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A new method for household energy use modeling: A questionnaire-based approach

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ABSTRACT

Japan needs to improve its residential energy efficiency to reduce energy consumption and thus achieve its greenhouse gas (GHG) emissions reduction targets. Understanding the differences in household behavior and energy use is important to evaluate the effect of energy conservation measures. In this study, the authors propose a new method for household energy use modeling based on questionnaire surveys on home appliances and hot water use. Fifteen-minute residential electricity and heat demand profiles with different seasons, household structures and lifestyles are obtained from the survey results, and compared with available statistical data. The replacement effects of refrigerators, TVs and lighting on residential electricity savings, net present value (NPV) and GHG reductions are evaluated using calculated energy demand. Variations in household energy use are considered under different change scenarios in household structure and by conducting an uncertainty analysis based on the Monte Carlo method. The results indicate that GHG emissions can be reduced by purchasing a new refrigerator, and electricity costs can be reduced by installing LED lamps in the living/dining room. It is also found that there is a wide range of uncertainty for NPV and GHG reductions after replacing a TV because different households watch TV for different lengths of time.

1. Introduction

The residential sector currently accounts for approximately one-fourth of global energy consumption and one-sixth of global CO_2 emissions. Therefore, it has significant effects on the global environment [1]. In Japan, the final energy consumption of the residential sector has doubled in the last 40 years, while industrial consumption has reduced by 20% in the same period [2]. According to Japan's Plan for Global Warming Countermeasures targeting Intended Nationally Determined Contributions (a 26% reduction of total greenhouse gas (GHG) emissions by FY2030 compared with FY2013), a drastic improvement of residential energy efficiency is required by FY2030, with aims to reduce the FY2013 level of GHG emissions by 40% [3].

Home appliances account for about 30% of final energy consumption in Japan's households, and improving the energy efficiency of home appliances is one promising energy conservation measure that does not involve a drastic lifestyle change [4]. In recent decades, government efficiency standards for home appliances have a major driving force behind improvements to the energy efficiency of home appliances [5]. In 1998, the Japanese government initiated the Top Runner Program to improve the energy efficiency of home appliances, office equipment, building materials and vehicles in Japan [6]. This program set a mandatory energy efficiency target for each product category, based on the most energy-efficient product on the market in the base fiscal year. The Top Runner Program covers 31 product categories that consume considerable energy, and has achieved significant efficiency improvement for the target products (e.g., a 43% efficiency improvement for refrigerators in FY2010 compared with FY2005 values) [7].

Energy labels on home appliances represent another key example of government intervention to promote the energy efficiency of home appliances [5]. Governments and international organizations throughout the world have issued various energy labels [8–11]. In Japan, a domestic labeling scheme, the Energy Saving Labeling Program, was launched in 2000 and covers 21 home appliance categories [12]. This label informs consumers of the target item's energy efficiency by means of a five-star rating system and expected annual

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Nomenclature

ANRE	Japanese agency for natural resources and energy
BEE	Indian bureau of energy efficiency
BEST	Building energy simulation tool
BMUB	German federal ministry for the environment nature conservation building and nuclear safety
CECED	European committee of domestic equipment manufacturers
COP	Coefficient of performance
EPA	United States environmental protection agency
ECCJ	Energy conservation center Japan
FY	Fiscal year
GHG	Greenhouse gas
IBEC	Japanese institute for building environment and energy conservation
LED	Light emitting diode
METI	Japanese ministry of economy trade and industry
MOE	Japanese ministry of the environment
MRI	Mitsubishi research institute
NHK	Japan broadcasting corporation
NPV	Net present value
OECD	Organisation for economic co-operation and development
TUS	Time use survey

electricity consumption and costs. In conjunction with this labeling program, the Japanese Ministry of the Environment (MOE) provides an online guide that compares the annual electricity consumption, electricity costs and CO_2 emissions of old and new appliances. Thus, it encourages consumers to use new energy-efficient appliances [13]. These labels and guide presume a certain pattern of energy use in homes. However, actual usage differs depending on the household behavior, which can markedly affect the economic and environmental performances of home appliances [14]. Another approach is therefore required for households to answer the question “Should I replace my old home appliance with a new energy-efficient one given my circumstances?”, and thereby effectively reduce residential energy consumption and GHG emissions.

Various models have been developed to clarify the relations between households' energy use and their characteristics such as household structure and lifestyle [15–17]. Swan and Ugursal reviewed various modeling techniques for residential energy consumption and classified those techniques into two categories based on modeling approaches: top-down and bottom-up [18]. Top-down approaches aim at forecasting the long-term transition of residential energy consumption at a national or regional level from macroscopic indicators (e.g., energy price, total housing stock, heating degree days, etc.) [19–24]. Detailed household characteristics are not the focus in this method.

In contrast, bottom-up approaches look into the detailed energy use of each household. Bottom-up approaches can be further classified into two sub-groups: mathematical methods and engineering methods. Mathematical methods use energy load data measured in houses to demonstrate whether there are any statistical relationships between the households' energy use and their characteristics (e.g., appliance ownership and floor area) [25–28]. Various data mining techniques such as time series analysis [29,30], clustering analysis [31,32] and neural networks [33,34] have been applied to the mathematical modeling of residential energy consumption, along with the development and dissemination of smart metering technologies. Energy use for a specific purpose has been investigated by analyzing data measured by plug load loggers and water tap flowmeters [35–37]. However, one disadvantage of this method is that large initial investments are required to install smart meters and home area networks into households. Furthermore, the conflict between utilizing households' energy load data and protecting their privacy is a further issue of smart metering [38–40].

Engineering methods use occupants' behavior data obtained from time use surveys (TUSs) instead of energy load data to simulate their in-home behaviors relating to energy consumption [41–46]. TUSs conducted by NHK (Japan Broadcasting Corporation) are regularly used for modeling the energy consumption of Japanese residential sector [47,48]; however, they do not provide detailed information on home appliances and hot water use. Therefore, existing engineering models based on the surveys require many assumptions to determine home appliances and hot water use from occupants' in-home behaviors (e.g., it is assumed that a rice cooker is used at the beginning of cooking by a mother or grandmother after 3 p.m. [48]), which is one of the difficulties when using engineering modeling to determine household energy use and evaluate the replacement effect of home appliances and water heaters.

In order to gather pieces of information that cannot be obtained from the Japan's TUSs, we conducted questionnaire surveys for approximately 1200 respondents on their home appliances and residential hot water use. Using these surveys results, the authors develop a new engineering model for household energy use in Japan. Information on residential electricity and heat demand profiles in different seasons, household structures and lifestyles are obtained from the survey results, and compared with the statistical data based on annual final energy consumption. The replacement effect of home appliances (refrigerator, TV and lighting) on residential electricity savings, net present value (NPV) and GHG reductions are evaluated using calculated residential energy demand. Variations in household energy use are considered under different household structures and by conducting an uncertainty analysis based on the Monte Carlo method.

2. Materials and methods

2.1. Questionnaire surveys

Online questionnaire surveys targeting 1227 people in Japan were conducted in the winter and summer of 2014. Respondents were males aged 20 years and older and housewives aged 30 years and older. Table 1 shows the survey periods and sample size of the surveys.

In the questionnaire surveys, each respondent was asked about his/her personal behavior in the most recent weekday or weekend day. The 24 h of the target day was divided into 96 time units of 15 min, and respondents were asked three questions for each time unit: 1) the room they were in, 2) what they were doing, and 3) were any home appliances or hot water used. Fig. 1 illustrates the format of the questionnaire surveys, and Table 2 summarizes the behavior classification and corresponding home appliances and hot water use.

In addition to these questions, female respondents were asked to provide a basic behavior schedules (e.g., sleeping, eating, bathing and outside activities) for their husband and child(ren) on the target day. The reason behind asking to female respondents is that

Table 1
Survey periods and sample size.

	Winter	Summer
Survey period	Jan. 16–23, 2014	Aug 18–25, 2014
Sample number	612	615
Number of valid responses	531 (190 males and 341 females)	442 (155 males and 287 females)