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Estimation of the contribution of the residential sector to summer peak demand reduction in Japan using an energy end-use simulation model

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ABSTRACT

The effect of electricity peak demand reduction by electricity saving measures in the Japanese residential sector on the power system scale during summer was evaluated through the use of a simulation model developed by the authors. In order to simulate the electricity peak demand on the power system scale, the model was improved so as to (1) represent the household distribution and residential stock on the power system scale and (2) improve the temporal resolution of the simulation. The proposed model is a bottom-up type model that simulates residential electricity demand based on occupant behavior considering numerous factors, such as family composition, residence floor area, and building insulation level. Therefore, the proposed model can be used to evaluate both occupant behavioral changes and energy conservation technologies. As a result, we determined that the most influential behavioral measure in reducing summer peak demand is turning off the lights. The peak demand reduction effect when 5% of households turned off the lights was 13 MW, which is equivalent to approximately 0.2% of the residential electricity demand during the daytime in summer in the Kansai region. The model also clarified differences in the electricity savings for each countermeasure among several family composition categories.

1. Introduction

Precise prediction of the peak electricity demand during summer is desired because the supply and demand balance within the power system in Japan is delicate. This is a recent development due to the suspension of all nuclear power plants after the Great East Japan Earthquake. Since then, there has been concern over the risk of blackouts caused by shortages of the power generation capacity of the utility grid during summer and winter. However, the balance between the supply and demand of electricity has been successfully controlled. Electricity saving efforts in the residential sector are considered to be among the largest contributors to balancing energy supply and demand.

Therefore, it is important to predict the effects of peak demand reduction resulting from electricity saving measures in the residential sector in order to discuss the balance between electricity supply and demand on a power system scale. Conventional methods for examining electricity saving effects are the measurement method and the simulation method. One challenge of the measurement method is finding sample households that accurately represent the household distribution. In addition, since it is difficult to measure the electricity consumption of numerous appliances separately, the electricity demand change cannot be identified. The simulation method can address these problems and so is used herein to predict the electricity saving effects.

Since residential electricity demand depends on various factors, such as family composition, appliance ownership, and building thermal specifications, the effects of electricity saving measures may differ among households. It is important to take this difference into account when predicting the effects of electricity savings efforts on the power system scale using a simulation model. Therefore, it is necessary to categorize the households in the target region and to determine the simulated electricity saving effects of the representative households of each category. This enables us to

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identify which measure is effective for each household category. Swan and Ugursal [1] grouped approaches used to simulate residential energy consumption into two categories: top-down approaches and bottom-up approaches. They defined a bottom-up approach as an approach that calculates the energy consumption of an individual household or groups of households and extrapolates the obtained results in order to represent a region or the nation. The bottom-up approach is actually frequently adopted for the estimation of residential building energy consumption. Bottom-up approaches consist of two methods: statistical methods and engineering methods. Swan and Ugursal reported that the engineering method has the capability of determining the energy consumption for each end-use because the engineering method considers various factors that affect residential energy demand, such as housing thermal specifications and climate conditions. Moreover, they reported that, among engineering methods, an archetype engineering model can explicitly address the change in occupant behavior.

One problem involved in the use of archetype engineering models is stock modeling, namely, categorizing the housing stock and determining the archetypes that represent each category. Parekh [2] reported the procedures for developing libraries of archetype building characteristics based on detailed surveys of thousands of Canadian residences. He classified residences according to the geometric configuration, thermal characteristics, and operating parameters. The archetype characteristics are determined based on the average, median, 25th percentile, and 75th percentile values of each category obtained from the survey data. Jones et al. [3] developed a model for decision making of city planning based on the Geographical Information System (GIS). They classified UK building stock according to, e.g., building dimensions, age, and built form. In addition to the GIS, they used a “drive pass” survey for cluster analysis. The survey provided information of built form, for example, number of stories, story height, and ratio of window area to wall area. Famuyibo et al. [4] focused on developing archetypes for domestic dwellings using detailed statistical analysis. They determined the four key variables impacting house energy use using a multiple liner regression analysis of a database of 150 Irish dwellings: typical weekly occupancy pattern, internal temperature, air change rate, and immersion heater weekly frequency. Representative values of these variables were determined based on the database.

The primary advantage of Michalik et al. [5] is its high-temporal resolution. Their model was developed during the 1990s for the application to the planning of a feeder network. The model simulates energy-use patterns in 15-minute intervals. Survey data for over 100 households are categorized based on family type (employment and children) and appliance possession, which are the important factors in determining the energy-use pattern.

Recently, a number of groups have been developing archetype engineering models with high-temporal resolution. Richardson et al. [6] developed a model that simulates the pattern of electricity use in domestic dwellings in 1-minute intervals. Based on the pattern of active occupancy (i.e., the. number of people who are at home and awake) derived from national statistics obtained through a time-use survey, appliance use is determined stochastically. The simulated electricity load curve was validated using the measured data for 22 dwellings. The model developed by Widén and Wäckelgård [7] consists of a Markov-chain model that generates electricity-dependent activities (e.g., away from residence, sleeping, and cooking) based on time-use data. The 1-minute activity profile is directly converted to electricity end-uses. The model was validated by either the aggregate demand (200 detached houses and 200 apartments) or the individual demands of 14 households. Tanimoto et al.[8,9] developed a methodology of generating time-varying inhabitant-behavior schedules that utilizes two published statistical data. By defining links between each behavior and an energy-consuming event, they simulated electricity, gas, water, and hot water demand with a 15-minute resolution. One of their advantages is stochastic modeling of turning the heating, ventilating, and air conditioning on/off, based on the Markov-chain theory.

The target scale of these high-temporal-resolution models is on the order of tens or hundreds (or sometimes thousands) of households because most of these models were developed for the purpose of designing local- or small-scale power grids. However, large-scale simulations with high-temporal resolution, for example on the power system scale with millions of households, are rarely performed and verified.

The authors previously developed a bottom-up model using an archetypal engineering method that simulates city- or nation-scale residential energy end-use (hereinafter referred to as the residential energy end-use model) while taking into consideration numerous factors affecting energy use, such as family composition, residence floor area, and building insulation level [10]. The model was originally developed in a previous paper in order to estimate annual energy consumption, and we used the model to estimate greenhouse gas emission reduction resulting from energy saving measures in the residential sector [11]. In the present paper, the model was improved in order (1) to represent the residential stock of the power system scale and (2) to improve the temporal resolution of the simulation.

As a result, the model improved the selection of representative households, the generation of occupant behavior, and the linking of occupant behavior and appliance operation. The accuracy of the simulated electricity demand is evaluated using the averaged load curve data for approximately 1200 households measured using smart meters. Using this model, the authors attempt to evaluate the peak demand reduction resulting from electricity saving measures for the residential sector on the power system scale. Assuming that a demand response program would be conducted during the daytime in summer, the effectiveness of the measures for reducing the peak demand is discussed. Since the proposed model simulates residential electricity demand based on occupant-behavior schedules and considers numerous factors within a household, the model can be used to evaluate both behavioral changes (e.g., raising the set temperature) and the adoption of energy saving technologies (e.g., installing a high-efficiency air conditioner) on an equal footing.

2. Simulation model

2.1. Outline of the simulation model

Fig. 1 shows a flowchart of the residential energy end-use model. The target region of the present paper is the Kansai region (including six prefectures, e.g., Osaka and Kyoto; population: 20.9 million; number of households: 8.6 million; and area: 27,000 km^2). A power company supplies electricity to the residential sector for the entire region. This model considers a total of 912 household categories made up of 19 family compositions, 12 building categories (6 categories for apartments and 6 categories for detached houses, which are set depending on the floor area), and 4 building insulation levels. The households in the region are classified into 912 categories based on the Population Census [13] and insulation level percentages for residential building stocks [11]. Table 1 shows the number of households for each category in the Kansai region. Maintaining this distribution, a total of 5000 households are chosen to represent the region. The mean electricity demand can be obtained by averaging these simulation results. The total energy consumption for the entire Kansai region is estimated by extrapolating the simulation results of the 5000 representative households to 8.6 million households.