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An Empirical Study of Electric Power Demand Control by Real-Time Feedback of Consumption Levels: Case of Nushima Island households

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Abstract

Electric power demand management will play an important role in the creation of smart-energy communities. We are conducting a field experiment on the real-time feedback of electric power consumption via smart meters and tablet PCs with the participation of 51 households on Nushima Island, one of Japan's remote islands. Our estimate of the effect of feedback in reducing power demand by panel data analysis has revealed that such feedback achieves a saving of 7.6 percent in electric power demand.

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Keywords: electric power consumption; real-time feedback; field experiment, demand management, panel data analysis

1. Introduction

In order to create smart-energy communities that are climate-friendly and resilient to disasters, energy demand management through feedback of power consumption will play a significant role.

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Nomenclature

AC	Number of air conditioners [units]
C	Constant
CDH	Cooling degree-hours [degree-hours]
CF	Number of commercial freezers [units]
DUME	Dummy variable for households where all energy is supplied by electric power
DUMK	Dummy variable for use of non-electrical heating equipment such as a kerosene heater
DUMT	Dummy variable for living in a timber house
DUMV	Dummy variable for summer vacation season
DUMX_Y	Dummy variable for feedback period (X: pattern of feedback, Y: month)
EC	Daily electric power consumption [Wh/day]
HDH	Heating degree-hours [degree-hours]
HH	Number of household members [persons]
RF	Number of refrigerators [units]
VC	Daily frequency of viewing electric power consumption on the tablet PC [times/day]
WS	Daily mean wind speed [m/s]
α	Partial regression coefficient
β	Individual effect of each household
d	Date
i	ID number of each household

Faruqui et al. [1] reviewed a dozen utility pilot programs that focused on either the energy conservation impact of in-home displays (IHDs) or demand-side management technologies. The study showed that the power demand of consumers who actively used an IHD decreased on average by about 7 percent when prepayment for electric power was not involved. Houde et al. [2] found that access to real-time feedback led to an average reduction in household electric power consumption of 5.7 percent and that significant declines continued for up to four weeks.

On the other hand, real-time information feedback through technology has been reported to produce reductions of up to 20 percent in residential energy consumption [1], with the level of reduction depending on the experimental conditions. In this context, we have been focusing our attention on the development of an effective feedback method for the management of power demand that is suited to regional conditions. We have been conducting a field experiment for this purpose on Nushima Island, located in Hyogo Prefecture, Japan. This paper describes the design of the experiment and reports the findings obtained from an empirical analysis.

2. Methodology

2.1. Outline of the experiment

This experimental study being conducted on Nushima Island is a three-year project that commenced in 2012. In 2012, smart meters were installed in the residences of 51 households. In May 2013, tablet PCs were distributed to the participants that presented feedback on their electric power consumption. The contents of the feedback are rotated monthly from Pattern 1 to Pattern 3. As shown in Fig. 1, each household can view its electric power consumption and per-capita consumption in real time via the tablet PC in Pattern 1. They are also able to compare their consumption with the average consumption of participating households in Pattern 2. Moreover, an electric power consumption ranking among the participating households is displayed in Pattern 3. Table 1 shows the schedule of the feedback from Pattern 1 to Pattern 3 in 2013. We are assessing the impacts of the feedback on the actual power demand by using data collected via smart meters.

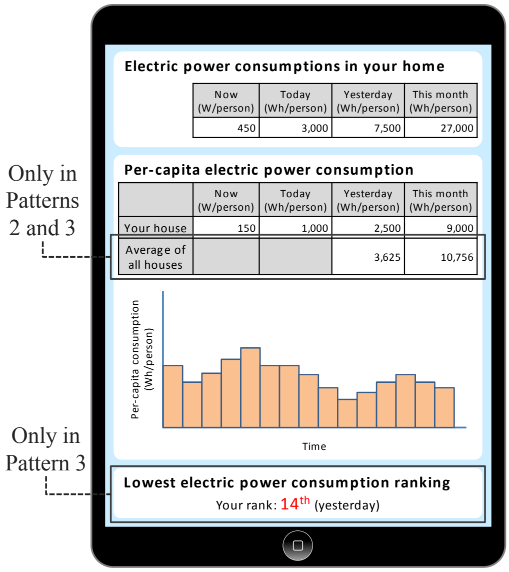

Fig. 1. Information displayed on a tablet PC.

Table 1. Schedule of feedback.

	Pattern		
	1	2	3
May	○		
Jun.	○		
Jul.		○	
Aug.			○
Sep.	○		
Oct.		○	
Nov.			○
Dec.	○		

2.2. Analysis method

In this study, we are implementing panel data analysis to assess the effect of feedback on the management of electric power demand. Power demand depends on a variety of factors, including temperature, household size, and types of electrical appliances used. Hence, it is significant to estimate the impact of feedback separately from other factors that may have an influence on electric power consumption taking the heterogeneity of the participating households into consideration.

We analyzed the daily electric power consumption of the 51 households from May to December 2013. Equation (1) is the estimating equation used to determine the impact of feedback on daily power demand. The equation defines daily electric power consumption in terms of an explained variable and three types of factors, namely, factors related to the external environment, internal environment, and feedback, as explanatory variables. The formula was originally developed for this study based on the authors' investigations.

First, daily electric power consumption values were observed from the smart meters. The external environmental factors were then obtained; namely, the cooling degree-hours, heating degree-hours, and daily mean wind speed. These data were collected from the *Climate Statistics* provided by Japan Meteorological Agency [3]. The cooling/heating degree-hours describe to what extent (in degrees) and for how long (in hours) the outside air temperature is higher/lower than a specific base temperature. The base temperature for cooling degree-hours was set at 24°C and that for heating degree-hours was set at 18°C.

The internal factors were composed of the number of household members, air conditioners, refrigerators, and commercial freezers for fishery; whether all of the energy in a household was supplied by electricity; whether non-electrical heating equipment was used; whether the household was living in a timber house; and whether the targeted period was the summer vacation season. Finally, the factors related to feedback consisted of whether feedback was introduced and the frequency of viewing electric power consumption on the tablet PC.

From the results of a Hausman test, we adopted a random effect model in which an individual effect was treated as a stochastic variable. The number of samples obtained excluding missing values amounted to 12,011, which were collected from the 51 households over a period of 275 days from April 1 to December 31, 2013.

$$
\begin{aligned}
&EC_{i,d} \\
&= C + \alpha_1 HH_{i,d} + \alpha_2 HH_{i,d}^{\frac{1}{2}} + \alpha_3 CDH_{i,d} + \alpha_4 CDH_{i,d}^{\ 2} + \alpha_5 HDH_{i,d} + \alpha_6 HDH_{i,d}^{\ 2} \\
&+ \alpha_7 WS_{i,d} + \alpha_8 AC_{i,d} + \alpha_9 RF_{i,d} + \alpha_{10} CF_{i,d} + \alpha_{11} DUME_{i,d} + \alpha_{12} DUMK_{i,d} \\
&+ \alpha_{13} DUMT_{i,d} + \alpha_{14} DUMV_{i,d} + \alpha_{15} DUM1\_5_{i,d} + \alpha_{16} DUM1\_6_{i,d} \\
&+ \alpha_{17} DUM1\_9_{i,d} + \alpha_{18} DUM1\_12_{i,d} + \alpha_{19} DUM2\_7_{i,d} + \alpha_{20} DUM2\_10_{i,d} \\
&+ \alpha_{21} DUM3\_8_{i,d} + \alpha_{22} DUM3\_11_{i,d} \\
&+ \alpha_{23}\left(VC_{i,d} \times DUM1\_5_{i,d}\right) + \alpha_{24}\left(VC_{i,d} \times DUM1\_6_{i,d}\right) \\
&+ \alpha_{25}\left(VC_{i,d} \times DUM1\_9_{i,d}\right) + \alpha_{26}\left(VC_{i,d} \times DUM1\_12_{i,d}\right) \\
&+ \alpha_{27}\left(VC_{i,d} \times DUM2\_7_{i,d}\right) + \alpha_{28}\left(VC_{i,d} \times DUM2\_10_{i,d}\right) \\
&+ \alpha_{29}\left(VC_{i,d} \times DUM3\_8_{i,d}\right) + \alpha_{30}\left(VC_{i,d} \times DUM3\_11_{i,d}\right)
\end{aligned} \tag{1}
$$

3. Results and Discussion

The estimation results obtained from the daily panel data analysis are shown in Tab. 2. The coefficients of *DUM1_5*, *DUM1_6*, *DUM1_9*, *DUM2_10*, *DUM3_8*, and *DUM3_11* are statistically significant at the 1 percent level. This indicates that the feedback had the effect of reducing electric power demand, except in August and December. The effect is estimated as a 7.6 percent reduction compared with the mean daily consumption of the participating households in May, June, September, October, and November 2013.

Table 2. Results of daily data analysis.

Variable	Coefficient		t value	Variable	Coefficient		t value
C	-6.515×10^4	**	-2.061	*DUM1_5*	-1,048	***	-5.758
HH	-2.101×10^4	*	-1.785	*DUM1_6*	-1,402	***	-6.395
$HH^{1/2}$	7.401×10^4	**	1.994	*DUM1_9*	-1,126	***	-5.220
CDH	8.352	**	2.027	*DUM1_12*	254.8		1.100
CDH^2	0.2177	***	6.764	*DUM2_7*	-265.8		-1.065
HDH	5.731	***	2.867	*DUM2_10*	-1,618	***	-8.586
HDH^2	5.696×10^{-2}	***	8.378	*DUM3_8*	1,981	***	7.559
WS	115.8	***	3.939	*DUM3_11*	-480.2	***	-3.097
AC	302.2		0.1308	*VC×DUM1_5*	29.34		-0.5105
RF	8,183	***	2.963	*VC×DUM1_6*	68.77		1.107
CF	1.005×10^4	***	3.889	*VC×DUM1_9*	-48.44		-0.7291
DUME	5,132	*	1.732	*VC×DUM1_12*	891.6	***	8.876
DUMK	-1,495	***	-10.23	*VC×DUM2_7*	-66.46	***	-3.198
DUMT	1,556		0.3644	*VC×DUM2_10*	63.14		1.009
DUMV	2,184	***	9.240	*VC×DUM3_8*	-192.8	***	-2.993
				VC×DUM3_11	364.6	***	4.904
Adjusted R-squared			0.3608	Durbin-Watson statistic			0.7139

*, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Additionally, the coefficients of (*VC×DUM1_12*), (*VC×DUM2_7*), (*VC×DUM3_8*), and (*VC×DUM3_11*) are also statistically significant at the 1 percent level. These results indicate that viewing frequency has an effect on electric power demand in both directions: a decreasing effect in July and August and an increasing effect in November and December. The differing effects may be related to consumers' perception gap between subjective savings and real savings, as reported by Attari et al. [4].

4. Conclusion

We found that real-time information feedback reduced electric power consumption by 7.6 percent on average, although the effects included both positive and negative factors in terms of energy savings. A further experimental study is to be implemented in the summer and winter of 2014 in order to estimate the additional effect of dynamic pricing.

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