Evaluation of CO₂ Reduction and Primary Energy Savings for Collective Housing with Fuel Cells Considering Variability in Demand

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Abstract: In Japan, residential FCs (fuel cells) are being introduced not only in detached houses but also in collective housing. In this context, the effects of FC introduction (e.g., primary energy savings) should be quantitatively evaluated, but this has not been done sufficiently for collective housing, particularly with regard to demand variability. Here, the authors propose a method taking into account demand variability to evaluate the effects of FC introduction into collective housing, based on a finite set of observational demand data. The method provides a new viewpoint for evaluating the effects of FC introduction. Numerical simulation results based on real-world data indicate the validity of these effects in terms of primary energy savings and CO₂ reduction considering demand variability.

Key words: Co-generation, distributed generation, fuel cell, residential system.

1. Introduction

The importance of efficiently using energy is broadly recognized, yet household energy demand in Japan continues to increase. A residential FC (fuel cell) system is a co-generation system that generates both electric power and heat energy and that has high efficiency and low environmental impact; thus, residential FC systems are expected to be an important appliance in balancing the supply and demand of household energy, and the introduction of FCs into collective housing is being promoted in Japan. Conventionally, FC utilization tends to be low, so the output of residential FCs is limited to the electric power demand of the house where the FC is installed. However, utilization can be kept high by interchanging electric power between units in collective housing. In this situation, it is very important to assess the effects of FC introduction (e.g., primary energy savings and CO₂ reduction), by taking into account the possible demand variability. In contrast to an office building of industrial complex which has highly predictable daily loads, a collective housing facility would have greater demand variability depending on the family structure and lifestyle of residents. Since a demand pattern in a collective housing is composed of a combination of various household demands, we should take account of variability in demand patterns in order to evaluate effects of introducing residential FCs. In previous studies [1-4], the effects of introducing residential FCs into a detached house or a collective housing facility have already been reported, but sufficient attention was not given to demand variability.

In this paper, the authors propose a method that considers variability to evaluate the effects of introducing residential FCs into collective housing, based on a finite set of demand data. The fundamental idea behind this method is based on the bootstrap...
method [5]. The variability in a population is expressed by using bootstrap sampling, and the uncertainty of FC introduction effects is evaluated by using probability densities. The numerical simulations show the effectiveness of the proposed method through evaluation of primary energy savings and CO₂ reduction for various collective housing sizes and seasons.

2. Collective Housing with FCS

2.1 Structure of Residential FC

In this section, we explain the properties and structure of conventional residential FC systems. Electric power is generated through the chemical reaction of hydrogen extracted from town gas and oxygen in the air. This reaction generates heat, which is stored in a hot water storage tank. The FC system has the following properties. First, the system achieves high efficiency in both electric power generation (35%) and exhaust heat recovery (45%), with the total efficiency reaching 80%. Second, residential FC systems are environmentally friendly: The only product of the FC’s chemical reaction is water, which means there are no CO₂ emissions. Third, the system is not strongly affected by weather conditions, in contrast to PV (photovoltaic) generation systems, which require abundant sunlight.

In this paper, the authors focus on PEFCs (polymer electrolyte fuel cells), which are widely used in residential FCs. The structure of a PEFC system is shown in Fig. 1. The town gas is sent to the fuel processor system where hydrogen is extracted. In the cell stack, electric power is generated by reacting the extracted hydrogen with oxygen from the air. The exhaust heat is stored as hot water. In Japan, power utilities do not purchase excess electric power generated by FC systems, so any excessive power is also transformed into heat by a heat exchanger and stored as hot water. When the maximum electric power generation does not satisfy the electric power demand, the required energy is purchased from the grid. The hot water stored in the tank is used according to the hot water demand. When the hot water demand exceeds the remaining quantity of hot water in the tank, the excess is supplied from a backup boiler. When the quantity of stored hot water exceeds the tank capacity, the excess is transformed into heat and emitted from a radiator. Even when the tank is completely filled with the hot water, the radiator allows continuous operation.

2.2 Operation Plan

There are two kinds of operation plans for an FC: DSS (daily start and stop) operation and continuous operation. In DSS operation, the FC is stopped once per day, and in continuous operation, the FC runs throughout the day. From the viewpoint of energy savings, DSS operation is superior to continuous operation in general. However, if we focus on the life time of the FC system, continuous operation is superior. In this paper, we assume that the residential FC systems are operated in DSS mode. An example of DSS operation is shown in Fig. 2. First, the hot water demand of next day is predicted. Then, the operation period is set to satisfy the predicted hot water demand. In this operation period, the generated electric power output follows the load, which is observed at the receipt point, under output constraints (e.g., output range and output change speed). Note that the output will not follow the load perfectly due to these constraints. In
this paper, the authors assume that FC operation is pre-planned based on prior knowledge about the amount of heat demand in each season.

2.3 Collective Housing with FCs

In this paper, we consider collective housing with FCs; each unit in the collective housing has its own residential FC system. For a typical collective housing facility, we consider an apartment building with 1, 3 or 5 stories, each of which contains 4 units. Here, we define collective housing size as the total number of units in the apartment building, so the size is assumed to be 4, 12 or 20. As an example, Fig. 3 shows collective housing of size 12 in which FCs are installed.

A conventional residential FC system in collective housing generates electric power and heat energy that is consumed in only the unit where the system is installed. In this paper, however, we assume that electric power generated by FCs can be used in other units in the same collective housing in order to maintain a high FC utilization rate from the viewpoint of efficient energy management. Note that generated hot water is not used in other units to avoid the large heat loss in piping.

3. Evaluation Method

Here, we propose a method for evaluating the effect of FC introduction into collective housing of size \( n \), considering variability in demand based on \( m \) observed demand data (\( m > n \)); this method uses a random sampling technique. Table 1 lists the notation used in this section. Let \( \{D_{rt}, D_{hrt}\}; \ t = 1, \ldots, T \} \) be the demand pattern of consumer \( i \). To evaluate primary energy savings and CO\(_2\) reduction for collective housing with \( n \) units, we first define the following indices.

(1) Primary energy consumption without FCs:

\[
F_{PE}^{CON} = \sum_{t} K_{PE}^{SYS} \cdot E_{t} + \sum_{t} \sum_{i} K_{PE}^{GAS} \cdot G_{B}^{B}(B_{h}) \tag{1}
\]

(2) Primary energy consumption with FCs:

\[
F_{PE}^{FC} = \sum_{t} K_{PE}^{SYS} \cdot E_{t} + \sum_{t} \sum_{i} \left[ K_{PE}^{GAS} \cdot \left\{ G_{B}^{FC}(C_{x}(x_{i})) + G_{B}^{B}(B_{h}) \right\} \right] \tag{2}
\]

(3) CO\(_2\) emission without FCs:

\[
F_{PE}^{CON} = \sum_{t} K_{CO2}^{SYS} \cdot E_{t} + \sum_{t} \sum_{i} K_{CO2}^{GAS} \cdot G_{B}^{B}(B_{h}) \tag{3}
\]

(4) CO\(_2\) emission with FCs:

\[
F_{CO2}^{FC} = \sum_{t} K_{CO2}^{SYS} \cdot E_{t} + \sum_{t} \sum_{i} \left[ K_{CO2}^{GAS} \cdot \left\{ G_{B}^{FC}(C_{x}(x_{i})) + G_{B}^{B}(B_{h}) \right\} \right] \tag{4}
\]

Here \( FC_{it} \) is the output of a single FC, \( E_{t} \) is the electric power purchased from the grid and \( B_{lt} \) is the output of a backup boiler, and these parameters are defined as follows:
Table 1: Notation.

| Symbol  | Parameter                                                                 |
|---------|---------------------------------------------------------------------------|
| $n$     | Size of collective housing                                               |
| $T$     | Total number of simulation intervals                                     |
| $E_t$   | Purchased power (kWh)                                                    |
| $G_{RB}$| Gas input for each backup boiler (m$^3$)                                  |
| $G_{RB}$| Gas input energy for each FC (m$^3$)                                     |
| $B_{rit}$| Output of each backup boiler (kWh)                                       |
| $FC_{rit}$| Output of each FC (kWh)                                                 |
| $K_{PESYS}$| Primary energy conversion factor (MJ/kWh) (purchased power)             |
| $K_{PESYS}$| Primary energy conversion factor (MJ/m$^3$) (town gas)                  |
| $K_{PESC02}$| CO$_2$ emission conversion factor (kg/kWh) (purchased power)            |
| $K_{PESC02}$| CO$_2$ emission conversion factor (kg/m$^3$) (town gas)                 |
| $x_{it}$| Operational state of each FC (running: 1; stopped: 0)                   |
| $De_{it}$| Electric power demand of each unit (kWh)                                 |
| $FC_{max}$| Maximum output of each FC (kWh)                                         |
| $FC_{min}$| Minimum output of each FC (kWh)                                         |
| $Dw_{it}$| Hot water demand of each unit (kWh)                                      |
| $Tw_{it}$| Supply of hot water from each tank (kWh)                                 |

Accordingly, we propose a method to evaluate these indices, taking into account demand variability. Assuming that the collective housing consists of the combination of $n$ typical units, we represent variability in demand by using $m$ ($>n$) typical household demand patterns; in other words, we represent variability in demand patterns based on a resampling technique, so that a demand pattern in collective housing of size $n$ is represented by one of $\binom{M}{n}$ possible demand patterns.

The procedure of our evaluation method is as follows:

- **Step (1):** set size of collective housing $n$;
- **Step (2):** set number of random samplings $I_s$, and $I = 0$;
- **Step (3):** randomly sample $n$ demand data from $m$ observations;
- **Step (4):** calculate Eqs. (8) and (9) for selected data in Step 3;
- **Step (5):** save $F_{PE}$ and $F_{CO2}$ calculated in Step 4;
- **Step (6):** set $i \leftarrow i + 1$ and return to Step 3 until $i = I_s$ holds.

The fundamental idea behind this method is based on the bootstrap method. Here, value $I_s$ controls the reproducibility of variety in the calculation results depending on target observations. In our simulation, we set the number of random samplings to $I_s = 10,000$. The flowchart of our evaluation procedure is shown in Fig. 4.

By using this method, the uncertainty of the FC introduction effect can be calculated based on $I_s$ demand patterns and evaluated as a probability density.

Note that the kernel density estimation [6] can be a useful tool for this evaluation. In this paper, we use the following Gaussian kernel density estimate:

$$p(x) = \frac{1}{I_s} \sum_{i=1}^{I_s} \frac{1}{(2\pi h^2)^{1/2}} \exp \left( -\frac{1}{2h^2} \|x - F_i\| \right)$$

where $F_i$ is a calculated index in the $i$th iteration, $h$ represents window width of the single kernel and $\sigma$ is the standard deviation of the random variable $F$.

Values of an index depending on demand, such as
the effect of FC introduction, change in various ways depending on which demand patterns are assumed when the index is evaluated based on a single demand pattern. By calculating the index based on multiple demand patterns in this method, the uncertainty of the index can be evaluated as, for example, a probability density.

4. Numerical Results

To verify the effects of introducing FCs into collective housing from the viewpoint of primary energy savings and CO₂ reduction, numerical simulations were performed based on real-world demand data sets observed in winter, summer and fall.

4.1 Simulation Conditions

In our numerical simulation, half-hourly electric power and hot water demand data collected from 40 units for one week in winter (January), summer (August) and fall (November) are used. Table 2 shows the specification of residential FC system, and Table 3 shows the prescribed values of primary energy and CO₂ emission conversion factors. Daily operation period of an FC system at each unit is from 6:00 to 21:00 in winter, from 16:00 to 21:00 in summer, and from 11:00 to 21:00 in fall. The heat loss for piping, the output change speed, and the standby power under the stopped state of each FC are not taken into consideration. The water temperature is constant in every season, and set to 8.7 °C in winter, 28.5 °C in summer and 15.7 °C in fall. The amount of hot water storage is assumed to be 20 L at the start of the first day and then greater than 20 L in the last time sections for all days. Note that the amount of hot water storage in the last time section of the previous day becomes the amount of initial hot water storage of the next day (except for the first day). We consider collective housing of size 4, 12 and 20. The number of random samplings is \( l_n = 10{,}000 \). In Eqs. (1) and (3), we assume that the electric power is purchased from the grid and hot water is supplied from the backup boiler according to demand in each house.

4.2 Simulation Results

Tables 4 and 5 show the 95% confidence intervals of the amounts of primary energy savings and CO₂ reduction per household, calculated from Eqs. (8) and (9) for

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**Table 2** Specification of residential FC system.

| Item                        | Value          |
|-----------------------------|----------------|
| Maximum/minimum power output| 750 W / 250 W  |
| Capacity of storage tank    | 200 L          |
| Temperature in storage tank | 60 °C          |
| Heat loss from storage tank | 1.0% of stored heat per hour |
| Start-up loss (electricity) | 0.5 kWh        |
| Start-up loss (town gas)    | 0.5 kWh        |
| Power generation efficiency (lower heating value) | 35% |
| Heat generation efficiency (lower heating value) | 46% |
| Boiler efficiency           | 80%            |

**Table 3** Conversion factor for electric power and town gas.

|                        | Electric power | Town gas |
|------------------------|----------------|----------|
| Primary energy conversion factor | Daytime: 9.9 MJ/kWh | Nighttime: 9.28 MJ/m³ |
| CO₂ emission conversion factor | 0.555 kg/kWh FC: 0.497 kg/kWh (rated output) | Boiler: 2.21 kg/m³ |
Table 4  95% confidence intervals for amounts of primary energy savings per household.

| Season | Collective housing size |
|--------|-------------------------|
|        | 4                       | 12                      | 20          |
| Winter | 59.1-250.4              | 104.5-205.8             | 119.7-186.2 |
| Summer | -4.7-61.5               | 11.9-48.1               | 17.8-42.7   |
| Fall   | 26.1-106.6              | 47.0-88.3               | 53.7-80.9   |

Table 5  95% confidence intervals for amounts of CO₂ reduction per household.

| Seasons | Collective housing size |
|---------|-------------------------|
|         | 4                       | 12                      | 20          |
| Winter  | 4.91-16.23              | 7.53-13.60              | 8.43-12.42  |
| Summer  | 0.45-4.25               | 1.45-3.55               | 1.80-3.25   |
| Fall    | 2.18-6.90               | 3.41-5.84               | 3.81-5.41   |

10,000 resampled sets of demand patterns for various collective housing sizes and seasons. The tables indicate that these indices are related to two factors: the collective housing size and the season. Fig. 5 shows probability densities of primary energy savings and CO₂ reduction per household for various collective housing sizes in winter. Here, the probability densities are given by using the kernel density estimation method with Gaussian kernels shown in Eq. (10). As shown in the results, these indices have variances; in other words, the effects of FC introduction depend on demand patterns. The figure also shows that the shape of the density distribution becomes sharper and narrower as the collecting housing size increases; this trend is also observed in summer and fall. Fig. 6 shows box plots of primary energy savings and CO₂ reduction per household for various collective housing sizes in winter. The upper and lower lines of the box indicate the third and first quartiles, respectively, and the line drawn in the center of the box indicates the median. The end of the line that extends from the top (bottom) of the box indicates the maximum (minimum) value. As shown in Fig. 6, the indices appear to be symmetric and free of bias. The median values are almost the same regardless of collective housing size. For a collective housing size of 20, the interquartile range is small, indicating that the fluctuation range will be small in large collective house facilities and that the effects of
FCs can be predicted more reliably. Similar results were obtained for summer and fall.

The authors next focus on seasonal effects in particular for collective housing of size 20. Fig. 7 shows box plots of primary energy savings and CO$_2$ reduction per household for winter, summer and fall. The results suggest that the primary energy savings and CO$_2$ reduction are larger in winter than in summer and fall. This finding implies that water is used efficiently in winter. In contrast, the primary energy savings and CO$_2$ reduction are much smaller in summer than in winter. The reason is that less hot water is used in summer and heat radiates from the tank, thus lowering efficiency. The figure also indicates that interquartile ranges are wider in winter than in the other seasons; the indices tend to have large variances in winter.

By using the proposed method, the uncertainty in the effects of FC introduction into collective housing can be evaluated based on a finite number of demand data, taking into account demand variability. The method is useful for analyzing the effects on primary energy savings and CO$_2$ reduction.

5. Conclusions

In this paper, the authors proposed a method for evaluating the effects of introducing FCs into collective housing. Specifically, we looked at primary energy savings and CO$_2$ reduction effects. Our method is inspired by the bootstrap method and is based on sampling technique for possible variability in real-world demands. In our numerical simulation, we used 40 demand data collected in winter, summer and fall, and evaluated weekly FC introduction effects for collective housing with sizes of 4, 12 and 20. Numerical simulation using the proposed method provided probability densities of the FC introduction effects. We also examined the properties of expected primary energy savings and CO$_2$ reduction, and the relationship between collective housing size and seasonal effects.

The results show that the effects of FC introduction depend strongly on hot water demand in each unit. We also note that hot water demand differs from house to house on account of family structure and lifestyle. We believe that our method will be a useful tool for evaluating FC introduction effects with consideration of demand variability.

In this study, the FC operation plans were fixed for all seasons. However, the FC operation plan should be appropriately controlled according to electric power demand and heat demand. We will develop an appropriate FC operation plan for collective housing in future work.

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