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Determining the relationship between a household's lifestyle and its electricity consumption in Japan by analyzing measured electric load profiles

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ABSTRACT

Since the Great East Japan Earthquake and Fukushima nuclear accident in 2011, both energy consumption and CO_2 emissions have been increasing in the residential sector of Japan. For this reason, smart meters have received much attention as a way to provide energy-use feedback to households and thereby encourage energy conservation. In order to provide effective feedback, it is necessary to take into account the lifestyle of each household, but little work has been done to develop a methodology to determine the relationship between a household's lifestyle and its electricity consumption.

This paper proposes two methods that identify a household's lifestyle from electricity use data. By using a frequency analysis of weekly load profiles, we verified that, except in winter (December 2013–February 2014), the average daily consumption of morning-oriented lifestyles is 5.3% less than that of night-oriented lifestyles. The results of cluster analyses of each household's daily electric load profiles suggest that most households consume less electricity when following a regular routine.

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1. Introduction

The residential sector accounts for 14.3% (2051 PJ/year) of the total energy consumed in Japan [1], and 475.9 Mton CO_2 is emitted due to energy consumption in the residential sector [2]. The energy consumption in this sector has doubled since 1973, and in recent years, CO_2 emissions have been increasing because all nuclear plants have been shut down and most electricity is now being generated by fossil fuel thermal power plants. Improving energy efficiency in the residential sector of Japan is thus a big challenge.

A smart meter, which is a component of a home energy management system (HEMS), is an innovative technology that can be used to reduce energy consumption in the residential sector. Smart meters have spread globally, primarily to developed countries, and over 800 million smart meters will have been installed into households by 2020 [3]. In Japan, the importance of a smart meter is mentioned in the new Strategic Energy Plan [4], which is the first plan to be drawn up since the Great East Japan Earthquake and the Fukushima nuclear accident in 2011. The plan suggests that deployment of an advanced metering infrastructure (AMI), including smart meters, is one of the various demand-side measures that can reduce and stabilize energy consumption in the commercial and residential sectors, and, as a first step towards deploying the AMI, the plan calls for the installation of smart meters in all households by the early 2020s.

Household energy consumption is influenced by various characteristics of buildings, home appliances, residents and their behaviors [5–7], and many studies on household energy modeling revealed that household energy load curves largely depend on the residents' behaviors [8–12]. Therefore, this study focuses on the relationship between household energy consumption and the residents' lifestyles. In this paper, we use the terms "behavior" and "lifestyle", as broader concepts than previous studies. The term "behavior" means the residents' condition that they are at home, and consume electricity at the same time, and the term "lifestyle" means the features of the residents' "behavior" in each household. These terms mean not just the residents' specific activities (sleeping, eating, bathing etc...), but also their use of air conditioning and lighting during they are at home. The energy consumption feedback provided by smart meters is effective for changing the behavior of residents and thus reducing household electricity consumption [13,14]. Many empirical studies of electricity consumption feedback [15–20] suggest that the contents, interface, and timing are all important. However, smart meters

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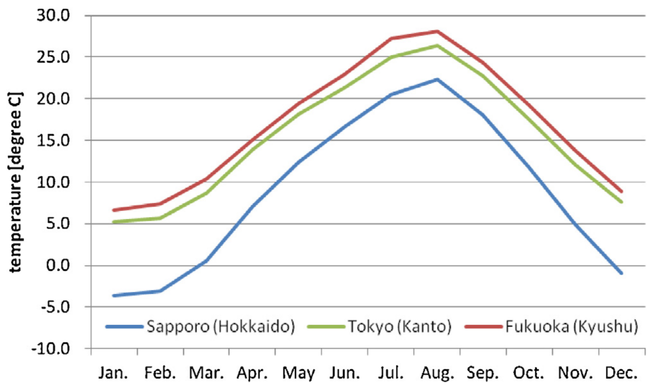

Fig. 1. Monthly mean temperature in Japan.

provide feedback about electricity consumption, CO_2 emissions, and electric power charges, and thus there is a barrier, since residents must first understand the feedback that they receive and then determine how and when they should change their behaviors. In order to provide more effective tailor-made feedback, it is necessary to take into account the lifestyle of each household. The simplest way to understand residents' lifestyles is to ask them directly; however it is difficult to carry out this kind of survey due to privacy protection. Most household energy consumption data are not linked with personal information. Thus, as the second-best way, we analyze household energy data and detect specific patterns in order to estimate lifestyles. This approach will become more important, because government has tightened regulations on collecting personal information. Therefore, we have performed frequency and cluster analyses of household electric load profiles identify different lifestyles. Frequency and cluster analyses can be regarded as complementary methods; in general, frequency analysis is good for extracting the general shape and periodicity of time series data, and in contrast, cluster analysis is good for detecting short-term or non-periodic differences of data.

There have been many frequency and cluster analyses of electricity use. The most popular method for frequency analysis is the Fourier transform (FT), which has been traditionally used to model and forecast the load profile of the aggregate electricity consumption [21–23]. Hybrid models using both FTs and other methods, such as the autoregressive moving average model (ARMA) [24] and self-organizing maps (SOM) [25], have also been developed. In recent years, FTs have been applied to forecasting electricity consumption in individual households. Riddell and Manson [26] emphasized the usefulness of FTs for characterizing the shapes of household load profiles. McLoughlin et al. [27] compared seven different methods (Fourier transforms, neural networks, Gaussian processes, autoregression, fuzzy logic, wavelets, and multiple regression/probability) to forecast and characterize household electricity consumption, and their results suggest that FTs are most suitable when electricity consumption is distributed evenly across the day. In general, FTs are good for extracting the general shape of a load profile. However, few studies have considered the relation between the periodicity of a household's electric load profile and its lifestyle.

Various clustering techniques have been adapted in order to group electric load profiles. Chicco [28] adapted 15 clustering techniques (including k-means, fuzzy c-means, SOMs, and hierarchical clustering) and evaluated their validity for analyzing electric load pattern data. Clustering of residential electricity consumption has been performed for the purpose of forecasting electricity demand [29–33], revealing the household characteristics (the number in the family, income, possession of appliances, and other factors) [34–37], and identifying residents' behavior [38]. Rhodes et al. [37] performed a cluster analysis of the load profiles of 103 households in the USA and showed a correlation between the shape of the load profiles and the household characteristics obtained by homeowner surveys. Beckel et al. [36] classified the load profiles of 4232 households in Ireland, and revealed household characteristics which are constant every day. On the other hand, we focused on the household features which can change from day to day. There are few studies that performed cluster analysis in order to distinguish the daily load profiles in every single household. Abreu et al. [38] focused mainly on the variation in load profiles throughout a year. They gathered up to 14-month load profiles of 15 households in Portugal and performed a cluster analysis of the load profiles in each household in order to identify each household's routines throughout a year. Their analysis discovered (1) persistent daily routines and (2) patterns of consumption or baselines typical of specific weather and daily conditions (e.g., hot working day, cold weekend day). In contrast to the study by Abreu et al., we focus on the relatively minute variation in load profiles for a specific period of the year (1 month), because household lifestyles may change by seasons and it is efficient to provide individual household feedback according to the load profiles in each month.

In this paper, we propose two methods for identifying household lifestyles for a specific period of the year by analyzing electricity use data, which were collected from more than 1000

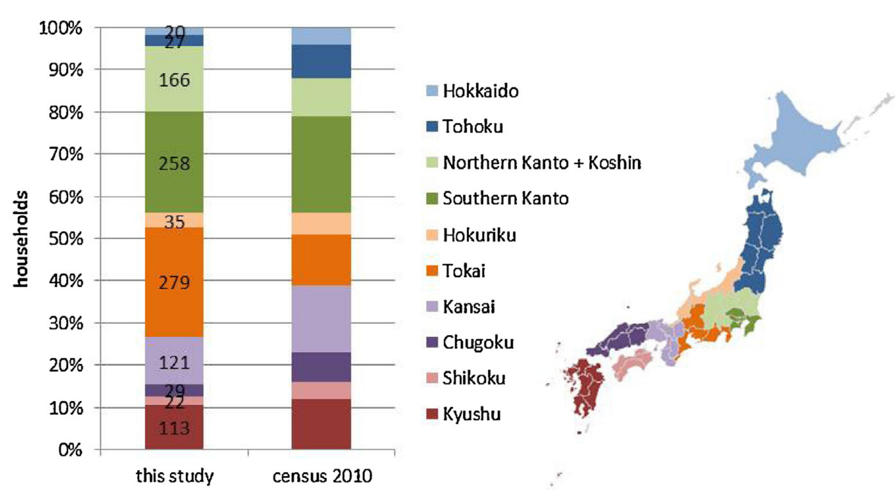

Fig. 2. Distribution of households used in this study, by region, and all households in Japan.

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