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High-resolution determinant analysis of Japanese residential electricity consumption using home energy management system data

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ABSTRACT

This paper examines seasonal panel data analysis at a higher resolution using commercial home energy management system data to identify the parameters that determine Japanese household electricity consumption. The electricity consumption data from 532 detached houses and 208 apartment-style houses is aggregated by use and time period and regressed with explanatory variables to indicate house and occupant attributes. Predictable significant impact factors such as outdoor temperature, floor area, household size, presence of a central air conditioning system, and a variety of appliances are estimated quantitatively. The differences due to appliance possession are estimated as 844 kWh/year for a water server, 885 kWh/year for an additional refrigerator, 491 kWh/year for a portable humidifier, and 443 kWh/year for an air purifier. We found previously unknown correlation between variables such as central air conditioning and hot water demand through this model. We also identified several important parameters that explain electricity demand by data collecting at different sites and time periods. Obtained knowledge will contribute to promoting further energy efficiency program in the Japanese residential sector. Households in our study were newer houses and additional data are required for a more stable and reliable model. In addition, a reverse estimation of household attributes from electricity load dynamics is an issue for future study.

1. Introduction

Global electricity consumption continues to rise at a high pace and residential electricity use represented 31% of electricity consumption in OECD countries in 2012 [1]. Households consumed 29% of the total electricity used in Japan in 2013 and household consumption has increased by 56% from 1990 to 2013 [2]. In June 2015, the Japanese government announced a new energy conservation target to be reached by all sectors by 2030, and the residential sector is required to reduce energy use by 24% from reference scenario within the same timeframe [3]. Japan should also consider deploying a residential demand response program, which would enable the use of massive amounts of renewable energy in the future power system of the country [4,5]. To realize energy conservation and demand response in the residential sector, it is key to fully understand the structure of household energy consumption. Recently, smart meters have grown in popularity around the world. Over 50 million smart meters had been deployed in the U.S covering over 43 percent of U.S. homes as of July 2014 [6] and the EU aimed to replace at least 80% of electricity meters with smart meters by 2020 [7]. At the same time, Japanese government aimed for the full deployment of smart meters into all houses by around the middle of the 2020s and the movement has been accelerated by deregulation of the retail electricity market in 2016 [8]. These meters allow for a detailed analysis of electricity consumption [9]. Moreover, home energy management systems (HEMS) have gained the support of the Japanese government, including the issuing of subsidies, following the earthquake of 2011. As of 2015, it is estimated that twenty thousand HEMS have been introduced to individual homes in Japan. Most commercially available HEMS can only monitor electricity use, and very few models can monitor gas or water usage. The time resolution of HEMS data is 30–60 min and usage resolution is either by a whole house or an 8–40 sub-meter, and HEMS can provide electricity consumption by usage, space heating, space cooling, water heating, and other variables. This paper analyzes the structure of household electricity consumption using HEMS data, which offers a higher resolution than a smart meter. Household electricity data is classified according to time period and usage, and a regression model is developed to disaggregate the impact of attribute data such as floor area and household size.

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We used one-hour interval HEMS data for 527 detached houses and 208 apartment-style houses between 2013 and 2014.

2. Background

There has been a great deal of effort to understand the structure of residential electricity consumption globally [10,11]. Previous studies have used either a top-down approach or a bottom-up approach. The top-down approach uses econometrics and a statistical/regression method for the aggregated residential sector, such as at the national level, and aims to clarify the relationship between electricity consumption of households and social parameters that include macroeconomic indicators (gross domestic product (GDP)), price, climate conditions, housing construction/demolition, appliance possession and so on. The bottom-up approach focuses on individual households and estimates the electricity consumption using physical, social, behavioral, and demographic characteristics per household. While most bottom-up models have used whole yearly or monthly electricity consumption data, our study aims to construct a bottom-up model with a higher resolution. Detailed information has been applied in some studies and regression using smart meter data or monitoring data has appeared as the accessibility to this information has increased [9,12–14]. McLoughlin et al. [12] examined the influence of dwelling and occupant characteristics on maximum electricity consumption, load factor, and time of use (TOU) indicator using data from 4200 dwellings with smart meters in Ireland. Kavousian et al. [9] examined structural and behavioral determinants of daily maximum and minimum consumption using smart meter data from 1628 households in the U.S. However, smart meters supply only whole consumption data, not individual usage data, and are insufficient for an in-depth understanding of the structure of residential electricity consumption. The influence of several household characteristics on electricity consumption by use was also examined using household monitoring data. Gram-Hanssen et al. [13] examined end-use electricity consumption in 70 Danish households for one month and the impact of resident age, household income, and propensity for energy saving. A load research project in central Florida in 1999 supplied 204 residences' monitoring data, including all sub-metered data and the impact of outdoor temperature and household size on space heating, space cooling, and hot water demand [14]. Sample sizes in monitoring projects were generally limited and, hence, were insufficient to determine the statistical significance in the work.

HEMS, which can monitor electricity consumption by sub-meter, are commercially available and several housing builders include HEMS as a standard feature in new houses in Japan. We collected HEMS data for approximately 1000 households from homebuilders, condominium developers, and HEMS data service providers to construct a HEMS database, which was created to include data with varied resolutions. In addition to energy consumption data, the database contains survey responses regarding household residents' attitudes, which were collected using questionnaires. The database is linked to meteorological weather data and appliance specification data to analyze these factors in connection with HEMS data.

This paper presents the determinants of household electricity consumption using the HEMS database, which has a higher resolution than a smart meter. Household electricity data is classified according to time zone and use, seasonal panel data analysis model was developed to disaggregate the impact of attribute data.

3. Data collection and analysis methodology

We used 740 household datasets collected between December 2013 and November 2014 from our HEMS database after screening for outliers and missing values. Three different HEMS datasets were analyzed, as shown in Tables 1 and 2. The difference in annual electricity consumption in Site 2 between central air conditioning (AC) system and non-central AC system is quite large, because most of central AC houses install a two-floor central AC system in Site 2. Sample households holding HEMS had a higher proportion of new houses and ages of heads of these households also recorded a majority in the 30–40 age group consequently. The largest households in Site 1 of the three sites have increased greatly the ratio of households with central air conditioning system and more than 97% of our detached houses install a photovoltaic generation system.

Electricity consumption data by sub-meters were aggregated by hot water, air conditioner, and other appliances. Note that the use of air conditioning included a main system only, which could be measured by sub-meters, and personalized air conditioning apparatuses such as halogen heaters or electric carpets were classified into a category of other appliances. The HEMS measurement method differs for three sites because those systems were

Table 1
HEMS dataset.

Site	Sample size	Dwelling type	Built year	Ratio of electrified house[a]	Ratio of central air conditioning system	Ratio of colder area[b]	Maximum number of measured sub meter	Measurement item	
								Main meter	Sub meter
Site 1	405	Detached	2011–2012	100%	66%	5%	8	Current and voltage	Current and voltage
Site 2	122	Detached	2012–2013	72%	17%	6%	32	Current and voltage	Current only
Site 3	213	Almost apartment (include 5 detached)	2010–2012	57%	0%	14%	8 or 16	Current only	Current only

[a] The term electrified house indicates the houses consume only electricity for main air-conditioning, hot water and other appliances.
[b] HDD(18-18) is more than 2500.

Table 2
Average annual electricity consumption [kWh/year household].

Site	Electrified house	Gas usage house	With central air conditioning system	Without central air conditioning system
Site 1	8692	–	8908	8167
Site 2	6878	4969	8941	5814
Site 3	5560	3486	–	–