2012 Electricity Saving Campaign for Residential Customers in Kansai Area, Japan

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ABSTRACT

After the 2011 Earthquake and Tsunami hit the Tohoku region, the nine main Japanese electric utilities faced shortages in their electricity supply capacities during the summer of 2012 because they could not restart their nuclear plants. Kansai Electric Power Company (KEPCO) was most affected because it had the highest proportion of nuclear energy in its electricity generation (48% from 2000 to 2010). To overcome the shortage, KEPCO conducted several campaigns to promote electricity saving especially for peak shaving. Using a statistical model of electricity demand based on observed demand in 2011 and 2012, this paper quantifies how much electricity demand was reduced among residential customers due to behavioral change during the summer of 2012 compared with 2011. General residential customers responded well to the campaign by reducing electricity demand for a few hours during KEPCO's peak time, with an average reduction of greater than 50 W. This reduction contributed significantly to reducing the total demand in the KEPCO service region which was estimated to be equivalent to 0.50 to 0.85 GW. This paper also analyzes in detail the effect of the Electricity Saving Trial campaign, or EST, in which a money coupon was provided to customers subscribed to the campaign according to their reductions compared to their use in 2011. Because of the incentive structure targeting total electricity demand, customers subscribed to the campaign reduced their electricity demand for longer hours, from 11h00 to 24h00, and sustained this behavior for a longer period of time.

Introduction

After the 2011 Earthquake and Tsunami hit the Tohoku region, the nine main Japanese electric utilities faced shortages of their electricity supply capacities during the summer 2012 because they could not restart their nuclear plants. To overcome the shortage, Kansai Electric Power Company (KEPCO) conducted campaigns to promote electricity saving by residential, commercial, and industrial customers. KEPCO, with 34.88 GW of generation capacity, was most affected because it had the highest proportion of nuclear energy in its total electricity generation, 48% from 2000 to 2010. KEPCO's electricity sales volume in 2012 was 50 TWh for 12.5 million residential customers and 96 TWh for 1.1 million commercial and industrial customers.

KEPCO published their estimate of their electricity demand in the summer of 2012 in April 2012 (KEPCO, 2012). The estimated peak demand ranged from 29.50 GW, with average climatic conditions within recent years, to 30.30 GW, with climatic conditions being the same as those of 2010 in which the mean temperature from June to August was the highest since 1898 (Japan Meteorological Agency, 2010). These estimates were much higher than the estimated supply capacity of 25.5 GW that was available without their nuclear power plants. It should be noted that in the estimation, 1.02 GW of electricity saving provided by the customers was included, based on the observed demand in 2011. Although the gap between estimated supply capacity and demand narrowed after two nuclear reactors in the Ohi power plant were restarted in July 2012, the supply capacity was still lower than the expected demand.

Table 1 summarizes the estimated peak demand, peak demand observed in 2012, and actual supply capacity (Union of Kansai Governments, 2014). The observed peak electricity demand was lower than the supply capacity by approximately 10%. KEPCO did not have such shortage in 2011 because some of their nuclear power plants were operated.

Four key factors could alter electricity demand. These are: 1) scale of economic activity, 2) climatic conditions, 3) consumers' electricity use behavior, and 4) energy efficiency of home appliance and equipment. Regarding factor 1), the scale of economic activity, the Union of Kansai Government (2014) reported that the scale of economic activity was almost the same as it had been in recent years. Regarding factor 2), Table 1 also lists the mean and maximum outdoor air temperatures during August in 2012 and 2010. The mean temperature in 2012 was lower than in 2010 by 1.13 °C, while the maximum temperature in 2012 was lower by 0.7 °C (Japan Meteorological Agency, 2014). According to KEPCO (2014), electricity demand increases by 0.7 to 0.8 GW with each 1.0 °C increase in outdoor air temperature when it is above 33 °C. Thus, the decrease in electricity demand can be mainly attributed to factors 3) and 4).

Table 1. Summary of peak demand and supply

Period	July 2 to 15	July 16 to 31	August	September 1 to 7
Estimated peak demand [GW]	27.57	29.87	29.87	29.02
Observed peak demand [GW]	23.05	26.73	26.82	24.94
Difference [GW]	4.52	3.14	3.05	4.08
Supply capacity [GW]	26.45	30.29	30.26	29.77
Mean temperature in 2012 [°C]	25.99	29.43	29.35	27.68
Maximum temperature in 2012 [°C]	34.1	35.9	36.7	34.1
Mean temperature in 2010 [°C]	26.37	29.38	30.48	30.18
Maximum temperature in 2010 [°C]	33.1	36.7	37.4	36.2

The purpose of this paper is to estimate the reduction in electricity demand during the summer of 2012 due to behavioral changes from 2011 among residential customers. For this purpose, the authors statistically analyzed hourly electricity demand, collected by smart meters from residential customers, from June to October in 2011 and 2012. For residential customers, the scale of economic activity was the same for these two years. To eliminate the influence of climatic conditions, a statistical model representing the behavior of electricity demand from June to October in 2011 and 2012 was developed on the basis of the observed electricity demand. This model inputs climatic conditions and outputs electricity demand with characteristics observed for each period. When climatic conditions in 2012 were input to the model for 2011, the predicted electricity demand for 2012 would clearly show if any behavioral change had occurred from 2011. Comparing the results of the two models quantifies any reduction due to behavioral change from 2011 to 2012.

This paper also analyzes the influence of one of the campaigns conducted by KEPCO, the Electricity Saving Trial (EST), in 2012. In EST, residential customers received money coupons that reflected their reductions. Approximately 1.6% (196,000) of the total residential customers subscribed to EST. It is important to note that the reduction was defined by the total electricity demand during July, August, and September in 2012 compared with the same period in 2011, because only total monthly consumption is metered for most residential customers. To evaluate how the EST incentive affected residential customers' behavior and the resultant electricity consumption, the same statistical model was developed on the basis of observed electricity demand from residential customers who subscribed to EST.

In the following sections, the analysis data and methodology used in this paper are first presented. Then, the statistical models developed are presented and validated. Reduction in demand due to behavioral change and energy efficiency increase from 2011 to 2012 and reduction due to EST are quantified using these statistical models. Finally, we discuss how general residential customers reduced electricity demand in 2012 and how the incentive structure provided by EST affected customers' electricity use behavior.

Analyzed Data

As explained above, we compared electricity demand in 2011 and 2012 of two groups with and without EST. Table 2 lists the number of households for which the electricity demand data was collected by smart meters. The electricity demand data was collected from the same households at 1-h intervals from 1st of June to 31st of October for both 2011 and 2012. For each time step, the mean and standard deviations within the households in each group were calculated.

For climatic conditions, the data for outdoor air temperature, humidity, pressure, wind speed, and amount of insolation observed at the Osaka Regional Headquarters of Japan Meteorological Agency (2014) was used. Figure 1 shows an example of the relationship between outdoor air temperature and electricity demand for the four groups listed in Table 2.

Table 2. Number of samples in each group

Analysis group	Year	Number of samples
No-EST2011	2011	1,237
No-EST2012	2012	1,237
EST 2011	2011	161
EST 2012	2012	161

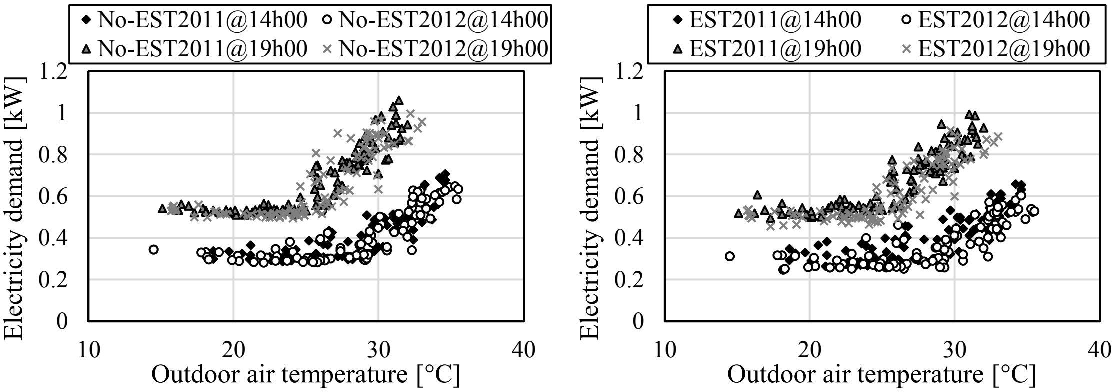

Figure 1. Observed electricity demand at 14h00 and 19h00 of the four groups listed in Table 2.

Analysis Methodology

The purpose of this analysis is to quantify the reduction in electricity demand during the summer of 2012 due to behavioral changes from 2011 among residential customers. In the design of the analysis methodology, two premises were used. First, it is assumed that there were no changes in people's basic daily behavior at each time of day in their homes during the analysis period. As shown in Figure 1, electricity demands differ at different times of day. This is because people's basic daily behaviors are different at different times of day. Based on this premise, when we focus on electricity demand at a particular time of day, a change in electricity demand can be attributed to a change in the operation of home appliances and equipment that accompanies people's basic daily behavior and a change in the load for home appliances and equipment.

The second premise is that there are two zones of outdoor air temperature that trigger different electricity demands. As shown in Figure 1, at lower outdoor air temperatures, electricity demand distributes in a small range. This electricity demand data reflects those in mid-seasons during which most residential customers do not use air conditioners. At higher outdoor air temperatures, electricity demand increases with increase in outdoor air temperature which is attributed to three causes: the number of air conditioners that are operating increases, the heat load managed by these air conditioners increases, and the energy conversion efficiency of the air conditioners decreases.

Based on these premises, we proposed the procedure explained below. First, the outdoor air temperature is divided into two temperature regions. Electricity demand at each time of day (clock time) was modeled to be constant in the lower temperature region, while a multiple regression model using climatic conditions as input was developed for the higher temperature region. Then, time-series electricity demand was modeled by combining these regression models developed for each clock time and a residual term. Finally, the electricity demand under the climatic conditions observed in 2012 were input to the time-series models. As the time-series models reflect the characteristics of electricity demand observed within each group, the difference in estimated electricity demand can be mainly attributed to the difference in people's daily behavior. It should be noted that a portion of the difference would be given by an increase in the energy efficiency of home appliances. We considered that this reduction was modest as discussed later. The remaining part of this section explains the process of each step in detail.

Two Temperature Regions for Electricity Demand

This section explains the method to divide temperature regions. Figure 2 illustrates the process of setting the boundary of temperature-distinguished regions for each clock time. We refer the temperature to the bifurcation boundary temperature, T_{bb} [°C]. First, a tentative T_{bb} is set to be at 18 °C. Then, a constant (C_L) representing the electricity demand in the region of outdoor air temperature lower than T_{bb} is determined as the mean of the electricity demands. The square test is then conducted to examine whether the distribution around the constant can be applied to the region with ΔT °C from T_{bb}. If the distribution fits the distribution within the ΔT °C region, T_{bb} is updated by increasing it by ΔT °C. This process is repeated until the square test does not fit to a new ΔT °C region. T_{bb} is determined as the last tentative value, and ΔT was set to 0.5 °C. If the number of samples within a ΔT °C region was smaller than 5, ΔT was increased by 0.5 °C.

Multiple Regression Analysis for Electricity Demand at Each Clock Time

As explained above, two regression models were developed for each clock time to estimate the mean electricity demand under given climatic conditions. As mentioned above, electricity demand at each time of day (clock time) was modeled to be constant in the lower temperature region, while a multiple regression model using climatic conditions as input was developed for the higher temperature region. For electricity demand in the temperature region above T_{bb}, a regression model was developed by using independent variables listed in Table 3. We confirmed that all variables do not have a correlation greater than 0.6. Some of these variables were selected by using the forward selection method of the Akaike information criterion (AIC) to eliminate less-significant variables while avoiding to lose the accuracy (Akaike 1973).

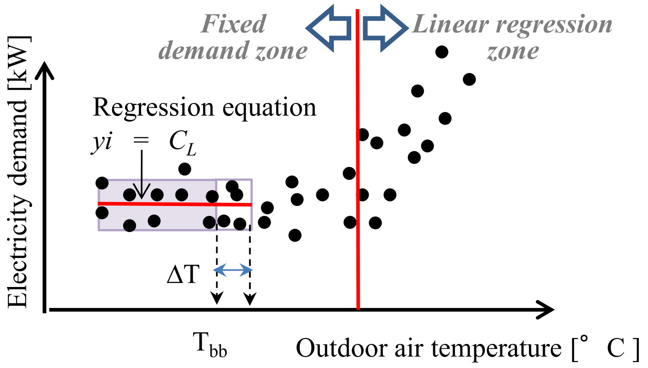

Figure 2. Illustration of two temperature zones.

Table 3 Initial set of independent variables examined for multiple regression analysis[1]

Independent variables	Abbreviation	Independent variables	Abbreviation
Outdoor air temperature	OAT	Atmospheric pressure	AP
Square of outdoor air temperature	OAT^2	Temperature difference A	TDA
Amount of insolation	INS	Temperature difference B	TDB

Time-Series Model Considering Autocorrelation

In the previous step, two regression models were developed for each clock time to estimate the mean electricity demand under given climatic conditions. Using the regression models, time-series electricity demand is modeled by Equation 1:

$$ED_t = MD_t(OAT_t, OAT^2{}_t, INS_t, AP_t, TDA_t, TDB_t) + RD_t \tag{1}$$

where ED_t is electricity demand, MD_t is mean demand given by the regression model for clock time t, and RD_t is a random term corresponding to the residual of the regression model. By combining the ED_t values corresponding to each clock time with climatic conditions listed in Table 3 during the analysis period, the time-series electricity demand was estimated.

In addition to the mean electricity demand, the random term, RD_t, is considered. The consideration of the random term is important to avoid underestimation of the peak electricity

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[1] There are two types of temperature difference in Table 3. While we assumed that electricity demand at a clock time was determined only by climatic conditions, electricity demand is not usually so sensitive to daily climatic changes. For example, once air conditioner use is habitual in a home, people keep using the air conditioner even if the outdoor air temperature drops. To reflect this behavioral aspect, two types of temperature difference, A and B, were considered. TDA is defined as the difference between the outdoor air temperature at the time and mean of the previous day's outdoor air temperature for the previous 6 h. TDB is defined as the difference between the outdoor air temperature at the time and mean of the outdoor air temperature at the time for the previous three days.

demand. We assumed a normal distribution with standard deviation given by the standard error of the regression model (σ_t). If the mean of the normal distribution is zero, the term may randomly become positive or negative. However, many time-series data have an autocorrelation by which the random term is influenced by that of the previous step. If an autocorrelation exists, the random term can be modeled by Equation 2:

$$RD_t = N(\rho \cdot RD_{t-1}, \sigma_t^{\ 2}) \qquad (2)$$

where the mean value of the normal distribution is given by the product of the random term of the previous step and autocorrelation coefficient, ρ [-]. The Durbin−Watson statistic is used to test the existence of autocorrelation.

Monte Carlo Simulation with Climatic Conditions for 2012

Until the previous section, a time-series model was developed to estimate electricity demand for the four groups listed in Table 3. By inputting the climatic conditions observed in 2012 to the developed models, we estimated electricity demand that was normalized by climate conditions. As the time-series models reflect the characteristics of electricity demand observed within each group, the difference in estimated electricity demands can be understood as based on differences in electricity use behavior. Since the model contains a random term, a trial was conducted 1,000 times and the estimated electricity demand was statistically evaluated.

Indicators for Comparison

Table 4 lists the indicators used for comparison among the four groups listed in Table 3.

Table 4. Indicators for comparison

Indicator	Definition
Total electricity demand	Sum of electricity demand during the examined period [kWh]
Average hourly electricity demand for weekdays	Electricity demand at each clock time is averaged among weekdays in August [kW]
Load duration curve	Frequency distribution of electricity demand within the peak time from 13h00 to 16h00 on weekdays, arranged in descending order of magnitude
Peak electricity demand	Electricity demand at 0, 1, and 5% of frequency in the load duration curve [kW] (1% is 6 hours from the highest demand)
Peak electricity demand at peak time of KEPCO	The electricity demand at 15h00 on August 3 at which the highest electricity demand [kW] was observed in the KEPCO service region in 2012

Result: Development of Time-Series Electricity Demand Model

Division of Temperature Region

Figure 3 shows the estimated bifurcation boundary temperature, T_{bb}, for each clock time on weekdays. Because of the method, T_{bb} is sensitive to dispersion of electricity demand data. This is the reason discontinuity is observed. The result shows that T_{bb} was higher during daytime than during evening and night time. This implies that the habitual practice of air conditioner use is more influential than outdoor air temperature.

Multiple Regression Analysis for Electricity Demand at Each Clock Time

Table 5 lists the Regression coefficients for the regression model developed for the representative times of 8h00, 14h00, and 19h00.

Time-Series Model Considering Autocorrelation

Table 6 shows estimated autocorrelation coefficients and Durbin−Watson statistics. The autocorrelation coefficients for the four groups were all statistically significant within a 5% significance level.

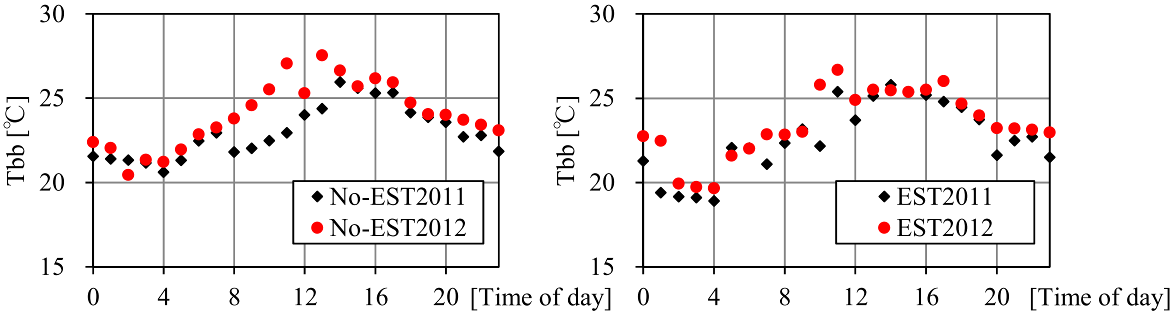

Figure 3. Process of setting temperature-distinguishing region.

Table 5. Regression coefficients for regression models

Group	Time	OAT	OAT^2	TDA	TDB	AP	INS
No-EST2011	8	−0.949	0.222		−0.934		−0.278
	14		0.682		−0.193	−0.365	0.382
	19	0.617		−0.689	−0.288	0.285	
No-EST2012	8		0.456	−0.754	−0.415		−0.125
	14		0.744	−0.915	−0.826		−0.142
	19	0.617		−0.689	−0.288	0.285	
EST 2011	8		0.339	−0.936			
	14		0.696		−0.169	−0.367	
	19		0.965	−0.750	−0.944		−0.343
EST 2012	8	−0.157	0.000		0.334		−0.119
	14		0.000	−0.265			0.000
	19	0.562			0.000	0.000	

Table 6. Autocorrelation coefficients and Durbin−Watson statistics

Group	Autocorrelation coefficient	Durbin−Watson statistics
No-EST2011	0.79	0.42
No-EST2012	0.76	0.48
EST 2011	0.69	0.62
EST 2012	0.69	0.73

Validation of Time-Series Model

To validate the model for the four groups, Figure 4 compares the observed and estimated electricity demands. To estimate the demands, climatic conditions observed in 2011 and 2012 were input to the models of 2011 and 2012, respectively. The figure lists the coefficients of determination (R^2). These are high, indicating that the model fits well to the observed electricity consumption.

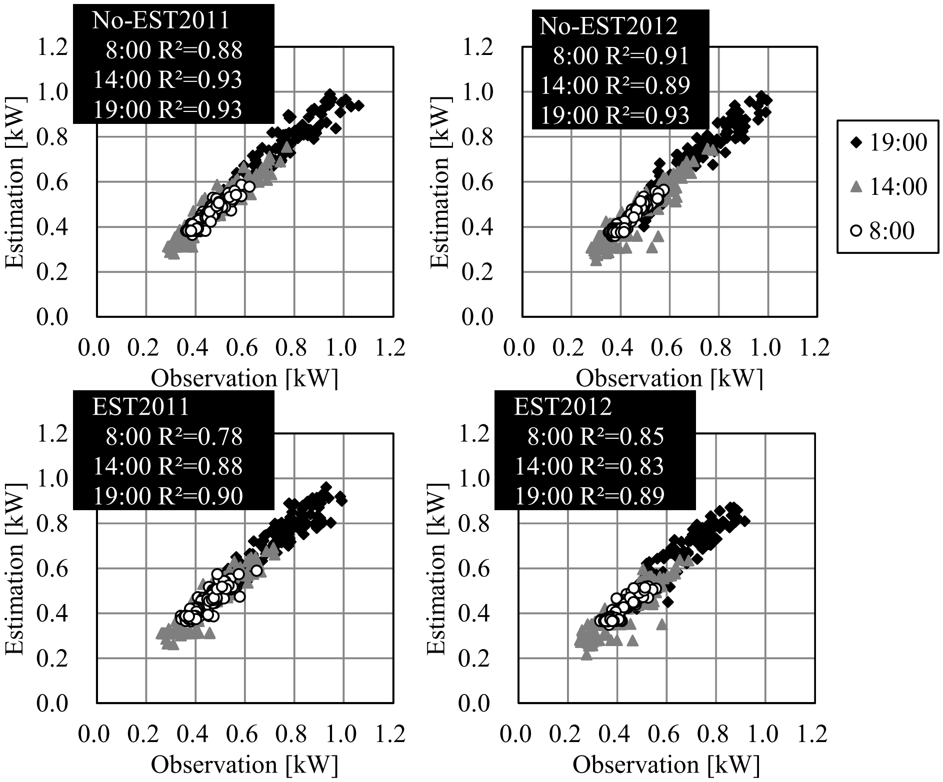

Figure 4. Process of setting temperature-distinguishing region.

Estimation of Electricity Savings Effect

Total Electricity Demand

Figure 5 shows the total electricity demand from June to October estimated using climatic conditions observed in 2012. The difference between No-EST2011 and No-EST2012 can be understood as the reduction achieved by a change in people's basic daily behavior in general households in the KEPCO service region. It is 2.1% for demand in August, 2.7% from July to September, and 2.6% over the five-month period. The reduction from 2011 to 2012 made by EST group is higher by approximately 5% compared with No-EST group as the reduction in August was 7.2%, 7.9% from July to September, and 7.9% over the five months[2].

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[2] The difference between No-EST 2011 and EST 2011 is due to the difference between the two groups. The demand of EST 2011 was slightly larger by approximately 2%. This result shows that EST group did not have smaller electricity demand in 2011 compared with No-EST group.

Average Hourly Electricity Demand for Weekdays

This section shows how the reduction in the total electricity demand distributes over the time of day. Figure 6 shows hourly electricity demand averaged for weekdays in August. The left axis shows the demand and right axis shows the difference between 2011 and 2012. As shown in the left figure for No-EST 2011 and 2012, electricity demand was comparable except for the peak time from 12h00 to 14h00. This implies that, first, general households reduced electricity demand during KEPCO's peak time during which electricity saving was requested. Second, the impact of energy efficiency was limited and the reduction can be attributed to a change in the customers' electricity use behavior. Figure 7 only shows the difference between 2011 and 2012 calculated for each month from June to October. As shown in the left figure, the reduction is larger for the peak time especially in July and August.

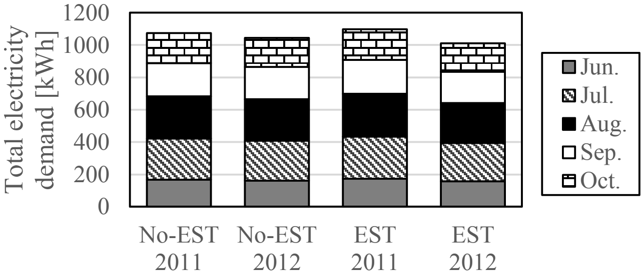

Figure 5. Total electricity demand estimated under climatic conditions observed in 2012.

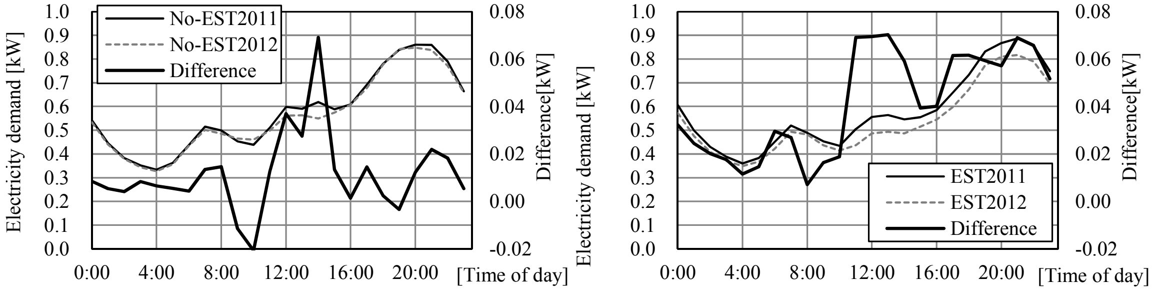

Figure 6. Average electricity demand on weekdays in August.

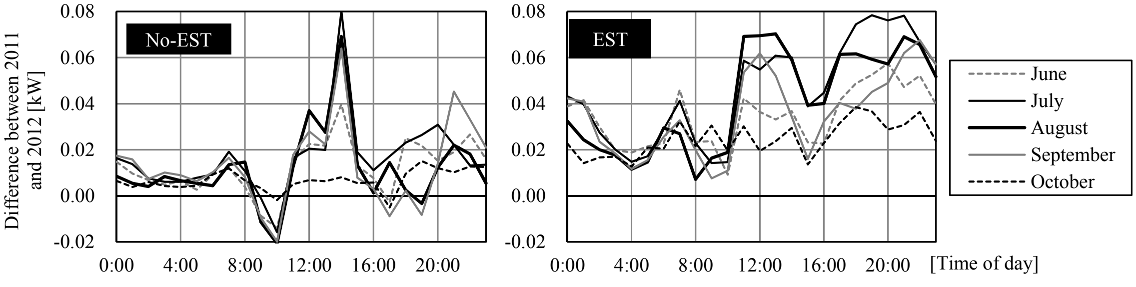

Figure 7. Reduction in electricity demand from 2011 to 2012.

Figure 6 and Figure 7 shows the same result for EST groups. The reduction from 2011 to 2012 in August was more than 40 W lower from 11h00 to 24h00. This implies that households subscribed to EST reduced their electricity demands for longer hours. It should be noted that reducing air conditioner use contributed significantly[3]. As shown in Figure 7, the reduction was sustained for a longer period of time until October.

Load Duration Curve

This and next sections explains how the change in electricity use behavior contributed to reducing the electricity demand within the peak time of KEPCO. Figure 8 shows the load duration curves of the estimated electricity demand from 13h00 to 16h00 on weekdays in August arranged in descending order of magnitude. The figure also shows the actual load duration curves observed in 2012 (Ob. No-EST and Ob. EST). The estimated results agreed well with the observed demand. Figure 9 shows the electricity demand corresponding to 0, 1, 5, 20, 40, 60, and 80% of the load duration curves. The electricity demand at the 1% duration point of No-EST 2012 is 68 W lower than that in 2011. The demand at the 5% point is lower by 54 W. This result corresponds with that shown in Figure 6, indicating that electricity demand was reduced only during the peak time.

This reduction is significant as the reduction at the 1 and 5% duration points is equivalent to 0.85 and 0.68 GW, respectively, if the reduction is extrapolated to the entire residential customer base, 12.5 million households, in the KEPCO service region.

Further reductions were made by the No-EST group. The 1 and 5% point demands are lower by 82 and 69 W, respectively, than those in 2011, equivalent to 16.1 and 13.5 MW.

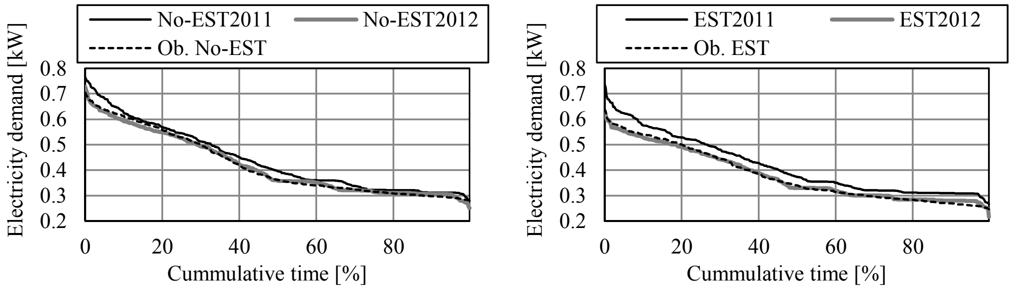

Figure 8. Average electricity demand on weekdays in August.

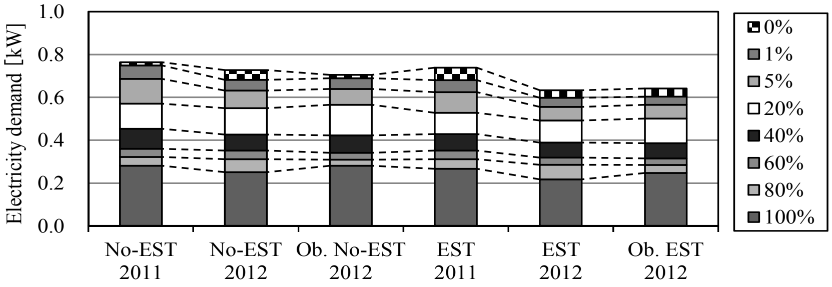

Figure 9. Average electricity demand on weekdays in August.

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[3] To confirm this point, we developed a simple regression model of the electricity demand at 15h00 observed when the outdoor air temperature was higher than 30 °C. The independent variable is the outdoor air temperature. The regression model is $Y=0.051 \cdot OAT-1.09$ for No-EST2011, $Y=0.048 \cdot OAT-0.99$ for No-EST2012, while $Y=0.045 \cdot OAT-0.91$ for EST2011 and $Y=0.028 \cdot OAT-0.41$. The regression coefficient [kW/°C] represents the electricity demand increase due to an increase of 1 °C in outdoor air temperature. In addition to the smallest demand of EST 2012, the regression coefficient of EST 2012 is significantly smaller than that of the other groups.

Peak Electricity Demand at KEPCO Peak Time

This section quantified the contribution of the reduction made by the general residential customers to the electricity demand at 15h00 on August 3, 2012, when the highest electricity demand was observed in the KEPCO service region. The observed demand at the time was 0.655 kW (referred to "Ob. No-EST").

Figure 10 shows the distribution of estimated electricity demand at the peak time of KEPCO. The mean demand of No-EST 2012 and No-EST 2011 was estimated to be 0.70 and 0.75 kW, respectively. The probability at which electricity demand lower than 0.655 kW occurs was estimated to be 14.5%. Electricity demand of No-EST 2012 at the same point was estimated to be lower by 45.6 W than that of No-EST 2011. If the reduction is extrapolated to the entire residential customer base in the KEPCO service region, this reduction is equivalent to 0.52 GW of electricity demand. In other words, the demand of residential customers at the peak time could have been higher by 0.52 GW if behavioral changes were not made in 2012, compared with 2011. If the mean point and 1% highest point of No-EST 2011 occurred in 2012, the demand could have increased by 1.0 and 2.3 GW, respectively.

It should be noted that there seems to be a consistent shift of the observed demand (Observations of No-EST2012 and EST2012) to lower end of the curves. This implies that the demand does not randomly distribute. One potential explanation of this point is that the general residential customers reflected information provided by KEPCO and the government about the demand and supply situation of KEPCO.

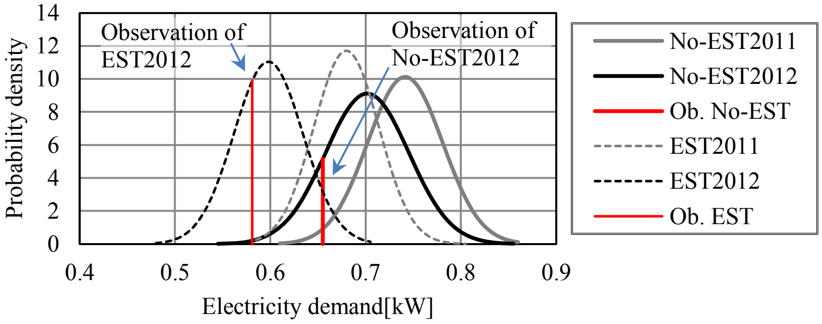

Figure 10. Probability density distribution of power demand.

Discussion

Effect of Electricity Saving Effort in General Residential Customers in KEPCO Service Region

As observed in the results for No-EST 2011 and No-EST 2012, general residential customers reduced electricity at the peak time from 12h00 to 14h00 by changing their electricity use behavior. The reduction by electricity saving effort was estimated to be more than 50 W per household during the peak period, which is approximately 8% of demand. The reduction at peak time was much larger than the reduction in the total electricity demand in August, approximately 2%. The reduction at peak time during the peak period was equivalent to 0.85 GW in the KEPCO service region (reduction at the 1% duration point of the load duration curve).

Specifically, the demand at 15h00 on August 3, 2012 could have been higher by at least 0.52 GW if electricity saving effort from 2011 had not been made.

Influence of Incentive Structure of EST on Electricity Use Behavior

A characteristic of the Electricity Saving Trial, EST, is that the reduction from 2011 to 2012 was defined by the total electricity demand from June to September. This incentive structure significantly affected the behavior of residential customers subscribed to EST. The customers reduced electricity demand for longer hours, as shown in Figure 6, and for a longer period, as shown in Figure 5, than general residential customers. The authors did not include any analysis on concrete methods conducted to achieve the reduction in this paper. However, it was evident that reduction of air conditioner use contributed significantly as the observed electricity demand of EST group in 2012 observed while outdoor air temperature was higher than 30 °C as well as its simple regression coefficient for outdoor air temperature were significantly smaller than that of the other groups.

Conclusion

This paper quantifies the effect of electricity saving effort during the summer in 2012 compared to 2011 among residential customers on electricity demand. Among general residential customers, reduction was made only during the peak time from 12h00 to 14h00 by changing their electricity use behavior, however it contributed significantly to reducing the total demand in the KEPCO service region which was estimated to be equivalent to 0.50 to 0.85 GW during peak time. The electricity demand on August 3, 2012, when the highest demand was observed in the KEPCO service region, could have been higher by 0.5 to 2.3 GW if behavioral changes were not made in 2012, compared with 2011. This paper also analyzes the influence of the financial incentive reflecting the electricity demand reduction provided by the Electricity Saving Trial in which the reduction was defined by the total electricity demand from July to September. While reduction in electricity demand was made for limited hours at peak time among the general residential customers, significant reductions were made for longer hours, from 11h00 to 24h00 and a longer period of time among the customers who subscribed to the trial, EST. As explained here, this paper quantified how the change in electricity use behavior contributed to the demand reduction in KEPCO service region during the summer of 2012, the authors did not discuss the direct measures carried out to reduce the electricity demand. The authors will investigate this point in our future works.

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