The Possibility of Japanese Households’ Acceptance of Power Outages as an Incentive-Based Demand Response Program for Power System Maintenance

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I Introduction

To boost electricity generation from renewable energy (RE) resources, Japan enacted Feed-In-Tariff policy on July 2012 (METI, 2012). In 2013, Japan decided to reform its electricity system, under which the retail electricity market is planned to be fully liberalized by 2020 (METI, 2015a). In 2015, Japan set a goal to increase the total share of renewable energy in 2030 to account for 22%-24% of electricity generation, about 2.5 times bigger than RE share in Japan’s electricity generation in 2011 (METI, 2015b). These efforts strongly indicate a large-scale integration of RE in Japanese power system.

However, due to the variability of RE resources, a large deviation of electric frequency or voltage may happen due to an over-generation of renewable power supply. An inadequacy of supply during peak demand may cause unplanned outages. Demand Response (DR) is a considerable approach to alleviate the variability of renewable resources. DR is a demand-side approach defined as changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized (Kathan et al., 2012).

Because of its capability to provide fast, predictable and reliable response during contingencies, DR can be used as ancillary services including reserve provision through load shifting and peak demand reduction through load curtailing (Aghaei and Alizadeh, 2013). Peak demand reduction can benefit the power system operators in various cost reduction, including operating cost of peaking power plants (Lund et al., 2015). From the consumers’ viewpoint, the DR approach offers the opportunity to obtain benefits in the form of acceptable rebates (Aghaei and Alizadeh, 2013) and more options to buy electricity. The effect of DR in the form of pricing control during peak demand (price-based DR) on the electricity consumption of Japanese residential customers has been studied in Ito et al. (2015).

RE resources are low-density, unstable regional resources that are rich in rural areas. To supply RE in large quantities, many supply-plants or huge areas are needed. Inevitably, supply-plants are scattered in many rural areas. Considering the characteristic of the RE resources, decentralized small-scale supply and demand system can be more applicable for RE resources development, as demonstrated in a study of an existing off-grid system in Scotland that effectively harnesses electricity from solar, wind, and hydro in remote areas (Chmiel and Bhattacharyya, 2015). Hence, in planning RE resources development in rural areas, studies on a feasibility of the small-scale system are required from the engineering point of view.

This study investigates the level of willingness of Japanese residential electricity customers to participate in incentive-based DR programs in the context of large-scale integration of renewable energy in Japanese power system. This study is a preliminary study on the feasibility of decentralized power grid development in rural areas where many renewable energy resources are found. A questionnaire survey was conducted to achieve this research objective.

II Survey Design and Statistical Model Specification
1. Survey Design

The survey questionnaire consisted of two parts, referred as “warm-up” and “binary choices” parts. In the “warm-up” part, the respondents were asked about their socioeconomics condition and their actual activities of energy savings. In the “binary choices” part, background information about DR, reliability levels of electricity supply in Japan and other developed countries, and the purpose of the survey were presented to the respondents. The respondents were then asked to decide whether they would accept a sequence of DR programs. The offered DR programs were 36 hypothetical annual planned outage scenarios (with various duration-frequency combinations) that the electric power supplier would conduct in case of contingencies due to intermittence of renewable energy supply. Of the 36 outage scenarios, 16 outage scenarios were offered with no (zero JPY) monetary incentive in the first choice situation. In the second, third, and fourth choice situations nine identical outage scenarios were offered, each with 10,000 JPY, 15,000 JPY, and 20,000 JPY annual electricity bill reduction, respectively. The offered amounts were about 10%, 15%, and 20% of the Japanese households’ average annual electricity bill, respectively. The setting of the cost variable in the range of 10%-20% of the average electricity bill are not uncommon in choice experiment studies. For example, Abdullah and Mariel (2010) set the outage cost of 10%, 17%, 27%, and 40% of the respondent’s average electricity bill.

The questionnaire forms, prepared after conducting a preliminary survey, were sent out and collected by post or were filled out via a website. The survey forms were selected randomly from a list of survey collaborators aged 20 or over and residing in densely inhabited districts (DID) or non-DID regions. Approximately 200 subjects were selected from each representative prefecture of eight Electric Power Companies precincts. The representative prefectures (precincts) were Aomori (Tohoku), Kanagawa (Tokyo), Shizuoka (Chubu), Ishikawa (Hokuriku), Hyogo (Kansai), Ehime (Shikoku), Okayama (Chugoku), and Kumamoto (Kyushu). While selecting subjects, due consideration was given to avoid major bias in terms of gender, age, or region of residence. The survey was conducted with 1,668 subjects during the period between November 2012 and January 2013.

2. Statistical Model Specification

In this study a series of binary discrete choice experiment was conducted to gauge the Japanese residential customers’ preference on various planned outage scenarios. Every respondent was asked to choose one alternative in each choice situation. The respondents are assumed as rational decision makers who would choose an alternative that provides maximum utility (or profit). The utility a respondent gains from an alternative in a choice situation, labeled $U_{ijc}$, is assumed to be represented by a linear model as in Eq.1:

\[ U_{ijc} = \sum_{m=1}^{M} \beta_m x_{ijcm} + \epsilon_{ijc} \quad (Eq.1) \]

where $x_{ijcm}$ is a set of $m$ variables observed by the analyst, including the attributes of the alternative $j$ and the socio-economic characteristics of the respondent. The coefficients, $\beta_m$, is a vector of parameters representing the weights the respondent puts on $x_{ijc}$. The random error term $\epsilon_{ijc}$ is assumed to follow Gumbel distribution.

The marginal willingness to accept compensation (MWTA) for a change in attribute $x$ is defined as:

\[ MWTA_x = \frac{\partial U}{\partial x} = \frac{\partial U}{\partial x_{\text{incentive}}} = \frac{\beta_x}{\partial x_{\text{incentive}}} \quad (Eq.2) \]

where $\partial U/\partial x$ is the derivative of the utility function with respect to the attribute $x$ and $\partial U/\partial x_{\text{incentive}}$ is the derivative of the utility function with respect to the incentive attribute. In estimating the coefficients and the MWTA, we rely on the random parameter logit model (RPL) instead of multinomial logit model (MNL) because RPL treats some coefficients as random values (in contrast to fixed values as in MNL), hence can better accommodate respondents’ preference heterogeneity (Train, 2009).

The utility function in this study is defined as a linear function of outage attributes and respondents’ attributes:

\[ U_{ijc} = ASC_j + \beta_1 \text{dur}_{ijc} + \beta_2 \text{freq}_{ijc} + \beta_3 \text{bill}_{ijc} + \beta_4 \text{dur}_{ijc} \text{freq}_{ijc} + \beta_5 \text{bill}_{ijc} \text{income}_{ijc} + \beta_6 \text{bill}_{ijc} \text{family}_{ijc} + \beta_7 \text{bill}_{ijc} \text{age}_{ijc} + \beta_8 \text{bill}_{ijc} \text{outexp}_{ijc} + \epsilon_{ijc} \quad (Eq.3) \]

where $ASC$ is the alternative-specific constant of the alternative, which is coded 1 whenever the respondent accepts an outage scenario and 0 otherwise, $\text{dur}$ is the the outage duration (in hour), $\text{freq}$ is the outage frequency (in time(s)/year), $\text{bill}$ is the amount of annual bill reduction specified in each choice situation (in 1,000 JPY), $\text{durfreq}$ is an interaction term between $\text{dur}$ and $\text{freq}$, $\text{gender}$ is the respondent’s gender (dummy-coded 0 for male), $\text{agegr}$ is the respondent’s age group (dummy-coded as 0 for age group of 40-50 years old), $\text{famsize}$ is the family size (in persons), and $\text{incomegr}$ is the household’s yearly income group (dummy-coded as 0 for annual income of less than 5 million JPY), and $\text{outexp}$ is the respondent’s experience of outages (dummy-coded as 0 for having no outage experience in the past).

To accommodate preference heterogeneity among respondents, the coefficients of $\text{dur}$ and $\text{freq}$ are set as random parameters and are assumed to come from Triangular distributions. The simulation is conducted in $R$ statistical computing environment (R Core...
III Results and Discussion

1. Respondents’ Description and Their Acceptance of Outage Scenarios

Fifty-two percent of the respondents of this study were male. Half of the respondents were between 20-50 years old. The average household of the respondents consisted of 3.07 family members. About three-quarters of the respondents had earned yearly income less than 10 million JPY. Total sample size was 1668 respondents, of which 1611 respondents completed all 36 choice tasks. There was no significant difference between responses in DID and non-DID, probably because the reliability and the quality of electricity supply in both types of regions were not significantly different. The proportion of “Yes” response for some outage scenario choices are presented in Fig. 1. As Fig. 1 shows, more than 50% of respondents stated that they would be willing to accept three no-incentive outage scenarios (i.e. scenarios in which no electricity bill reduction is offered). These scenarios were a 30-minutes outage occurring twice (Two 30m), three times (Three 30m), and four times (Four 30m) in a year, accepted by 67.4%, 58.2%, and 55.8% of respondents, respectively. Two other no-incentive outage scenarios (not shown in Fig.1) were also accepted by more than 50% of respondents. These scenarios were a 30-minutes outage occurring once (One 30m) in a year and 1-hour outage occurring once in a year (One 1h), accepted by 75.0% and 50.4% of respondents, respectively. Fig. 1 also shows that, all other conditions (such as incentive amount) being equal, several short outages are more preferable than a single long outage.

As for scenarios with annual bill reduction of 15,000 JPY and 20,000 JPY, eight scenarios were accepted by more than 50% of respondents. These scenarios were six scenarios each of which has 30-minute outage that occurs twice to four times per year (Two 30m, Three 30m, Four 30m), and two scenarios each of which has 1-hour outage that occurs twice per year (Two 1h). Compared to the same combination of outage duration-frequency in no-incentive scenarios, the scenarios with annual bill reduction of 10,000 JPY, 15,000 JPY, and 20,000 JPY gained increases in acceptance proportion with the range of 2.3%-8.7%, 4.8%-10.3%, and 9.7%-15.8%, respectively. A Cochran’s Q test shows that all of these increases are statistically significant at 1% level.

2. Random Parameter Logit Estimation

Table 1 presents the means and standard errors of parameters that affects the utility function in both of MNL and RPL. The ASC is positive and is statistically very significant in the both model. It indicates that the customers tend to accept an incentive-based outage scenarios presented in the survey. The standard deviations of random parameters in RPL, namely as outage duration and outage frequency, are statistically highly significant, implying that there is actually high heterogeneity among respondents in their preferences on outage duration and frequency. This heterogeneity is not captured in MNL. The interaction variable between the duration and frequency is negative and significant in RPL, implying that the negative effect of outage duration on the respondents’ preference is larger in cases of more frequent outage events. This reasonable and important effect is not captured in MNL, in which this variable is not significant. The incentive coefficient is positive and is highly significant. It strongly indicates that an increase in the incentive offered in any outage scenario will significantly increase the respondents’ preference on the scenario.

Interaction terms between the incentive variable with socioeconomic characteristics show how the effect of the incentive on respondents’ preference varies depending on different segments of the respondents. The interactions between incentive and the respondents’ income levels are mostly negative and statistically significant. It indicates that for the same amount of increase in the incentive, all else being equal, the average respondents with high annual income (e.g.: more than 20M JPY) would value the increase in income resulted from the incentive significantly lower than those with low income (less than 5M JPY) would do. This result is consistent with the well-known concept that marginal utility of income decreases with income (Layard et al., 2008). This is also the probable explanation for the negative coefficient of the interaction term between the incentive and age group 50-60 years old because among all age groups, this age group has lower proportion of respondents with low income (less than 5M JPY) than the
reference group (the age group of 40-50 years old).

Overall, RPL shows much better fit to actual choice data than MNL, as reflected in the higher value of pseudo R². However, the standard deviation of the outage frequency variable is bigger than the mean. It implies that some respondents preferred more frequent outage events. This implausible behavior indicate this model’s weakness. An alternative way to improve this model is to constrain the range of standard deviation in the simulation setting, as suggested in Hensher et al. (2015).

3. Estimate of Marginal Willingness to Accept (MWTA)

The MWTA of each outage attribute is estimated based on the ratio of coefficients as indicated in Eq.2. Because the coefficient of incentive is a constant, when the coefficient in the nominator is a random parameter, the MWTA will also be random parameter. Based on the estimates presented in Table 1, the calculation of mean MWTA estimate for an outage frequency is conducted using Eq.4. The marginal WTA calculated in Eq.4 represents the amount of incentive a customer with specific characteristics would be willing to accept as the compensation for a change in the frequency of an outage that has a specific duration.

\[
MWTA_{freq,RPL} = \frac{\beta_2 + \beta_{id,freq}\text{triangle}(-1,1) + \beta_{duration}}{\beta_3 + \beta_{5,gender} + \beta_{6,incmogr} + \beta_{7,famsiz} + \beta_{8,agegr} + \beta_{9,outexp}}
\]

(Eq.4)

where \text{triangle}(-1,1) represents random numbers drawn from a standard Triangular distribution.

| Parameters                     | MNL | RPL | t-value | t-value |
|--------------------------------|-----|-----|---------|---------|
| Constant                       | ASC 1.9746*** | 0.0782 | 25.24    | 6.8905*** | 0.1883 | 36.59 |
| outage duration per event: mean | $\beta_4$ | $-1.4642***$ | 0.0626 | $-23.40$ | $-6.2656***$ | 0.1656 | $-37.84$ |
| outage frequency per year: mean | $\beta_5$ | $-0.3056***$ | 0.02476 | $-12.34$ | $-0.7730***$ | 0.0583 | $-13.26$ |
| Standard deviation             | $\beta_{id,\text{freq}}$ | --         | --       | 4.9870***    | 0.0885 | 56.36  |
| bill reduction                 | $\beta_7$ | 0.0188*** | 0.0028 | 6.75        | 0.1032*** | 0.0066 | 15.63  |

Interaction terms

duration:frequency: $\beta_2$ | 0.0026 | 0.0205 | 0.13 | $-0.5329***$ | 0.0464 | $-11.49$ |
bill:gender (Female): $\beta_3$ | 0.0248*** | 0.0014 | 17.34 | 0.0119***    | 0.0035 | 3.40    |
bill:income of “5M-10M” : $\beta_8$ | $-0.0042*$ | 0.0017 | $-2.42$ | 0.0023      | 0.0042 | 0.54    |
bill:income of “10M-15M” : $\beta_9$ | $-0.0104***$ | 0.0027 | $-3.83$ | $-0.0166*$  | 0.0069 | $-2.39$ |
bill:income of “15M-20M” : $\beta_{10}$ | $-0.0217***$ | 0.0057 | $-3.78$ | $-0.0052$  | 0.0140 | $-0.37$ |
bill:income of “>20M” : $\beta_{11}$ | $-0.0228***$ | 0.0066 | $-3.44$ | $-0.1181***$ | 0.0161 | $-7.34$ |
bill:income of “Don’t Know” : $\beta_{12}$ | $-0.0221***$ | 0.0024 | $-8.97$ | $-0.0178**$ | 0.0066 | $-2.68$ |
bill:family size : $\beta_3$ | 0.0037*** | 0.0005 | 7.26    | 0.0059**    | 0.0012 | 3.15    |

Table 2 The MWTA (in JPY, per event, per person) of an average base group respondent (The confidence interval is calculated with Krinsky and Robb method using 5000 resampling as suggested in Hensher et al., 2015)

| Outage Duration | MNL | RPL |
|----------------|-----|-----|
| Mean | 95% Confidence Interval | Mean | 95% Confidence Interval |
| 30m | 9,017 | $-3,499$ | 22,408 |
| 1h | 11,242 to 28,810 | 11,328 | $-1,188$ | 24,914 |
| 2h | 15,951 | 3,423 to 29,735 | 3,423 to 29,735 |

1 The estimates of the random coefficients are resulted from simulation using 500 Halton sequences from Triangular distribution.
2 N = 1661; Observations = 36 × 1661=57,996.
3 Since the random parameters are not drawn from Normal distribution, the t-values presented in RPL estimates are asymptotic t-values.
4 Significance codes: ‘***’ p<0.001; ‘**’ p<0.01; ‘*’ p<0.05. ‘ ’ p≥0.05
Based on Eq. 4, the mean and confidence interval estimates of MWTA of the base group are presented in Table 2. The base group refers to the group of representative socioeconomic characteristics, which were: gender of male, annual income of less than five million JPY, family size of 3.07 persons, age group of 40-49 years-old, and having no outage experience in the past. Table 2 show that, for the respondents in the base group, the mean MWTA for an 1h-outage occurring once a year is 11,328 JPY in RPL. It means that, a base group customer would be willing to accept a 1h-outage scenario per year in return of electricity bill reduction of 11,328 JPY in average. Hence, if it would occur twice a year, the required bill reduction would be 22,656 JPY in average. The negative MWTA, which is implausible, is an artifact of this RPL model due to a large deviation of outage frequency, as described in Section 2.2.

IV Conclusion

Demand-side control is one of the options for reducing reserve power capacity in renewable electricity systems, in addition to supply-side improvements. The results of this study show that the Japanese residential customers show considerable acceptance of incentive-based DR in the form of planned outages. The acceptance of majority of the respondents of five outage scenarios (One 30m, Two 30m, Three 30m, Four 30m, and One 1h) with zero incentive in the context of renewable energy acceleration also provides evidence of the Japanese households’ awareness of energy savings.

The study results demonstrated that the monetary incentives significantly affect the customers’ preferences on the outage scenarios. In addition, a few respondent properties may have an influence on WTA so that WTA is clearly affected by income level in the study. The mean WTA estimation based on the random parameter logit model shows that the average residential customer’s mean WTA for an 1h-outage occurring once a year is 11,328 JPY (96 USD) per event or about 10% of the annual electricity bill. This value is relatively comparable to the result in Hensher et al. (2014). This result indicates the validity of our result.

As a result of the research, it is considered that Demand Response is able to carry out in the Japanese private household sector and that a monetary incentive approach of Demand Response contributes to increase acceptance of power outage. Because reduction in peak demand is effective to increase the stability of a power system equipped with an unstable power supply facilities and to decrease backup capacity, the research result indicates that Demand Response could be useful measure to reliability improvement of a decentralized power system with generation units using renewable energy resources.

To design decentralized power system to use renewable energy resources effectively, further studies are necessary to estimate the amount of system capacity and cost reductions that would be resulted from the peak demand reduction. In addition, further studies are necessary to estimate the effect of the Demand Response of an incentive scheme on the peak demand reduction compared to the effect of the Demand Response of a penalty scheme, in which the electricity fee during peak demand time zone is set higher (Ito et al., 2015).

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再生可能エネルギー資源は、エネルギー密度が小さく、不安定であるため、大量供給には多数、大面積の設備整備を必要とするとともに、それぞれの資源特性に適した分散型生産・需給システム運用が必要になる。したがって、より効率的な再生可能エネルギーの生産供給を実現するためには、とくに資源が豊富に賦存する農村地域を中心に、分散型のエネルギー需給に関する技術工学的な研究が求められる。このような認識に基づいて、本研究では農山村地域における分散型電力グリッドの可能性を検討するための予察的検討として、再生可能エネルギーの大量導入を前提に、電力削減インセンティブによる需給システムの電力システム維持プログラムへの参加可能性を調査・分析した。調査は、対象の属性、省エネルギー行動・意識などに加えて、受容できる停電の回数・時間の長さと年間電気料削減額の組合せ（Demand Responseシナリオ）を選ぶ選択型アンケートとし、北海道と沖縄を除く8電力管内のDID（Densely Inhabited Districts）・非DIDの調査会社登録の20歳以上のモニターから調査対象を選定して実施した。停電受け入れ条件として削減額を推計するために使用できる有効回答数は1,611であった。

Demand Responseシナリオの受入れに対しDIDと非DIDの違いによる差は認められなかった。また、どのDemand Responseシナリオにおいても年削減額を増加させると受け入れ率は増加した（Fig.1）。

選択型アンケート結果の分析には、回答者が選択肢を選択したときの効用として線形モデルで表されるランダム変数を想定したrandom parameter logit model（Train, 2009; Hensher et al, 2015）を用いた（Eq.1）。効用パラメータの平均値は、回答者の効用パラメータ分布として三角分布からハルトン数列でサンプリングして得られる分布を仮定して推定した（Table 1）。効用パラメータの推定に基づき、Eq. 4を用いてDemand Responseシナリオ別の平均削減額（平均Willingsness-to-Accept）を求めた。その結果は、Table 2のとおりで、年1回・1時間の停電受け入れの平均Willingsness-to-Acceptは11,328円と見積もられた。

本研究の結果は、Demand Responseが日本の中小規模システムにおいて実行可能であること、金銭的インセンティブが停電受け入れの増加に貢献することを明らかにしたといえ、Demand Responseは安定な再生可能エネルギー利用の分散型電力システムのパックアップ容量削減や信頼性向上に有効な選択肢になると考えられた。

Keywords（キーワード）: demand response（デマンドレスポンス）、binary choice experiment（二項選択実験）、random parameter logit model（ランダムパラメータロジットモデル）、decentralized power system（分散型電力システム）、renewable energy（再生可能エネルギー）