Ex-ante Evaluation of Economic Costs from Power Grid Blackout in South Korea

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Abstract – South Korea is recently under serious situation in supplying electricity with enough power reserve. A single fault of power plant at a peak-load time may lead to a total blackout for whole area connected by a single electric grid and isolated from other grids. Despite of the seriousness of blackout, however, there are scarce studies with ex-ante analysis of the economic costs from blackout. In order to evocate the seriousness, we calculate the economic costs for both industrial and household sectors with using some survey data and statistical methodologies. As a result, total economic costs are 39.23 trillion KRW (35.83 trillion KRW for industrial sector, 3.40 trillion KRW for household sector).

Keywords: Electricity, Blackout, Outage, Interruption cost, Contingent valuation method

1. Introduction

In 2011, Korea experienced first-ever national-wide emergency rolling blackout even without any prior notifications. Over a million households, hundreds of banks and hospitals suffered cuts in electricity supply from several minutes up to several hours and met with great inconvenience and economic loss. The loss would be much greater if increasing electricity demand exceeded total supply, paralyzed whole power system and caused total blackout national-widely. Total blackout does not lead to a discontinuance of electricity supply but also affect huge area dependent on electricity including industry, household, medical services, transportation and national defense. More severe problem would be caused in electric generation because electric auxiliary use takes a large share (4.14%) of gross generation [1]. For this reason, the outage leads to the halt of generation and the restoration from total blackout would take a long time. For instance, 24 of 223 blackouts in North America from 1984 to 2006 took over 100 hours in duration [2]. In addition, since Korea has only a single electric grid and is isolated from other grids, the restoration of power system in Korea is much harder than other countries.

Recent data of Korea shows that total blackout is possible enough now. (See Fig. 1) Ratio of days with under 10% reserve margin rapidly increased from 2009 and days with under 4 million kW reserve margin of power also have been increasing. In this situation, a single fault of major power plant such as a nuclear power plant or failure of a major overhead transmission line can lead to a total

blackout. For instance, the lowest power margin of Korea was 4.19GW while the capacity of Hanbit nuclear power plant was around 5.87GW and the capacity of each reactor was around 1GW. Thus, unless lowest power margin increases enough, total blackout of overall power system is not an unrealistic situation.

There are many examples of total blackout world-widely. The famous 2003 Northeast Blackout in America affected over 50 million people and its estimated cost is put in range between \$4 and \$10 billion [3]. Moreover, July 2012 India Blackout which is the largest blackout in history affected around 620 million people, about 9% of the world population and is estimated to hit the revenues of power generation companies by Rs. 550 crore (around \$87 million) [4]. There are also cases of 2003 Italy Blackout which affected similar number of people with 2003 Northeast Blackout and 2009 Brazil-Paraguay Blackout
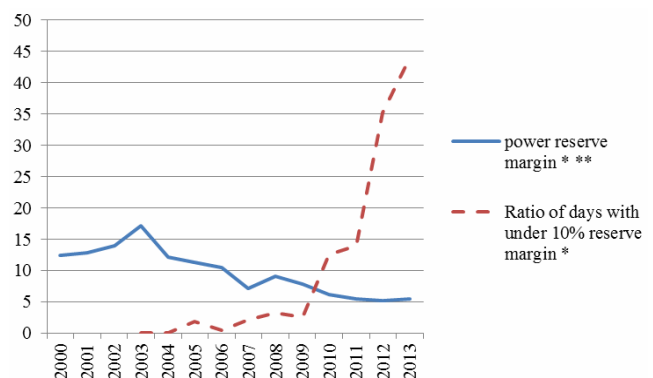
* For 2013, data indicates the average number from January to August.
** Lowest power reserve margin in the year is calculated based on hourly mean, thus the momentary least margin could be much lower.

Fig. 1. Annual change of power reserve margin in Korea[1]

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1   Korea Power Exchange, Electric Power Statistics Information System , https://epsis.kpx.or.kr

which affected more than 80 million people [5]. As these cases have shown, a total blackout affects a large number of people and causes a huge economic loss. Despite of the seriousness of blackout, however, there are scarce studies with ex-ante analysis of the economic loss from blackout. Most of studies considering the economic loss of power outage deal with instant voltage sags or regional blackouts and focus on either industrial or household sector. This study is distinguished from the fact that it analyzes the economic loss[2] from a *total blackout* not only in *industrial sector* but also in *household sector* in *South Korea*.

2. Previous Literature

The expected economic loss from power outage would be divided by two major economic sectors: Industry and Household. In case of industry, the loss can be calculated by assessing the cost from such as production failure and restoration of equipment. On the other hand, in case of household, the loss is much harder to quantify. Accordingly, a survey based method is needed to estimate the loss in household sector.

The division of sector in analysis is similar with [6] which also divided households, firms and the public sector to measure the costs of power outages in Austria. In [7], three methods are recommended to estimate the unit interruption cost of customers based on customer damage functions. The first one is contingent valuation approach and the second one is direct costing approach. This study used direct costing approach to estimate the loss in industrial sector and contingent valuation approach to estimate the loss in household sector.

2.1 The economic loss in industrial sector

Firstly, this study analyzes the outage cost from industrial sector. It is needed to consider that the loss in industrial sector will heavily depends on the economic scale and power usage characteristic of each sub-sector. There are many studies tried to estimate outage cost. [8] construct the method for estimating the magnitude and frequency of voltage sags and calculate the economic loss of them by multiplying the sag frequency and cost per sag by the number of customers affected. As a recent work, [9] evaluate the economic losses from power shortage in the industrial sector. They calculate the value of losses by introducing the concept of EHnP (Equivalent Hours of non-Production) as shown in Eq. (1)

$$Value = EHnP \times VoLL \times ELP \qquad (1)$$

In Eq. (1), EHnP is estimated from the annual length of

power interruptions and the depth of the voltage-sag. VoLL (Value of Loss Load) is assumed to be the annual value of Gross Domestic Product (GDP) divided by Total Energy Consumption. ELP (Equivalent Lost Power) is defined as the loss of power due to the interruption and assumed to be same as the peak power consumption of the industry so as to maximize the consequences. These two works show macroscopic and rough methods for estimation of outage cost.

Similar studies but focused on South Korean power market also exist. [10] estimate annual outage cost of South Korea by assessing IEAR (Interrupted Energy Assessment Rates) which equals GDP divided by Total electrical energy demand. They conclude that IEAR of South Korea in 2009 is 2,695 KRW/kWh[3] and multiplying this by EENS (Expected Energy Not Served), the annual outage cost is calculated to be 8.6 billion KRW.

In this section, our goal is estimating outage cost only from industrial sector. Thus, rather microscopic and direct method is more appropriate for more accurate estimation. There are many studies focusing on industrial sector and using more direct estimation of outage cost. A representative method fits our purpose is survey based method. [11] conduct surveys of Canadian electric utility customers in each sector. Particularly, they provide the analysis result of interruption costs by interruption duration and also by each industrial sub-sector. For instance, they show that average interruption cost of Canadian industry with 1 hour of interruption duration is 6.53 CAD/kW and average interruption cost of crude petroleum industry of the same condition is 214.54 CAD/kW. [12] is more recent work estimated the Load Drop Cost (LDC) of voltage sag using the survey result of [11]. They categorize the interruption duration by 4 categories based on IEEE standard, e.g. instantaneous interruption, and calculate the cost by multiplying cost weight from [10] by Load Drop Index (LDI) which is described roughly as Eq. (2).

$$LDI = \sum_{\text{Type of load drop events}} (\text{Drop Probability}) \\ \times (\text{Number of Events of Each Type}) \qquad (2) \\ \times (\text{Drop Load Ratio})$$

[13] conduct a survey of 18 South Korean industrial sub-sectors to estimate the outage cost. The study provides survey result of that average interruption cost of an industrial firm in 8 hours of interruption is 189 million. Similar survey is conducted by [14] which collect the survey from 1889 industrial firms all over the country. [14] conclude that the average interruption cost of South Korean industry is 708,000 KRW/kW.

2.2 The economic loss in household sector

Several studies are conducted to estimate economic costs

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of electricity supply interruptions. In [15], Sanghvi pointed out that electricity service interruptions can be generally caused due to "malfunctions or inadequate generating, transmission, or distribution capacity (p.181)", and the economic costs are dependent on "time-of-occurrence, duration, magnitude, warning time, frequency, persistence, and coverage (p.181)."[4] Sanghvi investigated that several methodologies had been used to measure a household's economic cost of the outage, for examples, lost leisure as measured by the wage rate and survey of willingness-to-pay to avoid outage. [16] also surveyed the methodologies used for outage cost up to date.

As one of the survey methods, contingent valuation method (CVM) is widely used to estimate a household level utility or disutility because it has advantages in incorporating outage attributes and customer characteristics [17]. When using the CVM, a researcher can ask direct costs of inconvenience [18, 19] or willingness-to-pay to prevent the outage [6, 16, 20].

For example, in [6], which is most similar to our study, estimated economic loss of a household in Austria as €1.4/1-hour ~ €17.3/24-hour outage by using the CVM. They analyzed that the WTP would be increased in winter for a male who has higher income, low education without experience of outages. In addition, the share of economic cost of households from total cost of society was expected to be 2.74% for a short-term outage and 9.05% for a long-term outage.

The estimated value of household's economic loss shows heterogeneity across the countries, while the estimation approaches are similar. However, up to our knowledge, there is no study on South Korea case for a household.

3. Analysis

3.1 The economic loss in industrial sector

As a first step, in order to obtain the outage cost of 3 days from industrial sector, our study uses the survey data of [14]. As stated before, [14] provides most recent data of the same research object: South Korean Industry. Moreover, it is the only study which conducted national-wide survey for outage cost in South Korea to date. Table 1 shows the summarized result of [14].

Based on the result shown in Table 1, we estimated Average Interruption Cost function (AICF) which is logarithmic function of interruption duration (T) with error term (ε) as shown in Eq. (3).

$$\ln AICF = c + \rho \ln T + \varepsilon \qquad (3)$$

In Eq. (3), we assumed that the AIC elasticity of

Table 1. Average interruption cost in industry by interruption duration [13]

Interruption duration (Seconds)	Average interruption cost (aic) in industrial sector (Million KRW/MW)
1	5
3	50
60 (1 min)	97
1200 (20 mins)	138
3600 (1 hour)	213
7200 (2 hours)	307
14400 (4 hours)	493
28800 (8 hours)	708

interruption duration (ρ) is constant. This equation is similar with the model used in [21] and [22]. In [21], LaCommare and Eto stated that outage cost has logarithmic nature and interruption cost declines after outage costs reach their maximum. In [22], the sector customer damage function which is similar to AIC function is assumed as non-linear function of duration. There are also evidences of diminishing marginal cost of blackout. For example, [7] shows that the unit customer damage function decreases by the length of duration in industrial sector. [23] show that customer damage per minute is decreasing in time. There is also explanation of [24] that marginal damage from outage is diminishing by time when initial damage such as cost of wasted materials, imperfect product, damaged equipment and extra maintenance is already done. Thus, we used Eq. (3) because it assumed the diminishing marginal cost and fits well to data. We estimated Eq. (3) by simple OLS estimation and obtained the result as shown in Table 2.

From the result of Table 2, it is able to expand the interruption duration by 1-day or 3-days. Adopting the

Table 2. Estimation result of AICF

	Mean	Std.	t-	P>|t|
ρ	0.372**	0.058	6.36	0.001
c	2.574**	0.419	6.15	0.001

**: Significant at the 1% level
R-Squared = 0.8710

Fig. 2. Forecasted AICF curve

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[4] However, it is not needed to consider all the factors because we assume suddenly occurred total blackout for relatively long time.
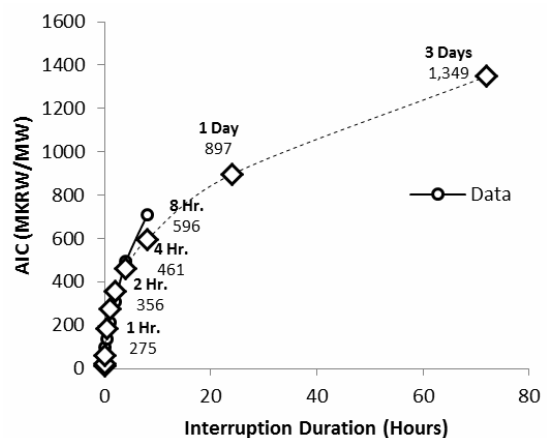
Table 3. Outage cost of industrial sector by interruption duration

Interruption duration	Forecasted AIC in industrial sector (Million KRW/MW)	Outage cost (Trillion KRW)
1	13	0.35
3	20	0.52
1 min	60	1.60
20 mins	183	4.86
1 hour	275	7.31
2 hours	356	9.46
4 hours	461	12.24
8 hours	596	15.83
1 day	897	23.82
3 days	1349	35.83

estimated parameter to AICF, we could get the AIC curve as shown in Fig. 2. Forecasted AIC of 1-day interruption is 897 million KRW/MW and 3-days interruption is 1,349 million KRW/MW. Outage cost (million KRW) from industrial sector can be obtained by multiplying AIC by power load (MW) related to industrial usage. In 2010, Korea Electric Power Corporation (KEPCO) provided 232,672 GWh (26.56 GW) to industrial sector.

Table 3 shows the estimation of outage cost in industrial sector. Multiplying the forecasted AIC by power load due to industrial sector, it is calculated that 1-day outage costs 23.82 trillion KRW and 3-days outage costs 35.83 trillion KRW where GDP of South Korea in 2010 is 1,173 trillion KRW. This makes 3-days outage cost 3.1% share of total annual production in Korea.

3.2 The economic loss in household sector

In order to elicit respondents' willingness-to-pay using CVM, several types of questions, such as open-ended question, bidding game, payment card, dichotomous choice, and others, can be used. Among those types, dichotomous choice is widely used and popular because it avoids several biases which can be caused by the other method [25] and reduces respondents' effort while it gives as reliable results as direct statement [26]. The dichotomous choice method is asking reference price for respondents to know they will accept or deny the price. It is called single bounded model if the survey is finished after respondents' answer, while double bounded model asks one more reference price based on their answers. In this study, we use double bounded dichotomous choice method for CVM survey.

Let $G(A_k)$ be the probability that a respondent k denies suggested price A_k. For the single bounded model, an Eq. (4) shows log-likelihood that all K respondents accept or deny the suggested price [27].

$$\log L = \sum_{k=1}^{K} I_k^Y \ln\left[1 - G(A_k)\right] + I_k^N \ln\left[G(A_k)\right] \qquad (4)$$

where indicator I_k^Y is equal to 1 if a respondent k accepts the price (otherwise 0), and I_k^N is equal to 1 if a

respondent k accepts the price (otherwise 0).

In case of the double bounded model, the log-likelihood function is shown as an Eq. (5) when A_k is initial suggested price, A_k^u is the second suggest price twice as much as the initial suggest price when a respondent k accepted the initial suggested price, and A_k^d is the other second suggest price half as much as the initial suggest price when a respondent k denied the initial suggested price. In addition, superscripts YY, YN, NY, NN of *I* means "accept & accept", "accept & deny", "deny & accept", and "deny & deny" for the initial and second price.

$$\log L = \sum_{k=1}^{K} I_k^{YY} \ln\left[1 - G(A_k)\right] + I_k^{YN} \ln\left[G(A_k^u) - G(A_k)\right]$$
$$+ I_k^{NY} \ln\left[G(A_k) - G(A_k^d)\right] + I_k^{NN} \ln\left[G(A_k^d)\right] \qquad (5)$$

Sometimes, high share of respondents may not be willing to pay at all. In this case, spike model [28] can estimate parameters more efficiently by incorporating zero willingness-to-pay respondents directly to the likelihood function as shown in an Eq. (6). To distinguish zero willingness-to-pay respondents, interviewer should ask one more to the respondents who answer "deny & deny". The I_k^{NNY} is equal to 1 if a respondent k has larger willingness-to-pay than zero although he/she denied both of first and second suggested prices (otherwise 0), and I_k^{NNN} is equal to 1 if a respondent k has zero willingness-to-pay (otherwise 0).

$$\log L = \sum_{k=1}^{K} I_k^{YY} \ln\left[1 - G(A_k)\right] + I_k^{YN} \ln\left[G(A_k^u) - G(A_k)\right]$$
$$+ I_k^{NY} \ln\left[G(A_k) - G(A_k^d)\right] + I_k^{NNY} \ln\left[G(A_k^d) - G(0)\right]$$
$$+ I_k^{NNN} \ln\left[G(0)\right] \qquad (6)$$

If we assume that the $G(A_k)$ follows logistic distribution $G(A_k) = \left[1 + \exp(a - bA_k)\right]^{-1}$, sample mean of the willingness-to-pay is represented by $(1/b)$ $\ln\left[1 + \exp(a)\right]$ and the share of zero willingness-to-pay respondents (spike value) is represented by $\left[1 + \exp(a)\right]^{-1}$ [28].

In a survey, we described the possibilities and expected problems on household related to the power grid blackout, and asked how much additional monthly electric charge they would want to pay to prevent blackout situation for 5 years[5]. Based on the double bounded dichotomous choice model, an interviewer suggested first and second prices, and asked they have no willingness-to-pay at all only for the respondents who denied both of first and second prices. We divided 1,000 respondents to 8 groups and suggested different initial price from 5,000KRW to 40,000KRW in

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Table 4. Demographics of respondents for CVM survey

Region	No. of respondents	Characteristics		No. of respondents
Seoul	236	Gender	Male	509
Busan	82		Female	491
Daegu	54	Education	High school diploma	473
Incheon	57			
Kwangju	33		Undergraduate school diploma	483
Daejeon	34			
Ulsan	20		Graduate school or higher diploma	44
Gyeonggi	231			
Kwangwon	27	Monthly income (million KRW)	under 1	14
Chungbuk	24		1~2	95
Chungnam	30		2~3	242
Jeonbuk	35		3~4	254
Jeonnam	24		4~5	207
Kyungbuk	52		5~8	154
Kyungnam	61		8~10	23
Total	1,000		over 10	11

Table 5. Estimation result for CVM survey

	Model A	Model B
a	-0.10571*	-0.10134*
b_0	0.00019**	0.0001742**
b_{Gender}	-	0.0000458**
$b_{Education\_M}$	-	-0.0000008
$b_{Education\_H}$	-	-0.0000107
b_{Income_M}	-	-0.0000548*
b_{Income_H}	-	-0.0000614*

order to avoid an initial price bias. 1,000 respondents were sampled based on the population and age of each area, except Jeju Island. Table 4 describes respondents' demographics, such as gender, education level, and income.

Using the maximum likelihood estimation method, the Eq. (6) can be estimated. Table 5 shows the estimation results of both case of when the parameter b has no covariate (model A) and the parameter b has several covariates (model B) as shown in an Eq. (7). The variable s_{Gender} is equal to 0 for males and 1 for females, $s_{Education\_M}$ and $s_{Education\_H}$ indicates medium level of education (undergraduate school diploma) and high level of education (graduate school or higher diploma), respectively, based on the low level of education (high school diploma), and s_{Income_M} and s_{Income_H} indicate medium level of monthly income (3 million KRW ~ 5 million KRW) and high level of monthly income (over 5 million KRW), respectively, based on the low level of monthly income (under 3 million KRW).

$$b = b_0 + b_{Gender}s_{Gender} + b_{Education\_M}s_{Education\_M} \\ + b_{Education\_H}s_{Education\_H} + b_{Income\_M}s_{Income\_M} \qquad (7) \\ + b_{Income\_H}s_{Income\_H}$$

Because mean value of willingness-to-pay is proportional to 1/b, the smaller a parameter is, the higher willingness-to-pay will be derived. That is, the men who have higher income will have the higher willingness-to-pay

to prevent blackout compared to the women who have relatively lower income, while education levels are not significantly effective. In addition, the estimated spike values for Model A and B calculated as 52.64% and 52.53%, respectively, have the similar value of actual share of zero willingness-to-pay respondents in a survey, 53.1%.

The expected mean value of willingness-to-pay calculated with the estimation results of Model A is 3394.0 KRW per month-household. If we assume that annual interest rate is 2.5%, which is equal to the standard interest rate announced by Bank of Korea in August 2013, total present value of willingness-to-pay of 17.95 million households to prevent the power blackout is estimated as 3.40 trillion KRW.

4. Discussion

This study focuses on measuring economic costs of total power grid blackout on two sectors: industries and households. Using the AIC function, in case of the industrial sector, total cost for 3-day outage is estimated as 35.83 trillion KRW. In case of the household sector, using the CVM, sum of the household's willingness-to-pay is estimated as 3.40 trillion KRW. That is, total cost is 39.23 trillion KRW, and the share of household's loss occupies 8.7% Table 6. The share of economic cost of households from total cost of society is similar to [6], 9.05% 48-hour outage in Austria. However, it is far less than we expected. It is also surprising that 53% of respondents have no willingness-to-pay to lower the blackout probability. In this circumstance, it would be difficult to reduce electricity over-consuming just by raising electricity charge which is exceptionally low now. It is needed that more people share current serious electricity situation and induce them to participate preventing the blackout risk. Although the number proposed in this study as economic loss due to blackout is not perfectly precise, we hope that the results help the government and people recognize the serious blackout risk by considering total blackout situation instead of short-term outage unlike the other previous studies for Korea.

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