accident, most consequences can, at least theoretically, be associated with an economic cost, which can be generally classified into two categories: direct and indirect (Lazo and Zarimpas, 1995). Direct economic consequences are normally described in terms of the cost of implementing countermeasures, such as the cost of evacuation or relocation, or the compensation for radiation-induced health effects experienced by the exposed population. In contrast, the indirect (or secondary) economic consequences would cover the effects experienced beyond the fields directly impacted by the contamination, for instance, the impact on the marketing of non-contaminated food, on tourism, or on the nation's nuclear program.

In this study, the direct cost factors are only considered because of the limitation whereby indirect cost factors are normally difficult to quantify or are unquantifiable a priori; however, they are amenable to an a posteriori evaluation. 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, as shown in Table 13. Note that the cost of fatal health effects was treated similarly to the estimated VSL. Table 14 shows a summary of the estimates of the cost factors according to sub-groups of population and health effect cases.

4.4.2. Calculation of the multiplication factor

Based on the external cost estimation framework in Eqs. (17) and (18), the multiplication factor is multiplied by the expected value of the NPP accident cost to reflect the disaster aversion behavior of the public. To evaluate the multiplication factor, a general risk situation characterized by various states of consequences, which are specified by their probabilities and their associated fraction of loss of wealth, was considered following Eeckhoudt et al. (2000). In the case of a risk-neutral individual and a risk-averse individual having a risk-neutral utility function, U_{RN}, and a CRRA utility function, U_{RA}, respectively, the expected utility of both cases can be given by

Table 12
Estimated individual probability of fatal, non-fatal, and no health effects.

Sub-group of population by emergency planning zone	PAZ	UPZ, not relocated	UPZ, relocated	LPZ
Number of individuals	3.81E+04	1.33E+05	1.20E+06	8.39E+06
Individual probability of accident with fatal health effects	0	1.08E−08	3.09E−09	8.02E−10
Individual probability of accident with non-fatal health effects	0	2.33E−08	7.13E−09	1.94E−09
Individual probability of accident with no health effects	1.43E−06	1.40E−06	1.42E−06	1.43E−06
Individual probability of no accident	9.99E−01	9.99E−01	9.99E−01	9.99E−01

Table 13
Assumptions for the direct cost factors and their estimates.

Direct cost factors	Cost estimates
Cost of evacuation/relocation	4.00E+03 \$/person
Loss of income for people unable to reach their workplace	Relocated: 1.11E+04 \$/person Not Relocated: 1.85E+03 \$/person
Loss of capital value and investment on land or property	Relocated: 3.62E+04 \$/person Not Relocated: 0 \$/person
Cost of fatal health effect (cancer fatality)	2.78E+06 \$/person
Cost of non-fatal health effect (cancer injury)	6.78E+03 \$/person

$$E\left[U_{RN}\right]=\sum_{i=1}^{n}p_iW_0(1-X_i), \tag{19}$$

$$E\left[U_{RA}\right]=\sum_{i=1}^{n}\frac{p_i(W_0(1-X_i))^{1-\sigma}}{1-\sigma}, \tag{20}$$

where p_i is the probability and X_i is the fraction representing the loss of wealth for the ith state of consequences from a total of n states of consequences regarding a certain risk situation. When assuming that an individual is willing to lose a certain amount of wealth in exchange for avoiding the risk situation, the maximum fractions of wealth that a risk-neutral individual is willing to loose, X_{RN} and X_{RA}, can be defined by introducing the following expected utility criterion:

$$E\left[U_{RN}\right]=\sum_{i=1}^{n}p_iW_0(1-X_{RN}), \tag{21}$$

$$E\left[U_{RA}\right]=\frac{\sum_{i=1}^{n}p_i(W_0(1-X_{RA}))^{1-\sigma}}{1-\sigma}, \tag{22}$$

To consider the risk aversion when estimating the external cost of an NPP accident, the expected value of an external cost is multiplied by a multiplication factor that is determined as the ratio of the maximum fraction of wealth for risk-averse individuals to the maximum fraction of wealth such that

$$M=\sum_{j=1}^{m}\frac{N_jM_{RA,j}}{N_jM_{RN,j}}=\sum_{j=1}^{m}\frac{N_j\{1-[\sum_{i=1}^{n}p_{i,j}(1-X_{i,j})^{1-\sigma}]^{\frac{1}{1-\sigma}}\}}{N_j[1-\sum_{i=1}^{n}p_{i,j}(1-X_{i,j})]}, \tag{23}$$

Note that the total multiplication factor to be applied to the cost of an NPP accident is obtained by considering the coefficients of risk aversion and risk neutrality, namely, $M_{RA,j}$ and $M_{RN,j}$, which are the maximum percentages of the wealth of a risk-averse and risk-neutral individual in the j-th population group, respectively. Table 15 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 results in Table 14. To derive the percentage for loss of wealth, the total wealth of an individual was assumed to be the sum of the estimated VSL and the average value of asset, including financial and property holdings, of an individual in Korea (Statistics Korea, 2015).

Based on Table 15, a total multiplication factor of 5.16 was obtained by substituting the values into Eq. (23). Considering the mean annual electricity production of 5759.36 GWh by Korean NPPs in 2013 (International Atomic Energy Agency, 2014), the external cost of an NPP accident was obtained by dividing the expected value of an NPP accident and multiplying by the estimated multiplication factor, which gives an external cost for an NPP accident of 4.39E−03 USD-cents/kW h.

Table 15
Lotteries faced by identified groups of population.

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

Table 14
Total individual cost for identified risk situations by population sub-group.

Sub-group	Risk situation	Individual cost of health effects	Individual cost of evac./relocation	Individual cost for loss of income	Individual cost for loss of property	Total individual cost
PAZ	Fatal health effect	2.78E+06	4.00E+03	1.11E+04	3.62E+04	2.83E+06
	Non-fatal health effect	6.78E+03	4.00E+03	1.11E+04	3.62E+04	5.81E+04
	No health effect	0	4.00E+03	1.11E+04	3.62E+04	5.13E+04
UPZ, relocated	Fatal health effect	2.78E+06	4.00E+03	1.11E+04	3.62E+04	2.83E+06
	Non-fatal health effect	6.78E+03	4.00E+03	1.11E+04	3.62E+04	5.81E+04
	No health effect	0	4.00E+03	1.11E+04	3.62E+04	5.13E+04
UPZ, not relocated	Fatal health effect	2.78E+06	0	1.85E+03	0	2.78E+06
	Non-fatal health effect	6.78E+03	0	1.85E+03	0	8.63E+03
	No health effect	0	0	1.85E+03	0	1.85E+03
LPZ	Fatal health effect	2.78E+06	0	0	0	2.78E+06
	Non-fatal health effect	6.78E+03	0	0	0	6.78E+03
	No health effect	0	0	0	0	0

5. Discussion

In this paper, an integrated framework for the external cost assessment of an NPP accident that measures the VSL and risk aversion coefficient for the NPP accident based on an individual-level survey was proposed. To estimate the VSL for an NPP accident, the individual estimates of the mean WTP for reducing the mortality risk in the case of an NPP accident was expanded based on the life-cycle consumption model. The estimated VSL of USD 2.78 million is similar to the individual cost of mortality, or fatal health effect, used in previous studies: USD 2.6 million in Markandya (1994); USD 4 million for radiation-induced mortality in Hirschberg et al. (2004) and USD 1.45–4.35 million in OECD (OECD, 2015). Although a direct comparison between the different estimated VSLs is difficult because of the different methodologies adopted in the studies, the estimated VSL in this study was well within the range of the base VSL values for OECD countries.

In terms of risk aversion toward an NPP accident, the RRA coefficient was estimated based on the EUT, in which the CRRA utility function was used to model the utility function of a risk-averse individual. Although the results are comparable to the estimates used in previous studies, the estimate was slightly higher than other estimates obtained using data from other experiments, implying a high risk aversion toward an NPP accident risk (Andersen et al., 2008; Tanaka et al., 2010). Although a direct comparison of the estimated parameters is difficult because the demographics of the participants were different and because the utilized set of hypothetical questions and the data acquisition methods varied among the studies, the higher risk aversion in this study may be driven by the different risk situation, in which the loss of wealth and its probability are extreme.

As previously discussed, the degree of risk aversion differs according to various key demographic indices such as education level and economic status. Because most of NPP sites in Korea are located in rural areas where most residents have both a low education level and a low income compared to the national average, a site-specific RRA that considers the key demographic characteristics of populations living near NPPs and site-specific cost factors must be estimated to facilitate a realistic analysis for estimating both the multiplication factor and the external cost of an NPP accident. In terms of the potential biases which may be introduced in the CV survey, such biases were treated carefully based on the pilot survey; thus, negligible evidence of self-selection bias was found based on respondents' attitude towards NPPs operating in Korea. However, follow-up surveys can be conducted to investigate possible bias, in particular the self-selection bias, in the sample (Heckman, 1979). From a practical standpoint, the test for selection bias resulting from self-censorship must be conducted by various stages of follow-up surveys and interviews (Edwards and Anderson, 1987). Therefore, the application of standard procedure to test for this source of sample-related bias, or self-selection bias, needs to be practiced in the future. In addition, because only the direct cost factors were considered when estimating the external cost of an NPP accident in this study, potential extensions that would add the indirect cost factors to the external cost estimation will be investigated in a future study for a more detailed evaluation of the NPP accident cost.

6. Conclusion and policy implications

Previous external cost assessment methods for an NPP accident included both the expected-value approach where the estimate is calculated as the summation of the probability of possible accident scenarios multiplied by the consequences resulting from the accident and the expected-utility approach where various rule of thumbs models were proposed and the risk aversion coefficient was estimated based on the risk averse behavior of investors. However, the detailed estimation for the external cost, including monetary valuation of life and the quantification of the RRA coefficient specific to the case of NPP accident remained further investigation (OECD/NEA, 2003; Biausque, 2010). 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.

To estimate the value of life for the equivalent fatality following an NPP accident, an individual's WTP for a given mortality risk reduction in the case of a hypothetical NPP accident was estimated. The average value of the VSL was calculated as the estimated sample mean of the WTP divided by the mortality reduction rate.

Because the public tends to exhibit a risk-averse behavior toward group accidents such as NPP accidents and tends to perceive them more seriously, the risk aversion coefficient for an NPP accident must be estimated. This can be achieved by considering that the risk situation faced by an individual in the case of an NPP accident can be described as a “low-probability with high-consequence” situation compared to the case of a general risk situation in economic markets. As a measure of risk aversion, the RRA coefficient was estimated under assumptions governed by the EUT, in which the CRRA utility function was used to demonstrate the risk-averse attitude of an individual toward an NPP accident.

To estimate both parameters, an individual-level survey was conducted on a sample of 1550 participants in Korea. The survey questionnaires were composed of hypothetical choice decision questions based on an MPL design to measure the risk aversion and questions based on a CV design, which elicited the respondent's WTP to reduce a suggested mortality risk for the case of an NPP accident. The monthly mean WTP estimate from the spike model was found to be KRW 25283.23, and the VSL regarding an NPP accident was USD 2.78 million, which indicated individual costs of mortality that are similar to those found in previous studies. The estimate of the RRA coefficient using the CRRA utility function as the utility function of risk-averse individuals based on the EUT was 1.315.

Based on the survey results, the external cost of NPP accident was estimated by assessing the consequence of a hypothetical NPP accident and by considering the direct cost factors regarding economic damage from an NPP accident. The number of equivalent fatalities from both fatal and non-fatal health effects, which were considered as the major potential hazards of an NPP accident, was estimated based on conservative assumptions using MACCS2. Based on the proposed external cost assessment framework, a multiplication factor of 5.16 was obtained and resulted in an external cost estimate for an NPP accident of 4.39E−03 USD-cents/kW h. The estimated external cost of NPP accident by the case study represents about 0.13% of the unit electricity generation cost of NPP (3.30 USD-cents/kW h) in Korea (IEA, 2010).

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 (NEA, 2012). 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 (Torvanger and James, 2011). In terms of filling the gap between social acceptability of the risk and the external cost estimation, the external cost assessment framework for an NPP accident proposed in this study can help energy policy decision-makers or regulators 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 by reflecting the estimated external cost of NPP accident into the unit electricity generation cost of NPP. In addition, consideration of external costs based on the proposed framework can also be beneficial for the energy policy decision of electric utilities since accounting for environmental externalities can help to avoid costs of future environmental or social controls and reduce the uncertainties in the utility's resource planning and utilization.

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