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

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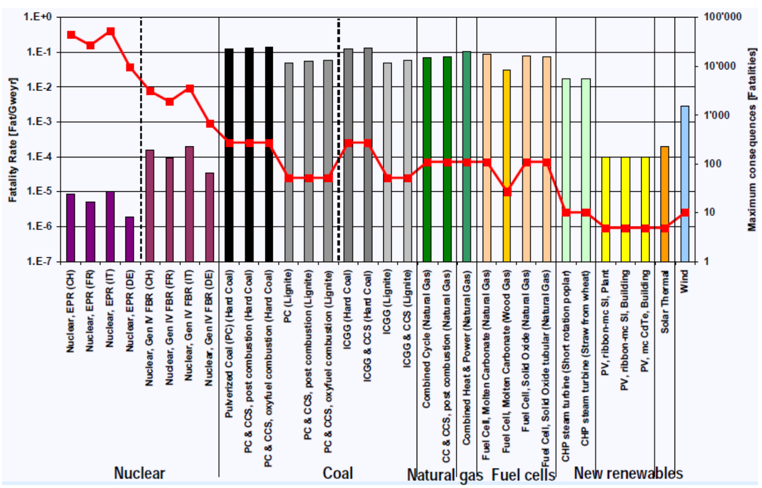
Contents

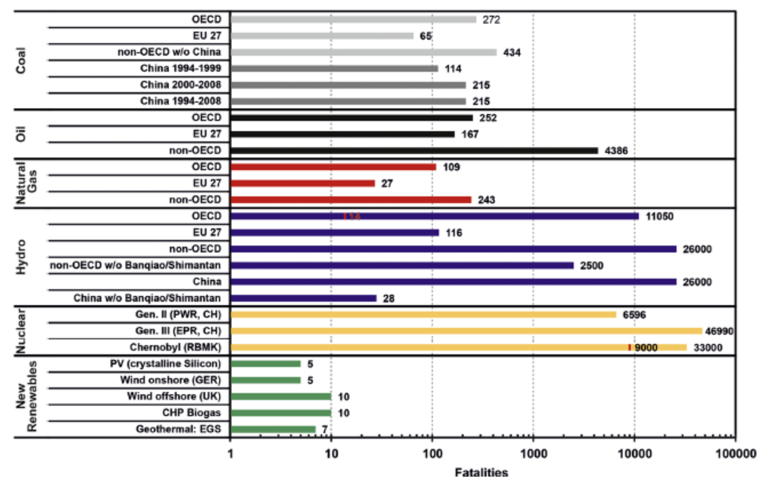
Introduction

- Public risk averse behavior toward severe accidents in energy sector
  - Phenomenon of “group accident” (Timothy, 1994)
    - “Group accident” : accidents which results in tens or hundreds of death because of the one accident (e.g. NPP accident, Dam failure, Oil spill and etc.)

Figure 1. (a) Fatality rates and (b) Maximum consequences of various energy sources (Burgherr P., 2014)



(a)



(b)

- Although the “group accident” incidents are not common and its risk is small compared to other accidents, the individuals perceive the “group accidents” differently to other accidents.
- These phenomena of “group accident” implies that there should be “multiplication factor” on estimating the external cost for “group accidents” to reflect the “disaster aversion” behavior of the public.

Introduction

- Previous studies on external cost estimation of NPP accident

  - Expected-Value Approach: The conventional methodology used to evaluate the impacts of accidental releases is based on analyzing the expected damages caused by NPP accident.

  - Expected-Utility Approach: Individuals process their perceived risk on the basis of conditional losses from an accident; thus, the relationship between the risk aversion and the accident consequence must be considered.

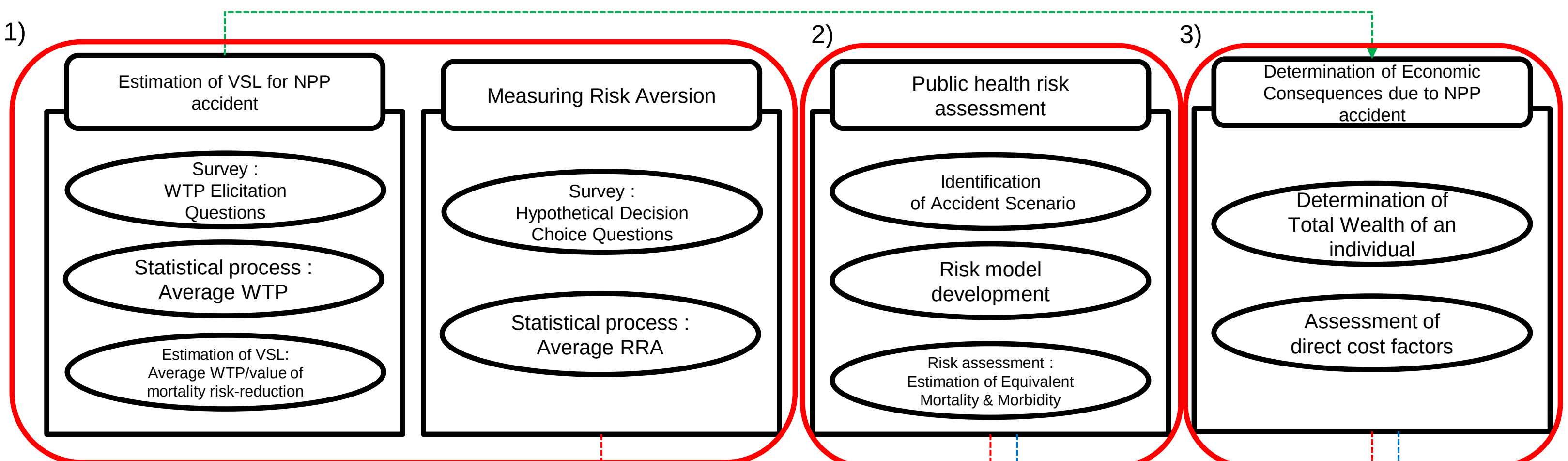
Table 1. Some suggested ratios of expected utility(EU) to expected value(EV) in case of the NPP accident risk

Author	Description	Multiplication factor (Ratio of EU to EV)
Ferguson, 1991	Use of 'rules of thumb' models (fN^2)	~30000*
Rocard and Smets, 1992	Use of 'rules of thumb' models ($300fN$)	~300*
Pearce, et al. 1992	Use of 'rules of thumb' models ($fN^{3/2}$)	~300*
Krupnick et al. 1993	Use of U.S. NPP accident risk= $6.2 * 10^{-5}$	~78
Ascari and Bernasconi, 1997	Similar to Krupnick et al. but adjusted for rank dependent probability (RDP) : 1) Probability : 10^{-5}, 2) Probability : 10^{-6}	1) 141 – 202 2) 660 – 1430
Eeckhoudt et al, 2000	Hypothetical European accident with low probabilities (=10^{-6})	20

*Accident frequency (f) and number of deaths per accident (N) are taken from the number of expected fatal cancers calculated by the National Radiological Protection Board(NRPB), as quoted from the Ferguson study(1991).

Objective and Scope

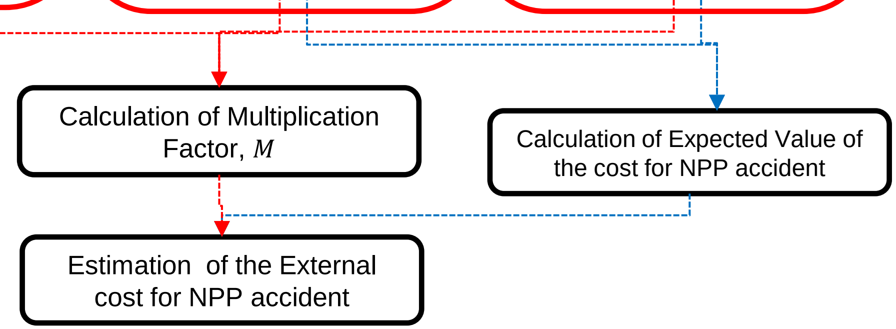
- In this study, the "Integrated Framework on the External Cost Assessment of Nuclear Power Plant Accident considering Risk Aversion" is proposed:
  - Estimation of VSL for NPP accident based on Contingent Valuation Method (CVM)
  - Measuring risk aversion toward NPP accident based on expected utility theory (EUT)
  - Estimation of the multiplication factor for NPP accident considering hypothetical NPP accident scenario
  - Calculation of the expected value of the cost for NPP accident considering various direct cost factors



1) Estimated based on the results of contingent valuation survey in Korea*.

2) Risk assessment using MELCOR Accident Consequence Code System 2 (MACCS2) following the guidance report (DOE, 2004).

3) Following OECD/NEA report, direct cost factors were identified and were quantified based on the previous studies/reports and reasonable assumptions.



* A total of 1,364 surveys were collected and conducted by Macromill embrain Co. LTD in Korea during March 12-23, 2015

Method

- Estimation of the Value of Statistical Life for an NPP Accident

  - In this study, single-bounded dichotomous choice (SBDC) model with a spike model was used to estimate WTP of the respondents for a given mortality risk reduction and the value of life regarding NPP accident.

$$G_{WTP}(A;\Theta) = \begin{cases} \dfrac{1}{1+\exp(\alpha-\beta A)} & if\ A > 0 \\ \dfrac{1}{1+\exp(\alpha)} & if\ A = 0 \\ 0 & if\ A < 0 \end{cases} \qquad WTP_{mean} = \frac{1}{\beta}\ln(1+\exp(\alpha))$$

, where $G_{WTP}(A;\Theta)$: logistic CDF for the WTP of the respondents
α, β: location and scale of $G_{WTP}(A;\Theta)$, A: suggested bid for a given change in risk situation

  - Using survey respondents' WTP elicitation, α and β can be estimated using maximum likelihood estimation (MLE) method for the log-likelihood function of respondents' WTP:

$$lnL(\alpha,\beta;y,S) = \sum_{i=1}^{N}\{\ln[1-G_{WTP}(A_i)] * \mathrm{I}(y_i = "yes")$$
$$+ln[G_{WTP}(A_i) - G_{WTP}(0)] * \mathrm{I}(y_i = "no-yes") + ln[G_{WTP}(0)] * \mathrm{I}(y_i = "no-no")\}$$

, where $\mathrm{I}(y_i = \text{"yes", "no–yes", "no–no"})$: Indicator function for the subject's response of "yes, "no-yes", "no-no", N : Number of respondents

  - Linkage between estimated WTP for mortality risk reduction and VSL can be constructed based on life-cycle consumption model:

$$VSL = \frac{WTP}{\Delta D}$$

, where ΔD: suggested mortality risk reduction

1. 원전의 중대사고 위험도를 줄이고 중대사고 피해를 최소화하기 위한 사고예방 및 대응정책을 실행하여, 원전의 중대사고로 인한 암 사망 위험률을 10000명당 2명에서 1명으로 감소시키고자 합니다. 귀하께서는 원전의 중대사고 예방에 대한 비용을 지불하실 의사가 있습니까?
   ① 예 → [2 문항으로 가십시오]
   ② 아니오 → [5 문항으로 가십시오]

2. 그렇다면, 귀하께서는 원전 중대사고 예방 및 대응정책을 지원하기 위해 매달 소득세를 통해 [M1] 원을 추가적으로 지불하실 의사가 있습니까?
   ① 예 → [4 문항으로 가십시오]
   ② 아니오 → [3 문항으로 가십시오]

3. 그렇다면, 귀하께서는 원전 중대사고 예방 및 대응정책을 지원하기 위해 매달 소득세를 통해 [M1/2] 원을 추가적으로 지불하실 의사가 있습니까?
   ① 예
   ② 아니오 → [5-1 문항으로 가십시오]

4. 귀하께서는 원전 중대사고 예방 및 대응정책을 지원하기 위해 매달 소득세를 추가로 최대 얼마나 지불할 의사가 있으십니까?
   (___________) 만원

5. 귀하께서는 원전 중대사고 예방 및 대응정책의 지원을 위해 단 1원이라도 지불할 의사가 없으십니까?
   ① 예 → [5-2 문항으로 가십시오]
   ② 아니오 → [5-1 문항으로 가십시오]

5-1. 적어도 1원 이상은 지불하실 의사가 있으시다면 매달 소득세를 추가로 최대 얼마까지 낼 의사가 있으십니까?
   (___________) 원

Figure 2. Survey Design for WTP/VSL Estimation

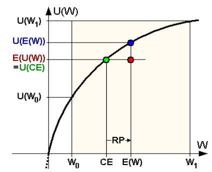
Method

- Measuring the Degree of Risk Aversion for NPP accidents

  - When evaluating risk situations such as NPP accidents, It is assumed that the risk-safe choices of individual over risky alternatives follow the EUT, where utility function of a risk-averse individual follows:

CRRA utility function: $U(W) = \frac{W^{1-\sigma}}{1-\sigma}$

,where W : amount of loss of wealth ,
σ: relative risk aversion (RRA) coefficient



  - Considering i-th decision question with K possible outcomes, the probability of subject's decision of either choice A (Risk-safe choice) or choice B (Risky choice) can be expressed as a probit model:

$$P(\nabla EU_i = EU_i^A - EU_i^B > 0) = \Phi(\nabla EU_i)$$

$$\nabla EU_i = \sum_{k=1}^{K} p_k * U_k \text{ ,} \nabla EU_i = EU_i^A - EU_i^B$$

,where p_k: Probability of each outcome, U_k: Utility of each outcome
EU_i^A : Expected utility of option A, EU_i^B: Expected utility of option B

  - Using survey respondents' choices, the RRA coefficient (σ) is derived using MLE method for the derived log-likelihood function:

$$lnL(\sigma; y, S) = \sum_{j=1}^{N} \sum_{i=1}^{M} [\, \ln(\Phi(\nabla EU_i)) * \mathrm{I}(y_i = A) + \ln\big(1 - \Phi(\nabla EU_i)\big) * \mathrm{I}(y_i = B) \,]$$

,where $\mathrm{I}(y_i = A, B)$: Indicator function for the subject's choice for option A, B
,M : Number of total decision questions, N : Number of respondents

원자력 발전소에 대한 위험회피계수 추정을 위한 조사

본 문항에서는 귀하께서 원자력 발전소의 안전성 및 중대사고 위험률에 대해, 이를 회피하고자 하는 정도를 조사하고자 하며 이를 통해 귀하께서 원자력 발전소의 안전한 운영과 중대사고 위험에 대해 어떠한 생각을 가지고 있는가를 간접적으로 파악하고자 합니다.

국내 원자력 발전회사와 정부는 현 시점에서 시행되고 있는 국내 원전의 안전향상을 위한 연구개발 및 설비투자와 더불어, 추가적으로 국내 원전의 중대사고 시 주민 및 환경 피해를 최소화하기 위한 사고 예방 및 대응 정책을 실행하기 위해 아래와 같은 두 가지 정책을 제안하는 상황을 가정해보고자 합니다.

국내 원자력 발전회사와 정부는 아래의 표에 나와 있는 바와 같이, 10가지 상황에 대해서 두 가지 선택을 제안하였으며, 각각의 상황에 따라 가구가 직면하는 자산피해의 확률은 모두 다르다는 점에 유의해주시기 바랍니다.

- 선택 A) : 가구 당 10만원의 세금을 부과하여 원전 중대사고 시 주민 및 환경 피해를 최소화하기 위한 정책을 실행하여, 징수된 세금은 원자력발전소 입지지역 및 주변지역의 생활정비, 원자력발전소 안전대책, 생업 민생 안정대책 비용 등으로 이용하고자 합니다.

- 선택 B) : 가구 당 세금을 부과하지 않고 현 시점에서 시행되고 있는 국내 원전의 안전향상을 위한 정책을 유지하지만 원전 중대사고 시 주민 및 환경 피해를 최소화하기 위한 정책을 실행하지 않습니다.

이때 아래 표에 나와 있는 바와 같이, 중대사고 시 원전 주변 지역의 가구에 대해 여러 가지 상황에 대해 다음과 같은 자산피해의 금액 및 자산피해의 확률로, 자산피해가 발생할 것으로 가정하며, 각각의 상황에 따라 가구가 직면하는 자산피해의 확률은 모두 다르다는 점에 유의해주시면서 **두 가지 선택 중 한 가지만을 선택해주시면 감사드리겠습니다.**

상황	선택 A)	선택 B)
1	□ 10만 원의 세금을 부과	□ 5/100 의 확률로 1억 원의 자산피해를 입음
2	□ 10만 원의 세금을 부과	□ 2/100 의 확률로 1억 원의 자산피해를 입음
3	□ 10만 원의 세금을 부과	□ 1/100 의 확률로 1억 원의 자산피해를 입음
4	□ 10만 원의 세금을 부과	□ 5/1000 의 확률로 1억 원의 자산피해를 입음
5	□ 10만 원의 세금을 부과	□ 2/1000 의 확률로 1억 원의 자산피해를 입음
6	□ 10만 원의 세금을 부과	□ 1/1000 의 확률로 1억 원의 자산피해를 입음
7	□ 10만 원의 세금을 부과	□ 5/10000 의 확률로 1억 원의 자산피해를 입음
8	□ 10만 원의 세금을 부과	□ 2/10000 의 확률로 1억 원의 자산피해를 입음
9	□ 10만 원의 세금을 부과	□ 1/10000 의 확률로 1억 원의 자산피해를 입음

Figure 3. Survey Design for RRA Estimation

Method

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

  - The external cost can be estimated as the multiplication of the expect value of NPP accident cost (value assuming risk neutrality) and the multiplication factor (which allows consideration on public risk aversion).

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

$$EV(\$/yr) = \sum_{j=1}^{m} N_j W_0 \left(\sum_{i=1}^{n} p_{i,j} X_{i,j} \right) \qquad M = \sum_{j=1}^{m} \frac{N_j M_{j,RA}}{N_j M_{j,RN}}$$

,where n : number of risk situations, m : number of groups for affected population,
N_j : number of population in group j, M : multiplication factor (definition adopted from Eeckhoudt et al, 2000)

$$M_{j,RN} = W_0 - \sum_{i}^{n} p_{i,j} W_0 (1 - X_{i,j})$$

$$M_{j,RA} = W_0 - \left[\sum_{i}^{n} p_{i,j} W_0 (1 - X_{i,j})^{1-\sigma} \right]^{\frac{1}{1-\sigma}}$$

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

,where $X_{i,j}$: Fraction of loss of wealth,
W_0 : Total wealth of an individual,
$M_{j,RN}$, $M_{j,RA}$: the maximum fraction of wealth willing to loss to avoid the risk situation for a risk-averse and risk-neutral individual in j-th population group

- Here, monetary valuation/probability assessment for various states of the consequence must be determined:

  - 1) W_0: Total wealth of an individual
  - 2) N_j: Number of affected population for radiological consequence due to NPP accident
  - 3) $p_{i,j}$: Probabilities, and $X_{i,j}$: associated fraction of lost wealth for corresponding j-th population group and i-th risk situation.

Survey Design and Implementation

- A total of 1,364 surveys were collected and conducted by professional survey interviewers* throughout a sample among Korea population during March 12-23, 2015.
  - Considering the national average value, the collected sample can be treated as a representative sample for the Korean population, thus, used as a valid data to estimate the parameters: WTP/VSL and RRA.

Table 2. Distribution of key sample statistics by demographics

Demographics		Observations	Korean Average**
Gender	Male	716	
	Female	648	
	Percentage of female (%)	48	50.32
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 (years old)	40.32	40.30
Average years of education (years)		16.22	
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
Average number of persons in household (persons)		3.18	2.7
Total Respondents		1,364	

*Conducted by Macromill embrain Co. LTD, (http://www.embrain.com/eng)

**Korean average value was adopted from Korean Statistical Information Service (KOSIS), Available from: http://kosis.kr/

Survey Design and Implementation

Reliability

- Survey Design for Willingness to Pay/Value of Statistical Life Estimation
  - Double-bounded questions were employed to maximize statistical efficiency while conducting the analysis based on SBDC-spike model to minimize potential bias.
  - About 22% among total sample showed zero responses which justifies the application of the spike model.
    - All zero responses are treated as true zero bids so as to conservatively estimate the value of statistical life for external cost estimation of NPP accident.

Figure 4. Survey Design for WTP/VSL Estimation

1. 원전의 중대사고 위험도를 줄이고 중대사고 피해를 최소화하기 위한 사고예방 및 대응정책을 실행하여, 원전의 중대사고로 인한 암 사망 위험률을 10000명당 2명에서 1명으로 감소시키고자 합니다. 귀하께서는 원전의 중대사고 예방에 대한 비용을 지불하실 의사가 있습니까?

   ① 예 → [2 문항으로 가십시오]

   ② 아니오 → [5 문항으로 가십시오]

2. 그렇다면, 귀하께서는 원전 중대사고 예방 및 대응정책을 지원하기 위해 매달 소득세를 통해 [M1] 원을 추가적으로 지불하실 의사가 있습니까?

   ① 예 → [4 문항으로 가십시오]

   ② 아니오 → [3 문항으로 가십시오]

3. 그렇다면, 귀하께서는 원전 중대사고 예방 및 대응정책을 지원하기 위해 매달 소득세를 통해 [M1/2] 원을 추가적으로 지불하실 의사가 있습니까?

   ① 예

   ② 아니오 → [5-1 문항으로 가십시오]

4. 귀하께서는 원전 중대사고 예방 및 대응정책을 지원하기 위해 매달 소득세를 추가로 최대 얼마나 지불할 의사가 있으십니까?

   (___________) 만원

5. 귀하께서는 원전 중대사고 예방 및 대응정책의 지원을 위해 단 1원이라도 지불할 의사가 없으십니까?

   ① 예 → [5-2 문항으로 가십시오]

   ② 아니오 → [5-1 문항으로 가십시오]

5-1. 적어도 1원 이상은 지불하실 의사가 있으시다면 매달 소득세를 추가로 최대 얼마까지 낼 의사가 있으십니까?

   (___________) 원

Table 3. Bid amounts for the willingness to pay used in 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	5,000	10,000	2,500
2	10,000	20,000	5,000
3	20,000	40,000	10,000
4	40,000	80,000	20,000
5	80,000	160,000	40,000

Table 4. Distribution of Responses by Bid Amount

First Bid (KRW)	Sample Size	Number of Responses [a]				
		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

[a] YY, YN, NY, NNY, and NNN indication ‘yes-yes’, ‘yes-no’, ‘no-yes’, ‘no-no-yes’, and ‘no-no-no’, respectively

Survey Design and Implementation

Reliability

- Survey Design for Risk Aversion Parameter

  - Based on multiple price list design (Andersen et al. 2006), individual-level survey questionnaire includes ten-paired hypothetical decision choices where each decision consists of both risk-safe choice and risky choice.

Figure 5. Survey Design for RRA Estimation

원자력 발전소에 대한 위험회피계수 추정을 위한 조사

본 문항에서는 귀하께서 원자력 발전소의 안전성 및 중대사고 위험률에 대해, 이를 회피하고자 하는 정도를 조사하고자 하며 이를 통해 귀하께서 원자력 발전소의 안전한 운영과 중대사고 위험에 대해 어떠한 생각을 가지고 있는가를 간접적으로 파악하고자 합니다.

국내 원자력 발전회사와 정부는 현 시점에서 시행되고 있는 국내 원전의 안전향상을 위한 연구개발 및 설비투자와 더불어, 추가적으로 국내 원전의 중대사고 시 주민 및 환경 피해를 최소화하기 위한 사고 예방 및 대응 정책을 실행하기 위해 아래와 같은 두 가지 정책을 제안하는 상황을 가정해보고자 합니다.

국내 원자력 발전회사와 정부는 아래의 표에 나와 있는 바와 같이, **10가지 상황에 대해서 두 가지 선택을 제안하였으며, 각각의 상황에 따라 가구가 직면하는 자산피해의 확률은 모두 다르다는 점에 유의**해주시기 바랍니다.

- 선택 A) : 가구 당 10만원의 세금을 부과하여 원전 중대사고 시 주민 및 환경 피해를 최소화하기 위한 정책을 실행하여, 징수된 세금은 원자력발전소 입지지역 및 주변지역의 생활정비, 원자력발전소 안전대책, 생업 민생 안정대책 비용 등으로 이용하고자 합니다.

- 선택 B) : 가구 당 세금을 부과하지 않고 현 시점에서 시행되고 있는 국내 원전의 안전향상을 위한 정책을 유지하지만 원전 중대사고 시 주민 및 환경 피해를 최소화하기 위한 정책을 실행하지 않습니다.

이때 아래 표에 나와 있는 바와 같이, 중대사고 시 원전 주변 지역의 가구에 대해 여러 가지 상황에 대해 다음과 같은 자산피해의 금액 및 자산피해의 확률로, 자산피해가 발생할 것으로 가정하며, 각각의 상황에 따라 가구가 직면하는 자산피해의 확률은 모두 다르다는 점에 유의해주시면서 **두 가지 선택 중 한 가지만을 선택해주시면 감사드리겠습니다.**

상황	선택 A)	선택 B)
1	□ 10만 원의 세금을 부과	□ 5/100 의 확률로 1억 원의 자산피해를 입음
2	□ 10만 원의 세금을 부과	□ 2/100 의 확률로 1억 원의 자산피해를 입음
3	□ 10만 원의 세금을 부과	□ 1/100 의 확률로 1억 원의 자산피해를 입음
4	□ 10만 원의 세금을 부과	□ 5/1000 의 확률로 1억 원의 자산피해를 입음
5	□ 10만 원의 세금을 부과	□ 2/1000 의 확률로 1억 원의 자산피해를 입음
6	□ 10만 원의 세금을 부과	□ 1/1000 의 확률로 1억 원의 자산피해를 입음
7	□ 10만 원의 세금을 부과	□ 5/10000 의 확률로 1억 원의 자산피해를 입음
8	□ 10만 원의 세금을 부과	□ 2/10000 의 확률로 1억 원의 자산피해를 입음
9	□ 10만 원의 세금을 부과	□ 1/10000 의 확률로 1억 원의 자산피해를 입음

Table 5. Description of ten-paired hypothetical choice decision

Question Number	Option A (Risk-safe Choice)	Option B (Risky Choice)	Gap in Expected Loss of Wealth (KRW)
1	A sure loss of 0.1 million KRW	A possibility of 5/100 to lose 0.1 billion KRW	-4.90E+06
2	A sure loss of 0.1 million KRW	A possibility of 2/100 to lose 0.1 billion KRW	-1.90E+06
3	A sure loss of 0.1 million KRW	A possibility of 1/100 to lose 0.1 billion KRW	-9.00E+05
4	A sure loss of 0.1 million KRW	A possibility of 5/1000 to lose 0.1 billion KRW	-4.00E+05
5	A sure loss of 0.1 million KRW	A possibility of 2/1000 to lose 0.1 billion KRW	-1.00E+05
6	A sure loss of 0.1 million KRW	A possibility of 1/1000 to lose 0.1 billion KRW	0
7	A sure loss of 0.1 million KRW	A possibility of 5/10000 to lose 0.1 billion KRW	5.00E+04
8	A sure loss of 0.1 million KRW	A possibility of 2/10000 to lose 0.1 billion KRW	8.00E+04
9	A sure loss of 0.1 million KRW	A possibility of 1/10000 to lose 0.1 billion KRW	9.00E+04

Table 6. Distribution of responses by questions asked

Decision Row	Choice A (Risk-safe choice)	Choice B (Risky choice)	Ratio of risk safe choice*
1	936	428	0.686
2	864	500	0.633
3	820	544	0.601
4	746	618	0.547
5	703	661	0.515
6	649	715	0.476
7	611	753	0.448
8	565	799	0.414
9	517	847	0.379

* "Ratio of risk safe choice" refers to the ratio of the number of samples who choose risk safe choice to the number of total sample

Survey Result Analysis

- Estimation of the Willingness to Pay/Value of Statistical Life for the NPP Accident

  - By constructing the SBDC-spike model, the coefficients for the covariates were estimated and the mean WTP of the respondents was estimated by the MLE method using STATA.
  - Internal consistency or theoretical validity of estimation result was tested based on the model with covariate.

$$WTP_{mean} = \frac{1}{\beta}\ln(1+\exp(\alpha))$$, where $\alpha = \alpha_0 + \sum_{i=1}^{n} \alpha_i x_i$ for the case of "with covariates"

Table 7. Estimation results of the spike model with and without covariates

Variables (x_i)	Sample Mean	Spike model [b]	
		Without covariates	With covariates (α_i)
Constant		0.6593 (13.43)***	0.130 (0.23)
GENDER	1.475 (0.500)		0.282 (2.71)***
AGE	2.654 (1.289)		-0.148 (-2.38)**
KNOWLEGDE	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 (β) [a]		-0.0426 (-1027.78)***	-0.043 (-540.81)
Wald statistic (p-value)			38.33 (0.0000)
Mean Monthly WTP [c]		25283.23 (33.24)***	23591.34 (8.09)***
95% confidence interval of WTP		23792.29 ~ 26774.17	17874.25 ~ 29308.43
Number of observations		1364	1364

[a] The unit of a coefficient estimate of bid amount is KRW 1000. [b]The numbers in parentheses below the coefficient estimates are t-values and ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. [c]The unit of WTP is KRW.

Survey Result Analysis

- Estimation of the Willingness to Pay/Value of Statistical Life for the NPP Accident

  - Based on the life-cycle consumption model (Dockins, 2004), the value of statistical life, VSL, was estimated to be equal to the value of average WTP divided by the value of risk reduction ($\Delta D = 1\text{E-}04$), specifically:

$$VSL = \frac{WTP}{\Delta D}$$

, where ΔD: suggested mortality risk reduction

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

Mean Yearly WTP[b]	Mortality risk reduction rate (ΔD)	VSL	
		Mean	95% confidence interval [a]
KRW 303398.76	1.00E-04	KRW 3.03 billion (USD 2.78 million)	KRW 2.86 – 3.21 billion (USD 2.62 to 2.94 million)

[a] The confidence intervals are based on the estimate results of WTP for reducing the mortality risk due to NPP accident.
[b] Mean Yearly WTP = Mean Monthly WTP (= KRW 25283.23)* 12 Months/year

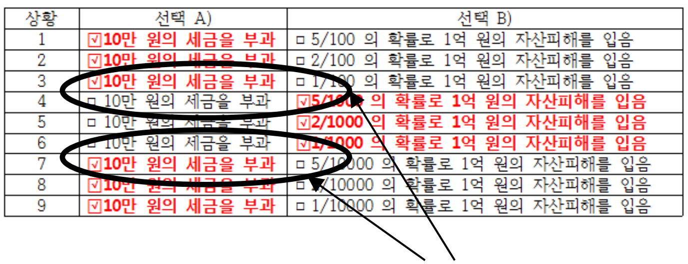
Table 9. Some regulatory practices for valuing VSL regarding mortality risk

Author	Method	Estimated Value of Statistical Life
Markandya et al. (1995)	Contingent valuation Method	USD 2.6 million for mortality (For non-fatal cancer, USD 0.45 million)
Hirschberg et al. (1998)	Hedonistic Price Analysis	USD 4 million for radiation-induced mortality (For non-fatal cancer, USD 0.4 million)
Environmental Protection Agency, (2000)	Viscusi (1992, 1993) literature review	USD 7.5 million (2007-USD) (USD 0.9 million - USD 21.1 million)
Food and Drug Administration, (2007)	Viscusi and Aldy (2003) meta-analysis	USD 5 million, USD 6.5 million (varies, no dollar year reported)
European Commission, (2009)	Environment Cost Benefit Analysis	EUR 1-2 million
OECD, (2011)	Recommended range of base values for OECD countries	USD 1.45 – 4.35 million (2005-USD)

Survey Result Analysis

- Estimation of Relative Risk Aversion Coefficient for the NPP accident
  - A limitation with the MPL design is considered that some subjects tend to switch back and forth between choices as they move down the decision rows; resulting in inconsistent sub-sample (Andersen et al. 2006).
  - In this study, only the consistent sample is used to estimate the risk aversion parameter by excluding samples with multiple switching behavior among the collected sample and used it to estimate RRA.

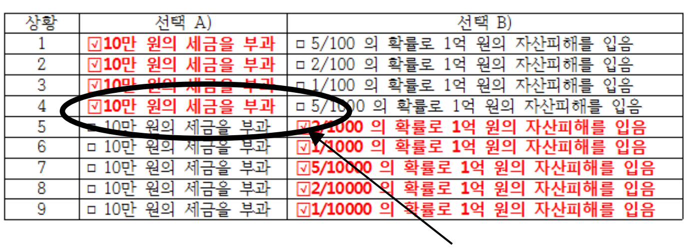
Figure 6. Example of inconsistent sample



상황	선택 A)	선택 B)
1	☑10만 원의 세금을 부과	□ 5/100 의 확률로 1억 원의 자산피해를 입음
2	☑10만 원의 세금을 부과	□ 2/100 의 확률로 1억 원의 자산피해를 입음
3	☑10만 원의 세금을 부과	□ 1/100 의 확률로 1억 원의 자산피해를 입음
4	□ 10만 원의 세금을 부과	☑5/1000 의 확률로 1억 원의 자산피해를 입음
5	□ 10만 원의 세금을 부과	☑2/1000 의 확률로 1억 원의 자산피해를 입음
6	□ 10만 원의 세금을 부과	☑1/1000 의 확률로 1억 원의 자산피해를 입음
7	☑10만 원의 세금을 부과	□ 5/10000 의 확률로 1억 원의 자산피해를 입음
8	☑10만 원의 세금을 부과	□ 2/10000 의 확률로 1억 원의 자산피해를 입음
9	☑10만 원의 세금을 부과	□ 1/10000 의 확률로 1억 원의 자산피해를 입음

Multiple switching of choices

Figure 7. Example of consistent sample



상황	선택 A)	선택 B)
1	☑10만 원의 세금을 부과	□ 5/100 의 확률로 1억 원의 자산피해를 입음
2	☑10만 원의 세금을 부과	□ 2/100 의 확률로 1억 원의 자산피해를 입음
3	☑10만 원의 세금을 부과	□ 1/100 의 확률로 1억 원의 자산피해를 입음
4	☑10만 원의 세금을 부과	□ 5/1000 의 확률로 1억 원의 자산피해를 입음
5	□ 10만 원의 세금을 부과	☑2/1000 의 확률로 1억 원의 자산피해를 입음
6	□ 10만 원의 세금을 부과	☑1/1000 의 확률로 1억 원의 자산피해를 입음
7	□ 10만 원의 세금을 부과	☑5/10000 의 확률로 1억 원의 자산피해를 입음
8	□ 10만 원의 세금을 부과	☑2/10000 의 확률로 1억 원의 자산피해를 입음
9	□ 10만 원의 세금을 부과	☑1/10000 의 확률로 1억 원의 자산피해를 입음

Single switching of choices

Table 10. Distribution of choices in the consistent sample

Number of times subject chooses risk-safe choice	Decision row in which subject switches to risky-choice	Observations	Percentage (%)
0	Always chooses 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 chooses risk-safe choice	402	37.02
Total		1,086	

Survey Result Analysis

- Estimation of Relative Risk Aversion Coefficient for the NPP accident
  - Based on the survey results, the RRA parameter (σ) which is described as a function of individual characteristics following the EUT specifications, is estimated by the MLE method using STATA.
  - Internal consistency or theoretical validity of estimation result was tested by examining the respondents' characteristic affecting likelihood that they choose risk-safe choices (option A) over risky choice (option B).

CRRA utility function: $U(W) = \frac{W^{1-\sigma}}{1-\sigma}$, where $\sigma = \alpha_0 + \sum_{i=1}^{n} \alpha_i x_i$ for the case of "with covariates"

Table 11. Maximum Likelihood Estimation Results of Risk Parameter

Variables(x_i)	Sample Mean	Without covariates	With covariates (α_i)
		Risk Aversion Coefficient (σ)[a]	
Constant		1.315 (128.91)***	-0.278 (-0.01)
GENDER	1.475 (0.500)	-	0.019 (4.16)***
AGE	2.654 (1.289)	-	0.004 (2.44)**
KNOWLEDGE	4.159 (1.272)	-	0.005 (2.38)**
INTEREST	4.740 (1.299)	-	-0.015 (-6.11)***
RISK PERCEPTION	3.212 (1.503)	-	0.011 (4.77)***
POLITICAL STANCE	3.600 (1.510)	-	0.006 (0.11)
WILLINGNESS	0.779 (0.415)	-	1.474 (0.04)
ALTERNATIVE	5.554 (1.144)	-	0.004 (2.15)**
EDU	1.585 (0.493)	-	0.021 (4.72)***
INCOME	2.646 (1.157)	-	0.001 (0.51)
Log-likelihood		-6752.4726	-6338.3586
Wald statistic (p-value)[b]		-	112.47 (0.0000)
Number of observation		1,086	1,086

[a] The numbers in parentheses below the coefficient estimates are t-values and ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. [b]The p-value for the hypothesis that all the parameters are jointly zero are reported in the parenthesis.

Case study – External Cost Estimation for Hypothetical NPP Accident

- Based on the proposed framework, public risk aversion behavior was integrated within the external cost calculation of an NPP accident by considering the expect value of NPP accident cost and the multiplication.

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

$$EV(\$/yr) = \sum_{j=1}^{m} N_j W_0 \left(\sum_{i=1}^{n} p_{i,j} X_{i,j} \right) \qquad M = \sum_{j=1}^{m} \frac{N_j M_{j,RA}}{N_j M_{j,RN}} = \sum_{j=1}^{m} \frac{N_j \{1 - [\sum_{i=1}^{n} p_{i,j} (1 - X_{i,j})^{1-\sigma}]^{\frac{1}{1-\sigma}}\}}{N_j [1 - \sum_{i=1}^{n} p_{i,j} (1 - X_{i,j})]}$$

,where n : number of risk situations, m : number of groups for affected population,
N_j : number of population in group j, M : multiplication factor (definition adopted from Eeckhoudt et al, 2000)

- W_0: Total wealth of an individual is considered to be the sum of two factors:
  - 1) Monetary value of statistical life = 2.78E+06 \$/person (Estimated VSL)
  - 2) Physical capital (Non-human capital) = 82,809 \$/person [a]

- N_j : Number of affected population according to area definition for evacuation planning in case of NPP accident
  - 1) PAZ area (~5km) - pre-accident evacuation; assumed to have $\rho_{pop} = 0$.
  - 2) UPZ area (5~30km) - post-accident evacuation or sheltering; ρ_{pop} = 485.6 residents/km2 [a]
  - 3) LPZ area (30~80km) – Long-term protective zone; ρ_{pop} = 485.6 residents/km2 [a]

- $p_{i,j}$: The "risk situation" for an individual can be defined for four cases:
  - 1) No accident; 2) Accident + No health effect;
    3) Accident + Fatal health effect; 4) Accident + Non-fatal health effect

- $X_{i,j}$: Direct cost factors associated with severe accident consequence of NPP are considered (OECD/NEA, 2000).
  - 1) Cost of countermeasures to reduce doses (Evaluation/Relocation)
  - 2) Cost of compensation for the affected population (Radiation-induced health effects, Loss of income, etc.)

[a] KOSTAT, available online at http://kosis.kr/ (ρ_{pop} = 485.6 residents/km2 : Average population density in Korea)

Case study – External Cost Estimation for Hypothetical NPP Accident

- Total individual costs for each population group and risk situation
  - In the UPZ area, residents are forced to be evacuated based on the radiological contamination assessment of the residential area [a], thus, the actual fraction of evacuation population is sensitive to the site-specific data.
    - In the study, the fraction of forced evacuation population (residing in high contamination zone) is hypothetically assumed to be 10% and the rest of the population (90%; residing in low contamination zone) is assumed to be temporarily sheltered inside the house or to near-by shelter.

Table 12. Total individual cost for corresponding population group and specified risk situation

Population group	Risk situation	Individual cost of health effects ($)	Individual cost of evac./relocation ($)	Individual loss of capita($)	Individual loss of property ($)	Total individual cost ($)	% of loss of wealth (%) ($X_{i,j}$)
PAZ	Fatal health effect	2.32E+06	4.00E+03	1.11E+04	3.62E+04	2.65E+06	98.90
	Non-fatal health effect	6.78E+03	4.00E+03	1.11E+04	3.62E+04	5.81E+04	2.03
	No health effect	-	4.00E+03	1.11E+04	3.62E+04	5.13E+04	1.79
UPZ (evac./relocated)	Fatal health effect	2.32E+06	4.00E+03	1.11E+04	3.62E+04	2.65E+06	98.90
	Non-fatal health effect	6.78E+03	4.00E+03	1.11E+04	3.62E+04	5.81E+04	2.03
	No health effect	-	4.00E+03	1.11E+04	3.62E+04	5.13E+04	1.79
UPZ (not evac./relocated)	Fatal health effect	2.32E+06	-	1.85E+03	-	2.60E+06	97.17
	Non-fatal health effect	6.78E+03	-	1.85E+03	-	8.63E+03	0.30
	No health effect	-	-	1.85E+03	-	1.85E+03	0.06
LPZ (not relocated)	Fatal health effect	2.32E+06	-	-	-	2.60E+06	97.11
	Non-fatal health effect	6.78E+03	-	-	-	6.78E+03	0.24
	No health effect	-	-	-	-	0.00E+00	0

[a] 원자력시설 등의 방호 및 방사능 방재 대책법, [시행 2016.1.1.] [법률 제13388호, 2015.6.22., 일부개정]

Case study – External Cost Estimation for Hypothetical NPP Accident

- Estimation of individual probability of fatal, non-fatal and no health effect

  - Each health effect risk is assessed using MACCS2 based on MACCS2 code analysis guideline (DOE, 2004)
    - The case accident was assumed to be STC-19 (Kim et al. 2004).
    - It is assumed that 10% and 90% of population in UPZ is radially evacuated and sheltered, respectively.

Population group	Risk situation	% loss of wealth ($X_{i,j}$)	Probability ($p_{i,j}$)
PAZ (evac./relocated before accident, j = 0)	Accident + fatal health effect ($i = 1$)	98.90	0
	Accident + non-fatal health effect ($i = 2$)	2.03	0
	Accident + no health effect ($i = 3$)	1.79	1.43E-06
	No accident ($i = 4$)	0	9.99E-01
UPZ (evac./relocated after accident, $j = 1$)	Accident + fatal health effect ($i = 1$)	98.90	1.08E-08
	Accident + non-fatal health effect ($i = 2$)	2.03	2.33E-08
	Accident + no health effect ($i = 3$)	1.79	1.40E-06
	No accident ($i = 4$)	0	9.99E-01
UPZ (not evac./relocated, $j = 2$)	Accident + fatal health effect ($i = 1$)	97.17	3.09E-09
	Accident + non-fatal health effect ($i = 2$)	0.30	7.13E-09
	Accident + no health effect ($i = 3$)	0.06	1.42E-06
	No accident ($i = 4$)	0	9.99E-01
LPZ (not evac./relocated, $j = 3$)	Accident + fatal health effect ($i = 1$)	97.11	8.02E-10
	Accident + non-fatal health effect ($i = 2$)	0.24	1.94E-10
	Accident + no health effect ($i = 3$)	0	1.43E-06
	No accident ($i = 4$)	0	9.99E-01

[a] STC-19: Steam Generator Tube Rupture with Containment Bypass (having probability of 1.43E-06 /yr)

A Case study : Calculation of External Cost of NPP Accident

- Calculation of multiplication factor (adopting estimated RRA coefficient of $\sigma = 1.315$)

Area	PAZ (evacuated)	UPZ (evacuated)	UPZ (not evac./relocated)	LPZ (not relocated)
Number of population for each population group(N_j)	3.8139e+04	1.3349E+05	1.2014E+06	8.3906E+06
$M_{RA} = 1 - \left[\sum_i^n p_i (1 - X_i)^{-1}\right]^{-1}$	2.5937e-08	1.3385e-07	2.1268e-08	5.2316e-09
$M_{RN} = 1 - \sum_i^n p_i (1 - X_i)$	2.5630e-08	3.6213e-08	3.9379e-09	7.8348e-10

$$M = \sum_{j=1}^{m} \frac{N_j M_{j,RA}(\sigma = 1.315)}{N_j M_{j,RN}(\sigma = 1.315)} = \sum_{j=1}^{m} \frac{N_j \{1 - [\sum_{i=1}^{n} p_{i,j} (1 - X_{i,j})^{1-\sigma}]^{\frac{1}{1-\sigma}}\}}{N_j [1 - \sum_{i=1}^{n} p_{i,j} (1 - X_{i,j})]} = \frac{N_1 M_{1,RA} + N_2 M_{2,RA} + N_3 M_{3,RA} + N_4 M_{4,RA}}{N_1 M_{1,RN} + N_2 M_{2,RN} + N_3 M_{3,RN} + N_4 M_{4,RN}} = 5.1590$$

,where $X_{i,j}$: Fraction of loss of wealth, W_0 : Total wealth of an individual,
$M_{j,RN}$, $M_{j,RA}$: the maximum fraction of wealth willing to loss to avoid the risk situation for a risk-averse and risk-neutral individual in j-th population group

- Evaluation of expected value (EV) and external cost of NPP accident:

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

= 4.39E-03 USD-cents/kWh (5.07E-02 KRW/kWh)

where, $EV = \sum_{j=1}^{4} N_j W_0 (\sum_{i=1}^{4} p_{i,j} X_{i,j})$ = 4.9000e+04 USD/yr
Number of groups for affected population: m = 4; Number of risk situations: n = 4
$Mean\ annual\ electricity\ production\ (kWh/yr)$ = 5759.36GWh/yr = 5.76E+09 kWh/yr*

Discussion

- Although the external cost estimates are difficult to compare due to differences in methodologies and assumptions used in other studies, further study must be conducted to facilitate a realistic analysis for estimating external cost of NPP accident.

Table 13. Comparison of the result with the previous studies on the external cost assessment of NPP accident

Author	Risk aversion considered	Description	Estimated external costs
(in this study)	Yes	Use of Hypothetical NPP accident scenario (STC-19) Cost factors: Direct cost factors	4.39E-03 USD-cents/kWh
Hirschberg and Cazzoli (1994)	No	Target NPP : Miihleberg, Switzerland (BWR) Cost factors : health effects	1.2E-03 USD-cents/kWh
Masuhr and Oczipka (1994)	Yes	Target NPP : Swiss plants (BWRs and PWRs) Use of Chernobyl consequences Cost factors : health effects and some losses in agricultural production	1.0 – 31.8 Rappen/kWh (1.08 – 34.41 USD-cents/kWh)
Eeckhoudt et al. (2000)	Yes	Use of French accident scenario, ST21 Cost factors : COSYMA	4.60E-02 EUR-cents/kWh
Lee et al. (2013)	Yes	RRA adopted from Eeckhoudt et al.	0.3-203.1 KRW/kWh
Rabl and Rabl (2013)	No	considers Chernobyl accident as a consequence (cost of health effects, cleanup, lost agriculture, etc.)	3.80E-01 EUR-cents/kWh

- Further study that needs to be conducted include estimation of 1) site-specific RRA and 2) site-specific cost factors.
  - Since the degree of risk aversion differs according to various key demographic indices such as education level and economic status, a site-specific RRA that incorporates key demographic characteristics of populations living near NPPs must be considered.

Conclusion

- Risk averse behavior of the public toward group accidents (having low P./high C.)
  - These phenomena of "group accident" implies that there should be "multiplication factor" on estimating the external cost for "group accidents" to reflect the "disaster aversion" behavior.
- This study propose an integrated framework on estimation of the external cost associated with the NPP accident considering public risk aversion behavior:
  - Based on the constructed model, willingness to pay (WTP) of the public for the mortality risk reduction was estimated and derived the value of statistical life (VSL) regarding NPP accident.
  - Based on the expected-utility specification, the theoretical framework to quantify the risk aversion coefficient for the NPP accident was constructed assuming CRRA utility function.
  - As a case study, the risk and economic damages for a hypothetical NPP accident were assessed, and as a result, the multiplication factor and external cost of NPP accident was estimated.
- This study is expected to give insight on external cost estimation of both NPP and other severe accident cases of various energy sectors with consideration of public risk aversion behavior.
- The issues for further study to realistically estimate external cost of NPP accident includes:
  - Site-specific RRA considering demographics of populations living near NPPs must be considered.
  - Since only the direct cost factors were considered in a case study, potential extensions on including the indirect cost factors to the external cost will be investigated in the future study.

Thank you

Appendix I.

- To derive the degree of WTP and RRA by the characteristics of the respondents which may affect each specified likelihood function, heterogeneity in both WTP and RRA was allowed.
  - In this study, four demographic variables and six explanatory variables were used as covariates in the constructed likelihood model to examine the sensitivity of WTP and RRA to each variable.

Table I. 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 ener gy 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~)

Appendix II.

Table II. 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.

Appendix III.

Table III. External cost factors for NPP accident considered in the case study and their estimates

Cost categories		Estimates
Direct cost	Cost of evacuation/relocation 1)	4.00E+03$/person (FEMA, 2007)
	Loss of income for people unable to reach the workplace 2)	Evac./relocated : 1.11E+04 $/person * Not evac./relocated : 1.85E+03 $/person **
	Lost capital value and investment on land and property. 3)	Evac./relocated : 3.62E+04 $/person Not evac./relocated : 0 $/person
	Cost of fatal health (cancer fatality) effect 4)	2.78E+06 $/person
	Cost of non-fatal health (cancer injury) effect 5)	6.78E+03 $/person (Kim et al., 2009)

1) Reimbursement cost for hurricane Katrina evacuee (including forced relocation cost, food stamp, welfare programs, etc.)

2) Compensation of economic and social loss (e.g. business loss, loss of income due to joblessness)

* 1/2 year amount of GNI*** : 6 months of "disaster unemployment assistance" is assumed to be provided for those who have evacuated from high radioactive contamination zone around NPP site (Lerner, 2014)

** 1 month amount of GNI*** : In case of TMI accident(resulted in low radioactive contamination around NPP site), 98% of the population near by NPP had returned to their normal activities within three weeks. (Cutter, 1982)

***GNI per person (of Korea Rep.) = 28739 $/person-year (KOSTAT 2010)

3) Calculated as Average capita per person * Ratio of real estate property (75.8%) * Ratio of property first-owner (57.7%) (KOSTAT, 2010)

4) Estimated value of statistical life in this study (KRW 2.53E+09)

5) Medical care cost(Inpatient + Outpatient) + Non-medical care cost(Transportation + Caregiver time + CAM)

Appendix IV.

- Kim, Tae Woon, et al. *A Comparison Study on the Integrated Risk Estimation for Various Power Systems*. KAERI/RR-2513/2004, Korea Atomic Energy Research Institute (KAERI), Daejeon (Korea, Republic of), 2007.
  - "경수로형 및 중수로형 원전 모두 가장 큰 리스크 값을 나타내는 방사선원 방출군인 STC-19와 STC-8의 주요 초기사건은 증기발생기 세관파손 사고(SGTR)이다."

표 47 울진 3,4호기의 방사선원 방출군 특성

STC No.	지배적인 초기사건	격납건물 파손 형태	중대사고 발생빈도 (/년)
1	Large LOCA	Core melt stopped before Reactor Vessel failure	4.87e−5
2	Loss of Feedwater	Reactor Vessel failed, Containment do not failed	1.44e−5
3	Loss of Feedwater	Early Containment failure, Leak	1.71e−7
4	Small LOCA	Early Containment failure, Rupture	5.39e−8
6	Small LOCA	Late Containment failure, Leak	1.71e−6
7	N/A	Late Containment failure, Leak	6.57e−9
8	Station Blackout	Late Containment failure, Leak	1.60e−6
10	Small LOCA	Late Containment failure, Leak, Rupture	8.58e−8
11	N/A	Late Containment failure, Leak, Rupture	2.19e−9
12	Station Blackout	Late Containment failure, Leak, Rupture	7.87e−7
13	Loss of Feedwater	Basemat Melt−throough	1.22e−6
14	Loss of Feedwater	Alpha mode failure	3.22e−8
15	Large LOCA	Containment failure before RV failure	6.05e−7
16	Large LOCA	Isolation Failure	1.18e−8
17	Large LOCA	Isolation Failure	1.97e−8
18	V−sequence	V−sequence (Bypass)	1.20e−9
19	SGTR	Steam Generator Tube Rupture (Bypass)	1.43e−6

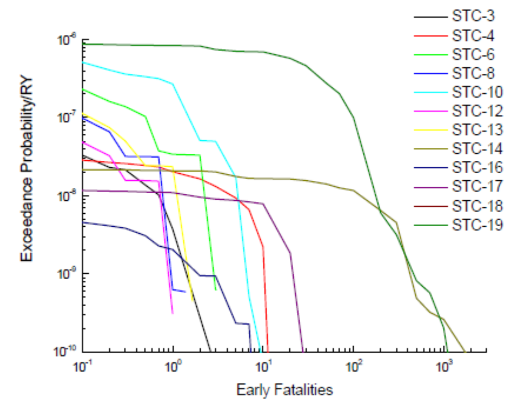


그림 38 울진 3,4호기 원전에 대한 방사선원 방출군별 조기사망 리스크

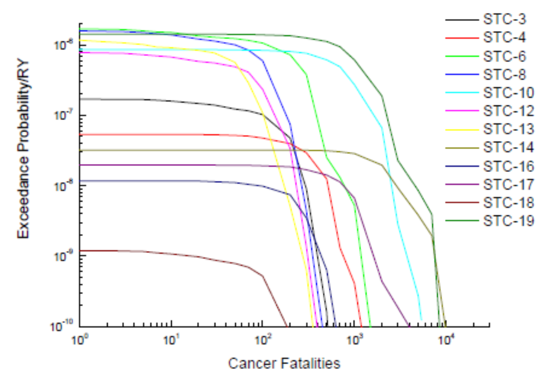


그림 40 울진 3,4호기 원전에 대한 방사선원 방출군별 암사망 리스크

Appendix V.

- External cost estimation of NPP accident in Lee et al. (2013)
  - "… '원자력손해배상법'은 원자력사업자의 제3자 손해배상한도를 3억 SDR로 제한하고 있으며, …, 보험가액을 부지당 500억원으로 제한하고 있어, … 원자력발전사업자의 손해배상책임제한을 정부의 암묵적인 보조금으로 보고 이를 추정하는 연구가 미국, 캐나다, 프랑스에 대해 각각 시도된바 있다. 이들 연구의 공통적인 접근법인 현행 보험료 데이터를 이용하여 원전사고 발생확률(모형)을 추정하고, 이를 이용하여 원전사업자의 배상책임제한이 원전사업자에게 주는 암묵적 보조금을 추산하였다.

표 4-3. 원전사고의 기대피해비용

중대사고 피해비용 \ 발생확률		$\frac{1}{7,000}$	$\frac{1}{1,000,000}$
100조 원	금액(억 원)	203.6	14.0
	단가(원/kWh)	2.2	0.1
500조 원	금액(억 원)	956.4	61.0
	단가(원/kWh)	10.2	0.6

표 4-10. 위험회피 성향을 반영한 외부비용

중대사고 피해비용 \ 발생확률		$\frac{1}{7,000}$	$\frac{1}{1,000,000}$
100조 원	금액(억 원)	4,073.2	279.3
	단가(원/kWh)	43.2	3.0
500조 원	금액(억 원)	19,128.5	1,219.9
	단가(원/kWh)	203.1	13.0

Appendix VI.

- T-statistics: 선형 회귀분석에서 각 공변량의 회귀계수에 대한 유의성 검정에 이용
- Wald-statistics : 로지스틱 회귀모형에서 각 회귀계수의 유의성 검정에 사용 (follows chi-square distribution)

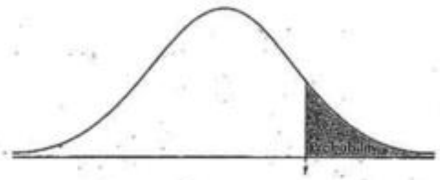


TABLE B: t-DISTRIBUTION CRITICAL VALUES

	Tail probability p											
df	.25	.20	.15	.10	.05	.025	.02	.01	.005	.0025	.001	.0005
1	1.000	1.376	1.963	3.078	6.314	12.71	15.89	31.82	63.66	127.3	318.3	636.6
2	.816	1.061	1.386	1.886	2.920	4.303	4.849	6.965	9.925	14.09	22.33	31.60
3	.765	.978	1.250	1.638	2.353	3.182	3.482	4.541	5.841	7.453	10.21	12.92
4	.741	.941	1.190	1.533	2.132	2.776	2.999	3.747	4.604	5.598	7.173	8.610
5	.727	.920	1.156	1.476	2.015	2.571	2.757	3.365	4.032	4.773	5.893	6.869
6	.718	.906	1.134	1.440	1.943	2.447	2.612	3.143	3.707	4.317	5.208	5.959
7	.711	.896	1.119	1.415	1.895	2.365	2.517	2.998	3.499	4.029	4.785	5.408
8	.706	.889	1.108	1.397	1.860	2.306	2.449	2.896	3.355	3.833	4.501	5.041
9	.703	.883	1.100	1.383	1.833	2.262	2.398	2.821	3.250	3.690	4.297	4.781
10	.700	.879	1.093	1.372	1.812	2.228	2.359	2.764	3.169	3.581	4.144	4.587
11	.697	.876	1.088	1.363	1.796	2.201	2.328	2.718	3.106	3.497	4.025	4.437
12	.695	.873	1.083	1.356	1.782	2.179	2.303	2.681	3.055	3.428	3.930	4.318
13	.694	.870	1.079	1.350	1.771	2.160	2.282	2.650	3.012	3.372	3.852	4.221
14	.692	.868	1.076	1.345	1.761	2.145	2.264	2.624	2.977	3.326	3.787	4.140
15	.691	.866	1.074	1.341	1.753	2.131	2.249	2.602	2.947	3.286	3.733	4.073
16	.690	.865	1.071	1.337	1.746	2.120	2.235	2.583	2.921	3.252	3.686	4.015
17	.689	.863	1.069	1.333	1.740	2.110	2.224	2.567	2.898	3.222	3.646	3.965
18	.688	.862	1.067	1.330	1.734	2.101	2.214	2.552	2.878	3.197	3.611	3.922
19	.688	.861	1.066	1.328	1.729	2.093	2.205	2.539	2.861	3.174	3.579	3.883
20	.687	.860	1.064	1.325	1.725	2.086	2.197	2.528	2.845	3.153	3.552	3.850
21	.686	.859	1.063	1.323	1.721	2.080	2.189	2.518	2.831	3.135	3.527	3.819
22	.686	.858	1.061	1.321	1.717	2.074	2.183	2.508	2.819	3.119	3.505	3.792
23	.685	.858	1.060	1.319	1.714	2.069	2.177	2.500	2.807	3.104	3.485	3.768
24	.685	.857	1.059	1.318	1.711	2.064	2.172	2.492	2.797	3.091	3.467	3.745
25	.684	.856	1.058	1.316	1.708	2.060	2.167	2.485	2.787	3.078	3.450	3.725
26	.684	.856	1.058	1.315	1.706	2.056	2.162	2.479	2.779	3.067	3.435	3.707
27	.684	.855	1.057	1.314	1.703	2.052	2.158	2.473	2.771	3.057	3.421	3.690
28	.683	.855	1.056	1.313	1.701	2.048	2.154	2.467	2.763	3.047	3.408	3.674
29	.683	.854	1.055	1.311	1.699	2.045	2.150	2.462	2.756	3.038	3.396	3.659
30	.683	.854	1.055	1.310	1.697	2.042	2.147	2.457	2.750	3.030	3.385	3.646
40	.681	.851	1.050	1.303	1.684	2.021	2.123	2.423	2.704	2.971	3.307	3.551
50	.679	.849	1.047	1.299	1.676	2.009	2.109	2.403	2.678	2.937	3.261	3.496
60	.679	.848	1.045	1.296	1.671	2.000	2.099	2.390	2.660	2.915	3.232	3.460
80	.678	.846	1.043	1.292	1.664	1.990	2.088	2.374	2.639	2.887	3.195	3.416
100	.677	.845	1.042	1.290	1.660	1.984	2.081	2.364	2.626	2.871	3.174	3.390
1000	.675	.842	1.037	1.282	1.646	1.962	2.056	2.330	2.581	2.813	3.098	3.300
∞	.674	.841	1.036	1.282	1.645	1.960	2.054	2.326	2.576	2.807	3.091	3.291
	50%	60%	70%	80%	90%	95%	96%	98%	99%	99.5%	99.8%	99.9%
	Confidence level C											

Table entry for p is the point (χ^2) with probability p lying above it.

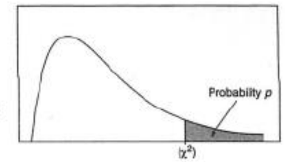


TABLE C χ^2 Critical Values

	TAIL PROBABILITY P											
df	.25	.20	.15	.10	.05	.025	.02	.01	.005	.0025	.001	.0005
1	1.32	1.64	2.07	2.71	3.84	5.02	5.41	6.63	7.88	9.14	10.83	12.12
2	2.77	3.22	3.79	4.61	5.99	7.38	7.82	9.21	10.60	11.98	13.82	15.20
3	4.11	4.64	5.32	6.25	7.81	9.35	9.84	11.34	12.84	14.32	16.27	17.73
4	5.39	5.99	6.74	7.78	9.49	11.14	11.67	13.28	14.86	16.42	18.47	20.00
5	6.63	7.29	8.12	9.24	11.07	12.83	13.39	15.09	16.75	18.39	20.51	22.11
6	7.84	8.56	9.45	10.64	12.59	14.45	15.03	16.81	18.55	20.25	22.46	24.10
7	9.04	9.80	10.75	12.02	14.07	16.01	16.62	18.48	20.28	22.04	24.32	26.02
8	10.22	11.03	12.03	13.36	15.51	17.53	18.17	20.09	21.95	23.77	26.12	27.87
9	11.39	12.24	13.29	14.68	16.92	19.02	19.68	21.67	23.59	25.46	27.88	29.67
10	12.55	13.44	14.53	15.99	18.31	20.48	21.16	23.21	25.19	27.11	29.59	31.42
11	13.70	14.63	15.77	17.28	19.68	21.92	22.62	24.72	26.76	28.73	31.26	33.14
12	14.85	15.81	16.99	18.55	21.03	23.34	24.05	26.22	28.30	30.32	32.91	34.82
13	15.98	16.98	18.20	19.81	22.36	24.74	25.47	27.69	29.82	31.88	34.53	36.48
14	17.12	18.15	19.41	21.06	23.68	26.12	26.87	29.14	31.32	33.43	36.12	38.11
15	18.25	19.31	20.60	22.31	25.00	27.49	28.26	30.58	32.80	34.95	37.70	39.72
16	19.37	20.47	21.79	23.54	26.30	28.85	29.63	32.00	34.27	36.46	39.25	41.31
17	20.49	21.61	22.98	24.77	27.59	30.19	31.00	33.41	35.72	37.95	40.79	42.88
18	21.60	22.76	24.16	25.99	28.87	31.53	32.35	34.81	37.16	39.42	42.31	44.43
19	22.72	23.90	25.33	27.20	30.14	32.85	33.69	36.19	38.58	40.88	43.82	45.97
20	23.83	25.04	26.50	28.41	31.41	34.17	35.02	37.57	40.00	42.34	45.31	47.50
21	24.93	26.17	27.66	29.62	32.67	35.48	36.34	38.93	41.40	43.78	46.80	49.01
22	26.04	27.30	28.82	30.81	33.92	36.78	37.66	40.29	42.80	45.20	48.27	50.51
23	27.14	28.43	29.98	32.01	35.17	38.08	38.97	41.64	44.18	46.62	49.73	52.00
24	28.24	29.55	31.13	33.20	36.42	39.36	40.27	42.98	45.56	48.03	51.18	53.48
25	29.34	30.68	32.28	34.38	37.65	40.65	41.57	44.31	46.93	49.44	52.62	54.95
26	30.43	31.79	33.43	35.56	38.89	41.92	42.86	45.64	48.29	50.83	54.05	56.41
27	31.53	32.91	34.57	36.74	40.11	43.19	44.14	46.96	49.64	52.22	55.48	57.86
28	32.62	34.03	35.71	37.92	41.34	44.46	45.42	48.28	50.99	53.59	56.89	59.30
29	33.71	35.14	36.85	39.09	42.56	45.72	46.69	49.59	52.34	54.97	58.30	60.73
30	34.80	36.25	37.99	40.26	43.77	46.98	47.96	50.89	53.67	56.33	59.70	62.16
40	45.62	47.27	49.24	51.81	55.76	59.34	60.44	63.69	66.77	69.70	73.40	76.09
50	56.33	58.16	60.35	63.17	67.50	71.42	72.61	76.15	79.49	82.66	86.66	89.56
60	66.98	68.97	71.34	74.40	79.08	83.30	84.58	88.38	91.95	95.34	99.61	102.7
80	88.13	90.41	93.11	96.58	101.9	106.6	108.1	112.3	116.3	120.1	124.8	128.3
100	109.1	111.7	114.7	118.5	124.3	129.6	131.1	135.8	140.2	144.3	149.4	153.2

Appendix VI.

- IAEA PRIS database
  - Statistics of electricity supplied by NPP at Korea in 2013.
  - Mean annual electricity production = 132465.24GWh-reactor/23reactor = 5759.36GWh ~ 5.76E+09 kWh

Electricity Supplied

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INDIA	21	30008.52
IRAN, ISLAMIC REPUBLIC OF	1	3893.67
JAPAN	50	13947.00
KOREA, REPUBLIC OF	23	132465.24

ISO Code	Unit	Type	Model	RUP [MWe]	Electricity Supplied [GWh]
KR	HANBIT-1	PWR	WH F	960	6911.44
KR	HANBIT-2	PWR	WH F	958	6277.11
KR	HANBIT-3	PWR	OPR-1000	997	4719.06
KR	HANBIT-4	PWR	OPR-1000	997	7563.57
KR	HANBIT-5	PWR	OPR-1000	997	8191.47
KR	HANBIT-6	PWR	OPR-1000	995	8531.74
KR	HANUL-1	PWR	France CPI	960	7233.32
KR	HANUL-2	PWR	France CPI	962	7446.49
KR	HANUL-3	PWR	OPR-1000	994	8731.76
KR	HANUL-4	PWR	OPR-1000	998	3307.10
KR	HANUL-5	PWR	OPR-1000	996	7476.53
KR	HANUL-6	PWR	OPR-1000	996	8716.35
KR	KORI-1	PWR	W △60	576	2515.74
KR	KORI-2	PWR	WH F	639	4501.64
KR	KORI-3	PWR	WH F	1011	8861.52
KR	KORI-4	PWR	WH F	1010	6681.28
KR	SHIN-KORI-1	PWR	OPR-1000	1000	2328.10
KR	SHIN-KORI-2	PWR	OPR-1000	1000	3560.31