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Measuring Nuclear Power Plant Negative Externalities through the Life Satisfaction Approach: The Case of Ulsan City†

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We have hypothesized that nuclear risk is significantly inversely related to the distance from residences to nuclear power plants and that the level of life satisfaction of residents therefore increases with the distance. We empirically explore the relationship between Ulsan citizens' life satisfaction levels and the distance between their residences and the Kori and Wolsong nuclear power plants (NPP) based on the life satisfaction approach (LSA). The dataset we used covers only Ulsan citizens from the biennial Ulsan Statistics on Citizen's Living Condition and Consciousness of 2014 and 2016. Controlling for micro-variables such as education, work satisfaction, gender, marital status, and expenditures, we found a statistically significant relationship between life satisfaction and the distance between the residences and the nuclear power plants. Nuclear negative externalities including (i) health and environmental impact, (ii) radioactive waste disposal, and (iii) the effect of severe accidents can be quantified in terms of LS units and monetary units. We were able to calculate the monetary value of NPP externalities at $277 per kilometer of distance for Kori and $280 per kilometer of distance for Wolsong at constant 2015 prices. These estimates are quite different from the traditional estimates made with the contingent valuation method, whereas they are similar to the findings of LSA studies abroad. Hence, the need to adopt the LSA in South Korea and policy implications are demonstrated.

Key Word: Negative Nuclear Externalities, Nuclear Risk, Life Satisfaction Approach, Non-market valuation, Nuclear Power Plants, South Korea
JEL Code: D61, H43, L94, Q41

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I. Introduction

The purpose of this paper is to analyze negative externalities related to Kori and Wolsong nuclear power plants (NPPs) using life satisfaction data as a proxy for the utilities. While nuclear energy generation offers the advantages of energy security, an absence of air pollution, marginal greenhouse gas emissions and low operating costs, there are also negative externalities for our health, the environment, and for property values. Such NPP negative externalities are geographically concentrated near nuclear power plants, while the benefits accrue for the population in general. In the past, NPP analyses took into consideration mainly positive externalities while neglecting to factor negative externalities into the analyses for a proper comparison with other sources of energy.

There Likewise, although shallow analyses have often mistakenly concluded that coal energy is the most economic energy source, these analyses have not considered a variety of hidden costs related to coal-powered plants borne by society as a whole (Amerasinghe, 2011). Failure to internalize the externalities of coal energy means that energy investment analyses have instead used distorted market prices. If this inadequate reflection of external costs continues in energy investment analyses, it will have detrimental effects on the global climate, environment, and efficient optimization of social wellbeing. To date, most governments have considered explicit internal costs but have not taken into account external costs in their energy sector investment decisions.

To correct market price distortions, appropriate analyses should capture the external costs associated with generating electricity from a given source as much as possible. Therefore, this study applies the life satisfaction quantitative approach to an economic analysis of the external costs and benefits associated with investment in nuclear energy sources in South Korea. This study, as far as we know, is the first in South Korea to use the life satisfaction approach to measure NPP negative externalities.

In an economy with resource constraints in general, all governments, both developed and developing, have adopted a public investment appraisal system to assess the rate of return of competing investment operations and maximize the net benefits of chosen investment opportunities. Traditionally, they consider only explicit internal costs and benefits while using market prices. However, distortions in market prices have become even clearer due to market imperfections, leading to increased government interventions in the market to correct market distortions or to achieve various policy objectives, such as redressing inequities and protecting the poor and/or the environment.

Therefore, both academics and public policy makers have realized the need to make, in parallel with financial assessments, economic analyses of proposed investment operations, using shadow prices. Currently it is standard practice for both governments in advanced countries and international development organizations to carry out financial and economic analyses of proposed investment operations and make the results available to policy makers. Such analyses have long covered mainly explicit internal costs and benefits and have included only qualitative assessments of externalities.

As concerns over environmental protection and adjustments to global climate change have become serious, both academics and policy practitioners have made creative efforts to internalize externalities, especially negative externalities, in their economic analysis framework in general (National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 1993).

More specifically, in conjunction with the 2016 agreements on the Sustainable Development Goals (SDGs) for 2030 at the UN and on sustainable environmental protection measures against global climate changes at Paris, both developed and developing countries have made adjustments to their future energy policies, enacting favorable trade-offs between different sources of energy. South Korea was no exception. Earlier conservative governments and the new liberal government that started in 2017 established or revised their long-term energy supply plans. However, greater government investment in a specific source of power relative to other sources of energy has had a significant impact on growth of the economy overall and on the wellbeing of society. Therefore, greater government investment in a specific source of energy should be determined in consideration of not only explicit internal costs and benefits but also the implicit external costs and benefits of different sources of energy. This approach will enable the government to choose a better investment opportunity that creates more net benefits and greater wellbeing for the economy than other options.

This study assumes that people's disutility from nuclear risk decreases (i.e., the level of life satisfaction increases) with the distance between one's residence and an NPP, as people in general prefer to be distant from NPP risks assuming all other factors are equal. Therefore, the greater the income is, the greater the distance between the residence and NPP risks becomes. By measuring the marginal utility of income and the marginal disutility of the Kori and Wolsong NPPs, the trade-off ratio between income and distance between the residence and NPP externalities, while maintaining the same level of life satisfaction, can be calculated in monetary terms (Frey *et al*., 2009), enabling us to estimate the negative externalities of NPPs.

The rest of this paper is structured as follows: this study initially defines the meaning and scope of the externalities of NPPs for this study. Secondly, it reviews previous studies through a literature review. Thirdly, it applies the life satisfaction approach to the Ulsan Metropolitan City with the introduction of the conceptual and empirical backgrounds to clarify the life satisfaction approach and to describe the Wolsong and Kori NPPs and the neighboring Ulsan districts. The study then elaborates on the method and strategy of the empirical analysis and discusses the empirical analysis results. Finally, the study summarizes the main findings of the analysis and discusses the policy implications of its findings.

II. Definition of Nuclear Externalities in this Paper

Ea Energy Analyses (2008) identifies, as the major elements of external costs, possible nuclear accidents and radioactive waste disposal and storage. Moreover, the Nuclear Energy Agency (NEA) also defines external costs as future financial liabilities due to (1) the decommissioning and dismantling of nuclear facilities, (2) the health impact and general impact of the radioactivity diffused during the operation of plants, and (3) spent fuel and effects of severe accidents (NEA, 2003). On the other hand, positive nuclear externalities also exist. They are, for example, security of the energy supply, cost stability, and declines in other pollutant gases due to the replacement of other sources of electricity by NPPs. However, these positive externalities have been studied, and the results indicate that positive externalities are not a major cause of price distortions (OECD/NEA, 2003).

Thus, this study not only disregards the positive externalities of NPPs but also does not take into account factors such as policy costs borne by the society that finances nuclear energy R&D, NPP neighboring community support, public acceptance, and government-funded nuclear related institutions. In sum, in this paper, nuclear externalities refer to (i) health and environmental impacts, (ii) radioactive waste disposal, and (iii) the effects of severe accidents that can be quantified in terms of LS units and monetary units, as we assume that these negative externalities are generally recognized by the citizens in Ulsan as factors affecting their life satisfaction levels.

III. Data and Estimation Strategy

In this section we review previous studies related to the measurement of nuclear externalities. In particular, this review focuses on not only the limitation of previous studies but also on the relative merits of the Life Satisfaction Approach.

In economics, literature on methods pertaining to how people value the environment can be categorized largely into three groups: (1) revealed preference methods such as the Hedonic Method (HM), (2) stated preference methods such as the Contingent Valuation Method (CVM), and (3) the Life Satisfaction Approach (LSA).

A. *Revealed Preference Methods (the HM)*

The Hedonic Method (HM), a typical example of a revealed preference method, has been widely used in research on environment evaluations. Since externalities have an impact on the differentiated market goods of housing and jobs, the housing and labor markets, as a result, reflect externalities. Wage and rent differentials serve as implicit prices and correspond in equilibrium to individuals' marginal willingness to pay for a public good (Rosen 1974). Yamane *et al*. (2013) studied property values around the Fukushima-Daiichi plant, which decreased with an increase in the level of local nuclear contamination, but not with proximity to the plant. Fink and Stratmann (2013) found no change in property prices relative to proximity to NPPs in the US, whereas Bauer *et al*. (2017) found that house prices near NPPs in Germany dropped by up to 11%.

The inconsistent results of HM studies stem from the assumption of hedonic locational equilibrium, i.e., that the housing and labor markets are perfectly in equilibrium. This assumption is justified only (a) when households have a high degree of information, (b) when there is a sufficiently wide variety of houses and jobs available, (c) when prices adjust rapidly, (d) when transaction and moving costs are low, and (e) when there are no market restrictions (Freeman 2003, p. 366), all of which cannot be readily satisfied in the real economy. In short, the HM yields biased results if housing and labor markets are not in equilibrium (Frey, 2009).

B. *Stated Preference Methods (the CVM)*

Many studies have attempted to measure the risk of nuclear power plants based on Contingent Valuation Methods (CVM), a typical type of stated preference method. Respondents are asked to value a specific public good under well-specified conditions of contingent markets (Carson *et al*. 2003). Lee and Kang (2016) assessed the statistical value of life based on the CVM in consideration of risk aversion to calculate the externalities of NPPs in South Korea. Approximately 1,550 participants answered hypothetical choice decision questions. The researchers argued that the estimated external cost of an NPP accident represents about 0.13% of the unit electricity generation cost of a NPP (or $0.00439/MWh) in South Korea.

In 2013, the Korea Environment Institute (KEI) measured NPP externalities by asking 1,000 respondents questions based on two survey designs. The first survey design asked about people's willingness to pay (WTP) for mitigating nuclear accident risk in general. Based on the results of this survey, KEI argued that NPP externalities for general nuclear risk range from $4.18 to $6.93/MWh. In the second survey design, people were asked about their WTP for avoiding the construction of NPPs in their neighborhood. Interestingly, the WTP for avoiding the construction of NPPs in close proximity is much higher than the nuclear risk in general ($57.31 to $104.39/MWh).

The CVM has an advantage that it does not require the goods or labor markets to be in hedonic locational equilibrium. However, the hypothetical nature of CVM survey questions and unfamiliarity with the task often lead to superficial answers and symbolic valuations (Kahneman *et al*. 1999) because most people are unfamiliar with assigning monetary value to nuclear risk, which is characterized as extremely high risk at an extremely low frequency. As a result, the CVM may not adequately represent the true value of nuclear risk due to information bias that arises when respondents are forced to value attributes with which they have little or no experience. Symbolic valuation in the form of attitudes, expressions, and superficial answers is likely to bias results (Frey 2004). Further, strategic behavior in the case of NPPs is more likely to bias the results of the CVM than it is with other projects, as the benefits of NPPs are diffused among many people, whereas the costs of NPPs are concentrated among a few people. Moreover, the majority of survey respondents are not residents in proximity to NPPs. Accordingly, bipolarized attitudes towards NPPs change the results of surveys depending on the structure of the survey questionnaires.

C. *Life Satisfaction Approach*

The Life Satisfaction Approach (LSA) is a complementary evaluation method that obviates the inherent problems with the CVM and HM (Frey *et al*. 2009). Because the LSA does not rely on the hedonic equilibrium assumption, it can avoid the biased results of the HM. Further, in the LSA, respondents are required not to value hypothetical NPP risk directly but to assess their life satisfaction levels with some degree of precision. In fact, people may not consciously notice that there is a relationship between an environmental condition such as NPP risk and their subjective well-being. The connection between life satisfaction and an environmental condition such as NPP risk is made ex-post by the researcher. Because the LSA requires fewer cognitive tasks and does not elicit strategic behavior, it negates the biased hypothetical nature of the CVM (Frey, 2009).

Although LSA has been applied to environmental programs and projects extensively abroad, it is not often applied to NPP externalities intensively. However, when Welsch and Biermann (2016) studied measuring nuclear power plant externalities in Switzerland, they found a significantly positive relationship between life satisfaction levels and greater distances from NPPs. In their research, they argued that living 1 km farther away from the nearest NPP is worth 0.5% of equalized disposable income, corresponding to $305 as of 2015. Because both the HM and the CVM have corresponding limitations, the LSA complements conventional methods of evaluating NPP externalities. This paper contributes to measuring NPP externalities by applying LSA for the first time in South Korea.

IV. Empirical Study of the Case of Ulsan City

A. *Conceptual Model and Assumptions*

In economics, a consumer's indirect utility function $u = v(p, w)$ shows that the consumer's utility u is a function of vector p of goods prices and the amount of income w. Given a person's income, as a consumer he/she chooses an affordable bundle of housing and a numeraire that maximizes his/her utility. The total expenditure cannot exceed income. Based on the utility maximization function, people realize their highest utility by optimizing their income to buy marketable goods at a given rent with regard to housing and perceived nuclear risk. Thus, the utility maximization function of an individual with personal characteristics denoted by θ takes the following form:

(1) $$u = v(I, NR, \theta)$$

In this formulation, u denotes life satisfaction (utility), I denotes income, and NR represents nuclear risk. This study expects that the sign of the coefficients for I is positive, whereas NR is negative. Percieved nuclear risk is divided into two factors. NR takes the following form:

(2) $$NR = D * \pi$$

In this formulation, D denotes expected damages associated with a nuclear accident, whereas π denotes the probability of being affected by an accident (Welsch *et al.*, 2009; 2016). This study assumes that expected damages decrease in proportion to the distance from the nearest NPP. Therefore, this specification indicates that risk-averse people and those who are pessimistic about nuclear energy are more likely to choose residences further away from NPPs. Therefore, on the basis of the assumptions for equation (2), equation (1) can be expressed as follows:

$$u = V\left(I, \text{distance}, \theta\right) \tag{1'}$$

In this formulation, individual life satisfaction depends on income I, the distance to NPPs, and a set θ of micro-level determinants of the LS. Ferrer-i-Carbonell and Frijters (2004) and many others argue that treating life satisfaction as ordinal or cardinal and applying the corresponding estimation methods have little effect on qualitative results.

B. *Empirical Background*

In 2016, a total gross capacity of 21.6 GWe is installed in the 24 operating NPPs in South Korea, consisting of 20 pressurized water reactors (PWRs) and four CANDU pressurized heavy water reactors (PHWRs). Table 1 shows the status of the NPPs in South Korea.

Out of 24 operating NPPs, 12 NPPs are located in the areas around Ulsan districts. Moreover, six additional NPPs in Kori are expected to enter operation in the near future. According to the research (SEDAC, 2015), Kori and Wolsong are

TABLE 1—NUCLEAR POWER REACTORS OPERATING IN SOUTH KOREA

S/N	Name	Reactor	Capacity (MWe)	Commercial Start	Planned Close
1	Kori 1	PWR	576	29.04.1978	2017
2	Wolsong 1	CANDU	645	22.04.1983	2022 or 2023
3	Kori 2	PWR	639	25.07.1983	2023
4	Kori 3	PWR	1,003	30.09.1985	2025
5	Kori 4	PWR	1,001	29.04.1986	
6	Hanbit 1 (YG)	PWR	958	25.08.1986	
7	Hanbit 2 (YG)	PWR	953	10.06.1987	
8	Hanul 1 (UC)	PWR	960	10.09.1988	
9	Hanul 2 (UC)	PWR	962	30.09.1989	
10	Hanbit 3 (YG)	System 80	998	31.03.1995	
11	Hanbit 4 (YG)	System 80	997	01.01.1996	
12	Wolsong 2	CANDU	653	01.07.1997	
13	Wolsong 3	CANDU	675	01.07.1998	
14	Hanul 3 (UC)	KSNP	994	11.08.1998	
15	Wolsong 4	CANDU	679	01.10.1999	
16	Hanul 4 (UC)	KSNP	998	31.12.1999	
17	Hanbit 5 (YG)	KSNP	988	21.05.2002	
18	Hanbit 6 (YG)	KSNP	995	24.12.2002	
19	Hanul 5 (UC)	KSNP	996	29.07.2004	
20	Hanul 6 (UC)	KSNP	996	22.04.2005	
21	Shin Kori 1	OPR-1000	996	28.02.2011	
22	Shin Kori 2	OPR-1000	993	20.07.2012	
23	Shin Wolsong 1	OPR-1000	991	31.07.2012	
24	Shin Wolsong 2	OPR-1000	1,050	24.07.2015	

Source: Korea Hydro Nuclear Power Website (2017).

ranked the first and third in terms of population exposure at 30km to the NPPs among mega-NPPs globally (a mega-NPP is defined as a site containing more than six NPPs). Kori has 3.4 million and Wolsong has 1.3 million citizens within 30km to the NPPs. In fact, it is safe to say that the citizens of Ulsan are completely besieged by mega-NPPs, as illustrated in Figure 1. Moreover, the citizens of Ulsan are exposed to nuclear waste because spent fuel is stored at the NPPs, as South Korea has yet to allocate funding for fuel storage sites. As a result, any disutility from the presence of NPPs includes the disutility from nuclear waste disposal.

In South Korea, issues related to NPPs are seriously discussed and broadcast by media, meaning that people are well aware of the exact locations of NPPs and any possible health and property risks associated with the NPPs. According to a future population trend survey taken in 2017, Ulsan's population in 1973 was 469,631, whereas Ulsan's population in 2017 was 1,165,646. Therefore, most survey respondents are assumed to have chosen their residences after the construction and commissioning of the NPPs, as the Kori and Wolsong NPPs have been operating since 1978 and 1983, respectively.

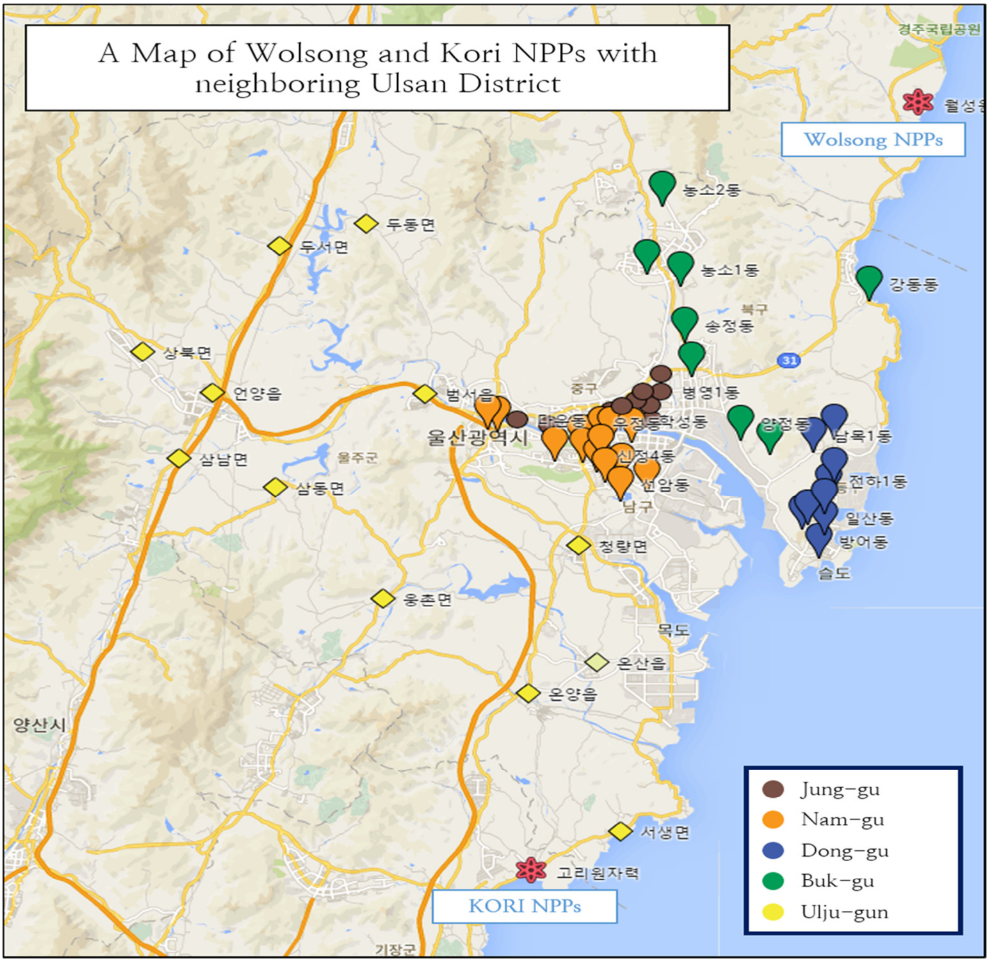

FIGURE 1. A MAP OF WOLSONG AND KORI NPPS WITH NEIGHBORING ULSAN DISTRICTS

C. *Estimation Method and Strategy*

NPP externalities can be measured using the first derivative of V with respect to distance (Equation 1'). The coefficient of distance from utility is assumed to be positive when income and individual characteristics are controlled. A change in the nonmarket good of $\Delta\text{distance}$ is valued by ΔI (corresponding to an implicit WTP) if the LS is constant. For a marginal change of distance, the marginal WTP can be derived when the derivative of LS = 0 (Mankiw, 2014)

$$\text{MWTP}=\frac{-\partial\text{income}}{\partial\text{distance}} \tag{3}$$

To calculate the cost of externalities of nuclear power plants, this study utilizes the Life Satisfaction Approach (LSA), especially in relation to equation (1'), as follows:

$$\begin{aligned}\text{LS}_i &= \alpha+\beta_1\ln\text{income}_i+\beta_2\text{distanceWolsong}_i \\ &\quad +\beta_3\text{distanceKori}_i+\delta\theta i+\varepsilon_i\end{aligned} \tag{4}$$

Here, LS is the life satisfaction index, θ denotes the socio-demographic characteristics (age, religion, work satisfaction, sex, marriage, and education), and ε_i is an error term. This study assumes that the self-reported life satisfaction of individual i depends on one's income; distance to NPPs; and micro-variables such as work satisfaction, monthly expenditures, education level, marital status, gender, and other related factors.

Based on Roy's identity, the marginal WTP for nuclear risk can be calculated as shown below.

<u>Stage 1: Partial derivative of life satisfaction with respect to distance</u>

$$\begin{aligned}&\frac{\partial LS}{\partial\text{distanceNPP1}} \\ &=\frac{\partial}{\partial\text{distanceNPP1}}\left(\alpha+\beta_1\ln\text{income}_i+\beta_2\text{distanceNPP1}_i+\beta_3\text{distanceNPP2}_i+\delta\theta_i+\varepsilon_i\right) \\ &=\beta_2\end{aligned} \tag{5}$$

By estimating β_2, the impact of the nuclear distance on life satisfaction can be measured.

Stage 2: Partial derivative of life satisfaction with respect to income

$$\frac{\partial LS}{\partial \text{income}} = \frac{\partial}{\partial \text{income}}\left(\alpha + \beta_1 \ln \text{income}_i + \beta_2 \text{distanceNPP1}_i + \beta_3 \text{distanceNPP2}_i + \delta\theta_i + \varepsilon_i\right) = \frac{\beta_1}{\text{income}} \quad (6)$$

By estimating β_1, the impact of income on life satisfaction can be measured.

Stage 3: Calculating marginal willingness to pay for distance

$$\text{MWTP} = \frac{-\partial \text{income}}{\partial \text{distance}} = \frac{\beta_2}{\frac{\beta_1}{\text{income}}} = \frac{\beta_2}{\beta_1} * \text{income} \quad (7)$$

In stage 3, the marginal WTP can be calculated when the derivative of life satisfaction is equal to zero.

Stage 4: Calculating the average marginal willingness to pay for distance

$$\text{Average marginal willingness to pay for distance} = \frac{\beta_2}{\beta_1} * \text{Mean Monthly Income} \quad (8)$$

D. *Data*

The dataset is derived from the biennial Ulsan Statistics on Citizens' Living Conditions and Consciousness in 2014 and 2016. This dataset contains 7,767 observations (0.7% of Ulsan's population) and information about the respondents' levels of life satisfaction. (The index of life satisfaction ranges from 0 = 'totally dissatisfied to 10 = 'totally satisfied' on an 11-point ordinal scale.). It also contains each respondent's address, household income, gender, age, education level, marital status, religion, work satisfaction, and occupation. The dataset does not have information about the distance between the residence and the NPPs, but it does contain detailed addresses of residences, allowing this study to estimate the distance between the residence and Wolsong and Kori NPPs, with corresponding total installed capacities of 4,693MW and 5,208MW, for each respondent. This study also uses the mean income of households from the Ulsan citizen survey, and the average number of persons in households in Ulsan from the South Korea Census in 2015 (Korea Census, 2015).

The dependent variable used to represent utility is the life satisfaction index. As the independent variable of interest, this study uses (a) the distance of each residence from Wolsong, and (b) distance of each residence from Kori. As independent variables, this study also uses (c) household income and (d) the sociodemographic characteristics included in regression (age, work satisfaction, gender, marriage, and education level). In this study, we control for factors that may be correlated with life satisfaction, such as work satisfaction, expenditures, marriage, and education, to avoid endogeneity issues. A set of descriptive statistics pertaining to the data is provided in the Appendix.

E. *Analysis Results*

The results of the estimation of the regression equation (8) are summarized in Table 2. As shown in Table 2, the signs of coefficients are identical and the ratios of the coefficients are similar regardless of whether life satisfaction is treated as ordinal or cardinal.

TABLE 2—RESULTS OF LIFE SATISFACTION REGRESSION – OLS AND ORDERED LOGIT ESTIMATION: WOLSONG AND KORI NPPS

Dependent Variable	OLS				Ordered Logit
	Model 1	Model 2	Model 3	Model 4	
Control Variables	**All included**	Excluding All Distances	Excluding Distance to Kori	Excluding Distance to Wolsong	Adj. Model 1
Log income	**0.212***** **(0.041)**	0.202*** (0.041)	0.209*** (0.041)	0.201*** (0.041)	0.258*** (0.04)
Distance from Wolsong NPPs (DW)	**0.028***** **(0.003)**	-	0.009*** (0.002)	-	0.038*** (0.005)
Distance from Kori NPPs (DK)	**0.028***** **(0.004)**	-	-	0.005 (0.003)	0.036*** (0.006)
Expenditure	**-0.044**** **(0.022)**	0.043** (0.022)	-0.043* (0.022)	-0.044** (0.022)	-0.048 (0.030)
Work Satisfaction	**0.592***** **(0.008)**	0.597*** (0.008)	0.596*** (0.008)	0.597*** (0.008)	0.956*** (0.016)
Male	**-0.099***** **(0.031)**	-0.101*** (0.031)	-0.103** (0.031)	-0.100** (0.032)	-0.155*** (0.043)
Marriage	**-0.074*** **(0.037)**	-0.062* (0.037)	-0.065* (0.037)	-0.063* (0.037)	-0.108* (0.051)
Education	**0.008** **(0.033)**	0.011 (0.034)	0.012 (0.034)	0.009 (0.034)	-0.009 (0.047)
Constant	**-0.127** **(0.263)**	1.251 (0.183)	0.988 (0.197)	1.128 (0.195)	-
Sample Size	**7,767**	7,767	7,767	7,767	7,767
R-squared	**0.4288**	0.4249	0.4258	0.4251	-
Adj. R-squared	**0.4282**	0.4244	0.4253	0.4246	-

Note: Standard errors in parenthesis. The dependent variable is measured on an 11-point life satisfaction scale. ***p<0.01, **p<0.05, *p<0.1

The results of the pooled-OLS estimation of model 1 show that life satisfaction is statistically positively related to income at the 1% significance level, and an increase in income by 1% is likely to increase life satisfaction by 0.21 points. Furthermore, a 1km increase in the distance from Kori or Wolsong is associated with an increase in life satisfaction by 0.028 points on the aforementioned 11-point scale.

For a robustness test of estimation model 1, the impact of income on life satisfaction is tested without considering the distances from the Wolsong and the Kori NPPs in model 2. As compared with Model 1, the coefficient of log income diminishes merely by 0.008, indicating that the impact of income on life satisfaction has a similar value with and without considering the distance from the NPPs in the estimation models, and income and distance independently affect the level of life satisfaction. Likewise, it was whether the distances from the Wolsong NPPs and the Kori NPPs independently affect the life satisfaction level (Models 3 and 4). When only the distance from the Wolsong NPPs is included in the estimation model without controlling for the distance from the Kori NPPs, the coefficient of the distance from the Wolsong decreases sharply compared to Model 1 (Model 3). The same is true when the distance from Kori alone is included in the model as an independent variable without controlling for the distance from the Wolsong NPPs (Model 4). Thus, these distances are inter-related in terms of how they affect the life satisfaction level. Therefore, the two distances should both be included in the estimation model, as in Model 1. Otherwise, the coefficient of the included distance variable will be biased due to the missing variable.

For a robustness test of the multicollinearity issue, this study conducted the Farrar-Glauber test for overall and individual multicollinearity diagnostics. The multicollinearity issue may be suspected in this study because Ulsan is located between the Kori NPPs and the Wolsong NPPs. As a result, it is expected that the correlation between the distance from the Kori NPPs (DK) and the distance from the Wolsong NPPs (DW) is negative. To conduct the test of multicollinearity, this

TABLE 3—IMPLICIT MONETARY VALUE OF NUCLEAR RISK IN RELATION TO INCOME AND DISTANCE

Life Satisfaction with Respect to Income and Distance	Value for Kori	Value for Wolsong	Note
Coefficient of ln income for LS	0.212	0.212	β_1
Coefficient of ln distance (1km) for LS	0.028	0.028	β_2 & β_3
Coefficient of ln distance / Coefficient of ln income for LS	0.1309	0.1323	
Mean Monthly Household Income	5,490*	5,490*	Constant 2015 US Dollar Price
The Average Number of Persons in a Household in Ulsan	2.59	2.59	Population Census in 2015
Individual Income = Household Income Divided by the Number of Family Members	2,116	2,116	Constant 2015 US Dollar Price
MRS from Equation (8) Externalities for a 1km Change in Distance	277.1	280.0	Constant 2015 US Dollar Price

Source: * Household Finance and Welfare Survey in 2017.

study used the variance inflation factor (VIF). If the VIF for an independent variable is more than 10, multicollinearity is likely. The values of VIF for all independent variables excluding factor variables is less than 2.1, indicating that the independent variables are not strongly correlated.

The monetary value of the distance from the NPPs is calculated by dividing the marginal life satisfaction level from the distance by the marginal utility of income, creating the marginal rate of the utility-constant substitution of income (MRS) for distance. Based on equations (3) through (8), this study calculates the monetary value of NPP externalities for a 1 km change in the distance using the values of Model 1 in Table 2.

For Ulsan residents, the linear specification of the distance produces $MRS = 0.1309 * \text{Mean Monthly Household Income}$. As a result, living 1km farther away from the Kori NPPs is worth $277.1. The estimated NPP external costs cannot be directly compared because every study estimates nuclear externalities for different amounts of electricity generated. Therefore, the levelized cost of electricity (LCOE) is a convenient way to compare the externalities for the different amounts of electricity generated on a consistent basis. In this study, nuclear externalities estimated by different studies are directly compared by the LCOE.

Table 4 shows a summary of the estimated externalities in this study and in previous studies. Note that the identification of nuclear externalities varies depending on the methodology used in the study. For example, the Korea Environment Institute measured people's willingness to pay (WTP) for mitigating the nuclear

TABLE 4—SUMMARY OF NPP EXTERNALITIES ESTIMATED IN THIS STUDY AND IN PREVIOUS STUDIES

Research Conducted by	LCOE Calculation	Estimated Externalities (USD/MWh)	Study Method
This Study	Kori Externalities / Electricity Generation by Kori NPPs	33.86	Life Satisfaction
	Wolsong Externalities / Electricity Generation by Wolsong NPPs	15.89	
KEI (2013)	Total Externalities / Electricity Generation by All NPPs in South Korea in 2012	4.18~6.93	Contingent Valuation Method
	1 NPP / Electricity Generation by 1 NPP (APR-1400) in South Korea in 2012	57.31~104.39	
Lee and Kang (2016)	Total Externalities / Electricity Generation by All NPPs in South Korea in 2013	0.00439	
Cho and Park (2015)	Externalities for Transmission Policy, and Risk Response Cost	9.75	Mutual Aid Method for Damage Compensation

accident risk in general, finding that it ranges from 4.18 to 6.93 USD / MWh. Moreover, the KEI measured people's WTP to avoid the construction of a NPP in their neighborhood, finding that this ranges from 57.31 to 104.39 USD / MWh. Furthermore, Lee and Kang estimated the external costs of NPP accidents, measuring the value of statistical life and the relative risk aversion coefficient. The comparison of all externalities of NPPs based on the LCOE shows that the previous estimates with the CVM were in general serious underestimations, while using the LSA leads to significant differences in the estimates.

V. Conclusion and Implications

Using the life satisfaction approach, this study measures the monetary value of nuclear power plant externalities. This paper used data on the officially reported subjective well-being of Ulsan citizens to test the hypothesis that the negative externalities from nuclear power plants are significantly related to Ulsan residents' income levels and distances from NPPs.

Our empirical results show a statistically significant positive relationship between the life satisfaction level and the distance between the residences and the nearest NPP. The ordinary least square regression estimation indicates that a 1km increase in the distance is valued at $277 for Kori and at $280 for Wolsong. The monetary value of nuclear negative externalities estimated by this study is roughly comparable to those found by previous studies which took place abroad, such as that by Farber in 1998 (range of $200~$300 per mile) concerning property values for residents of Boston in the U.S. and that by Welsch *et al.* in 2016 (305 USD per km), which used the life satisfaction approach for Swiss residents. However, the estimates in this study and previous domestic studies show significant differences. Previous studies which used the CVM method (e.g., Lee and Kang, 2016; KEI, 2013; Cho and Park, 2015) contained serious underestimations, demonstrating the practical utility of the LSA in South Korea. Unlike in advanced countries, where NPPs are generally located in remote areas and/or on uninhabited seashores, most NPPs in South Korea are located not far from populated towns and cities. Therefore, the LSA approach is more appropriate in the South Korean context.

This study provides several insights for energy policy decision-makers within the framework of economic analyses of NPPs in comparison with other energy sources by estimating the monetary value of NPP externalities using shadow prices (life satisfaction level) for NPP risks. When making investment decisions not only in the energy sector but also in many other sectors, policy makers should adopt an appropriate measure to internalize the cost of externalities as much as possible so as to correct market price distortions due to externalities. In this way, we can achieve the highest possible rate of economic growth and maximize national welfare.

APPENDIX

TABLE A1—NUMBER OF VARIABLES

Variable	ln income (Monthly)	Distance from Wolsong	Distance from DK	Monthly Expenditure	LS
Unit	ln (10USD)	1km	1km	7 Point Scale	11 Point Scale
Sample Size	7,767	7,767	7,767	7,767	7,767
Min	3.91	11.30	4.53	1.00	0
Max	6.48	42.80	37.47	7.00	10.00
Range	2.56	31.49	32.94	6.00	10.00
Median	5.40	24.35	24.88	2.78	5.00
Mean	5.42	24.01	24.95	2.76	5.76

TABLE A2—FACTOR VARIABLES

Sex	
Female	3,927
Male	3,840
Education	
Below University Graduate	5,311
Over University Graduate	2,456
Religion	
No Religion	3,367
Have Religion	4,400
Marriage	
Not in a State of Marriage	1,717
In a State of Marriage	6,050
Ages	
Under 20 Years Old	430
Over 20 Years Old	806
Over 30 Years Old	1,405
Over 40 Years Old	1,735
Over 50 Years Old	1,811
Over 60 Years Old	932
Over 70 Years Old	648

REFERENCES

Amerasinghe, N. and S. Porter. 2011. *Fossilized thinking: The World Bank, Eskom, and the real cost of coal*. Center for International Environmental Law (CIEL), Washington DC.

Bauer, T. K., S. T. Braun, and M. Kvasnicka. 2017. "Nuclear power plant closures and local housing values: Evidence from Fukushima and the German housing market," *Journal of Urban Economics*, 99: 94-106.

Carson, R. T., R. C. Mitchell, M. Hanemann, R. J. Kopp, S. Presser, and P. A. Ruud. 2003. "Contingent valuation and lost passive use: Damages from the Exxon Valdez oil spill," *Environmental and Resource Economics*, 25(3): 257-286.

Cho, Seongjin and Changuk Park. 2015. *Optimal energy mix in consideration with economic and social costs for nuclear power plants*, Korea Energy Economics Institute (KEEI), Ulsan.

Ea Energy Analyses. 2008. *Renewable Energy Costs and Benefits for Society* (RECABS), prepared for the IEA's Implementing Agreement on Renewable Energy Technology Deployment, Ea Energy Analyses, Copenhagen.

Farber, S. 1998. "Undesirable Facilities and Property Values: A Summary of Empirical Studies," *Ecological Economics,* 24: 1-14.

Freeman, A. Myrick. III. 2003. *The Measurement of Environmental and Resource Values: Theory and Methods*, Resources for the Future, Washington D.C.

Ferrer-i-Carbonell, A. and P. Frijters. 2004. "How Important Is Methodology for the Estimates of the Determinants of Happiness?" *Economic Journal* 114: 641-659. .

Frey, B. S., S. Luechinger, and A. Stutzer. 2009. "The Life Satisfaction Approach to Environmental Valuation," CESifo Working Paper Series No. 2836.

Frey, B. S., S. Luechinger, and A. Stutzer. 2004. *Valuing public goods: The life satisfaction approach*. CREMA Working Paper 2004(11).

Future population trend. 2017. [Data file]. Retrieved from http://kostat.go.kr/

Fink, A. and T. Stratmann. 2013. "U.S. housing prices and the Fukushima nuclear accident: To update, or not to update, that is the question," Working Paper 2013(4), International Center for Economic Research.

Household Finance and Welfare Survey. 2017. Retrieved from http://kostat.go.kr/

Kahneman D, I. Ritov, and D.A. Schkade. 1999. "Economic Preferences or Attitude Expressions?: An Analysis of Dollar Responses to Public Issues," *Journal of Risk and Uncertainty,* 19: 203-235.

Korea Census. 2015. [Data file] Retrieved from http://kostat.go.kr/

Korea Hydro Nuclear Power. 2017. Retrieved from http://www.khnp.co.kr/eng/content/529/main.do?mnCd=EN03020101

Korea Environment Institute (KEI). 2013. *Externalities of Nuclear Power*, Sejong.

Lee, S. H. and H. G. Kang. 2016. "Integrated framework for the external cost assessment of nuclear power plant accident considering risk aversion: The Korean case," *Energy Policy,* 92: 111-123.

Mankiw, N. G. 2014. *Principles of macroeconomics*, Cengage Learning. South-Western College Pub; 7th edition.

National Oceanic and Atmospheric Administration, U.S. Department of Commerce. 1993. "Natural Resource Damage Assessments under the Oil Pollution Act of 1990," *Federal Register*, 58 (10): 4601-4614.

Nuclear Energy Agency. 2003. *Nuclear Electricity Generation - What Are the External Costs?* Paris: OECD.

Rosen, Sherwin. 1974. "Hedonic prices and implicit markets: product differentiation in pure competition," *Journal of political economy,* 82(1): 34-55.

Socioeconomic Data and Applications Center (SEDAC). 2015. *Gridded population of the world (GPW)*, [Online].

Ulsan City. 2014 and 2016. Statistics on Citizen's Living Condition and Consciousness, Ulsan. Retrieved from: http://kosis.kr/statHtml/statHtml.do?orgId=207&tblId=DT_20704_084_2014&vw_cd=MT_OTITLE&list_id=207_A001_2014_002_003&seqNo=&lang_mode=ko&language=kor&obj_var_id=&itm_id=&conn_path=E1

Welsch, H. and J. Kühling. 2009. "Using happiness data for environmental valuation: issues and applications," *Journal of Economic Surveys*, 23: 473–494.

Welsch, H. and P. Biermann. 2016. "Measuring power plant externalities using life satisfaction data: A spatial analysis for Switzerland," *Ecological Economics,* 126: 98–111.

Yamane, F., H. Ohgaki, and K. Asano. 2013. "The immediate impact of the Fukushima Daiichi accident on local property values," *Risk Analysis*, 33(11), 2023-2040.