The amount of EMR that can be provided by residential buildings is important information to design methods to utilize EMR for electric power systems. However, it is difficult to quantify EMR from fields since the amount of EMR depends on local conditions, i.e. occupants' daily behavior and the ownership, operation, and specification of home appliances, in addition to climate condition and specification of house, that differ among houses. Based on this background, we applied an energy demand model of residential buildings to quantify the amount of EMR. In this model, the structure directly determining residential energy demand is replicated based on a bottom-up modelling approach in which total energy demand of a house is modeled as the sum of consumption of each appliance and equipment that is determined while taking into account the variety in the abovementioned conditions. The purpose of this paper is to introduce, validate the model and quantify the amount of EMR in a case study community.

METHODOLOGY

As explained in the definition, EMR depends on the operation and specification of appliances, which might differ among households. Thus, we first collected actual conditions on the operation and specification of appliances by analyzing electricity consumption measured at each circuit of distribution boards installed in 586 apartments in Osaka, Japan. Table 2 shows the number of households from which data was collected for the listed appliances. As shown in the table, the number of households is different from which data was collected. This is because we eliminated households that do not use the target appliances and households with a large scale of missing value. This information collected from the measured data was summarized in the indicators listed in Table 3 which was summarized in a cumulative frequency distribution. Finally we quantified EMR for a hypothetical apartment building in which 226 are living as a case study by using an energy demand model. In the case study, family composition, ownership, operation and specification of home appliances were given randomly. For EMR target appliances, specific conditions on the indicators were also randomly allocated by using the developed cumulative frequency distributions.

Table 1. *Three types of EMR and appliances*

Type of EMR	Definition	Appliance
Shiftable loads	Loads of appliances whose operation start-time can be delayed having no influence on the operation that follow	Dishwasher Laundry, Cloth dryer
Interruptible loads	Loads of appliances whose operation start-time can be delayed having an influence on the operation that follow	Refrigerator
Thermal loads	Loads given by adjusting the level of service considering occupants' thermal comfortable	Air-conditioner

Table 2. *The number of the object households*

[households]	Dishwasher	Laundry	Cloth dryer	Refrigerator	Air-conditioner
Operation probability	323	-	151	-	-
Others	252	406	21	445	226

Table 3. *Analyzed indicators for the specification and operation*

Indicator	Content	Target appliance
Operation duration	Duration during which appliance is active	Dishwasher, Laundry Cloth dryer Refrigerator
Power consumption in operation	Power consumption appliance consumes while it is active	
Operation probability	Probability using the appliance after corresponding behavior is conducted (i.e. eating meals or washing cloth)	Dishwasher, Cloth dryer
Defrosting span	Average time span between defrosting that is conducted by refrigerator	Refrigerator
Timer duration (0.25~5h, alwaysON, alwaysOFF)	Duration during which air-conditioner is operated while occupants are sleeping by using timer operation function	Air-conditioner (cooling, heating)

Table 4. *Constraint in shifting operation start-time for shiftable loads*

Appliances	Constraints
Dish washer	The operation must end before next cooking or meal begin
Laundry Cloth dryer	In the morning, operation must end a half hour before occupants undertake corresponding household maintenance (cloth washing) or leave home by 11 o'clock. In the afternoon, operation must end a half hour before any occupants go to bed.

Quantification of EMR

In this section, we define EMR more precisely and explain the method to quantify EMR in the energy demand model.

(1) Shiftable loads

We assumed dishwasher, laundry and cloth dryer as appliances with shiftable loads. These appliances consume electricity for several tens of minutes triggered by occupants' operation. The operation start-time of these appliances can be flexibly shifted after dish and clothes are set inside. We assumed the constraints listed in Table 4 to quantify EMR. EMR can be quantified by the model considering the constraints, since the model stochastically generates occupants' behavior like sleeping, cooking and eating meals.

(2) Interruptible loads

Refrigerators have defrosting operation to remove frost in container. In defrosting operation, refrigerators consume larger electricity than normal operation. The timing at which defrosting is conducted is theoretically flexible. Thus, we assume the difference in power consumption between defrosting operation and normal operation as interruptible loads. We assumed that the timing of defrosting can be shifted within the span of defrosting. It should be noted that power consumption for defrosting does not vary significantly over seasons, while that during normal operation significantly varies. It is rarely happen but when power consumption of normal operation is larger than that of defrosting, we assume that EMR is zero. To estimate EMR, we collected data on defrosting span, the duration and power consumption during defrosting from measured data.

(3) Thermal loads

In this paper, we considered electricity consumption of air-conditioners as thermal loads for EMR. We quantify the flexibility by the difference between power consumption calculated under the assumptions on room set point temperature listed in Table 5. We assumed that air-conditioner is operated when occupants are in rooms which equip an air-conditioner during summer and winter. We observed that many households use timer control of air-conditioner when they go to bed and the duration during which air-conditioner is operated differs among households. Thus, we collected frequency distribution of timer duration from the measured data to take into account the variety in operation condition in the model estimates.

Table 5. *The set point temperature of air-conditioner*

[degree C]	Cooling	Heating
Mode1 (Base)	26	22
Mode2	28	20

ENERGY DEMAND MODEL OF RESIDENTIAL BUILDINGS

This model has a database of the specification of houses, appliances and occupants' behavior to realistically simulate energy demand of residential buildings. When a household is defined, one family composition and house archetype are selected. The ownership and specification of home appliances are then given randomly based on a database. The specification of the abovementioned target appliances is given from the database which is introduced below.

The time resolution of the model is 5-minutes. The family composition defines attributes of occupants defined by age, gender, and occupation. For each attribute, different time use data is prepared. The time use data contains statistical information on time allocation for about 50 kinds of behavior on weekdays and holidays. The data is used to generate occupants' behavior stochastically on simulation days (Yamaguchi et al. 2014a). Based on the behavior, the room in which occupants spend time is determined based on an input file defining the relationship between behavior and room. This room information is used to determine the operation of space lighting, heating and cooling. The behavior is then converted to the operation of home appliances and equipment such as TV. Then, the information is converted to energy consumption while taking into account the specification of home appliances and equipment. The specification is given for each room respectively. Finally, energy demand of a household is quantified as the sum of consumption by all the appliances and equipment (Yamaguchi et al. 2014b). For space heating and cooling, a dynamic thermal load simulation based on the thermal circuit network method is conducted by utilizing building data, internal heat gain and meteorological data. The building data is defined by the given house archetype. Internal heat gain is calculated by using energy consumption of home appliances and lighting.

SURVEY OF SPECIFICATION AND OPERATION OF THE APPLIANCES

Figure 1 shows the cumulative frequency of the operation duration and power consumption observed for dishwasher, laundry, cloth dryer, and refrigerator's defrosting. Those for dishwasher and cloth dryer distribute more widely than laundry and refrigerator defrosting. This is because these appliances have a few operation modes, such as washing only, drying only or both of dishwasher. Figure 2 shows the operation probability for dishwasher and cloth dryer among households showing the probability at which the operation of appliances occurs in a day. For dishwasher, we distinguished operation after breakfast, lunch and dinner. This figure shows that more households use dishwasher after dinner than breakfast and lunch. The right figure shows the defrosting span of refrigerator. The observed defrosting span ranges from 10 and 40 hours. Figure 3 shows how frequently households use the timer operation function for air-conditioner equipped in living room during summer (left figure) and winter (right figure). The figure contains the distribution of the duration of timer operation listed in the graph legend over days in August and February. The data shows the result collected from the surveyed 226 households that are arranged on the horizontal axis in descending order of magnitude in the percentage of AlwaysON meaning that air-conditioner is operated while occupants are sleeping. During summer, approximately a half of households do not operate air-conditioner (AlwaysOFF), while the ratio increased to 80% during winter.

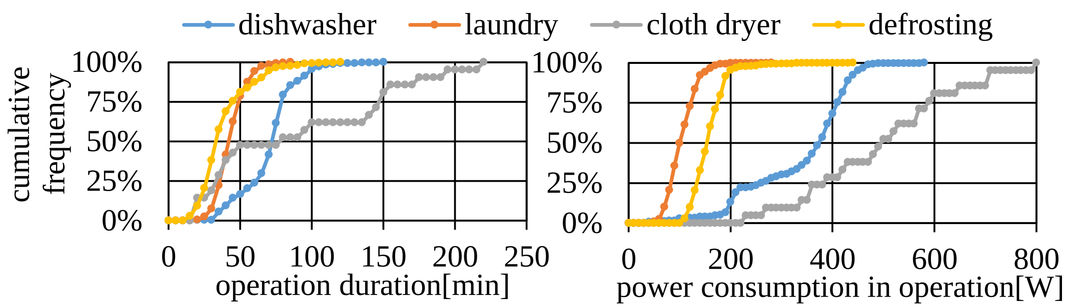

Figure 1. *Cumulative frequency of duration and power consumption in operation*

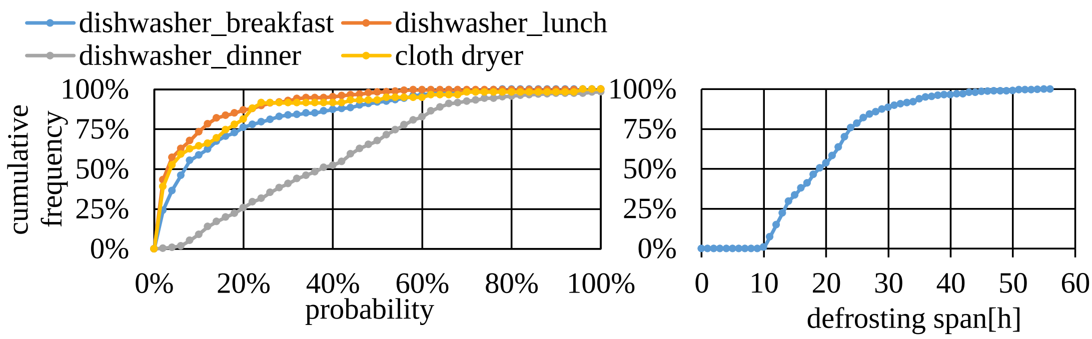

Figure 2. *Cumulative frequency of operation probability and defrosting span*

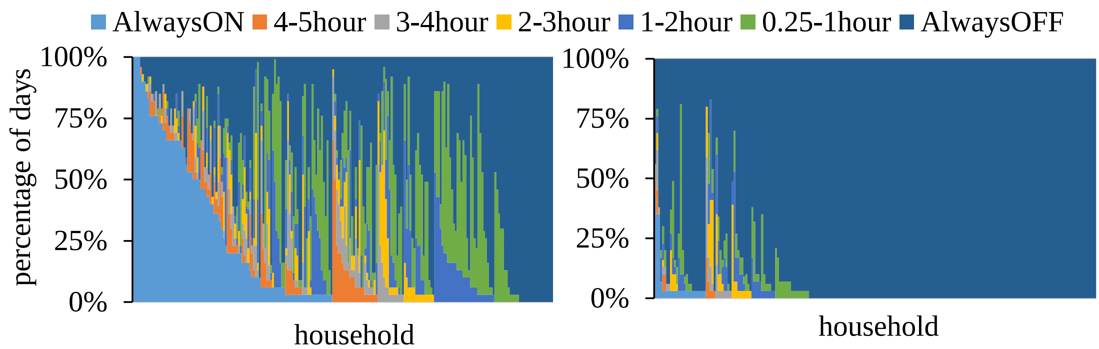

Figure 3.*Duration of AC's timer operation in living room (left: summer, right: winter)*

Validation of simulation result

We validated the model by comparing simulation result of the operation and power consumption of the considered appliances with measured data. As mentioned earlier, the model needs the information of house archetype and family composition. Table 6 shows house archetypes and family compositions given to simulated 226 households.

Figure 4 shows cumulative frequency of annual electricity consumption. The left figure shows measured data, while the right one shows simulation result. As shown these figures, the model underestimates electricity consumption of dishwasher. This underestimation is caused from underestimation of the frequency of operation in the model, 28% of days in a year, which was smaller than the actual, 45%. This is attributed to the small occurrence of cleanup behavior after meals in the model, which has only 73% of days in a year. Figure 5 shows power consumption of these appliances averaged among households on weekdays. Power consumption of dishwasher, laundry and cloth dryer especially during nighttime is small compared to measured data. The underestimations listed here are caused from the behavior model result. The model considers that these appliances are operated when occupants conduct cleanup behavior after meals for dishwasher and household maintenance on clothes for laundry and cloth dryer. However, actual occupants' behavior to push the switch of these appliances is not considered in the time use data, the input data of the occupants' behavior model.

Figure 6 shows power consumption of air-conditioner per household on weekdays. The left figure is for cooling, while the right one is for heating. The simulation result fluctuates more largely than the measured data. This can be attributed to the frequency of occupants' going out. In this model, we assumed that the operation of air-conditioner corresponds to occupants' being at home. The frequency of state transitions in air-conditioner was 2.9 times/day in August, which was larger than the actual, 1.5 times/day. That shows the frequency of occupants' going out and going to private rooms is larger than the actual. This is also a weakness of the model.

Estimation of EMR

Figure 7 shows estimated EMR per household averaged for weekdays of August and February. The data in the negative region shows EMR that can be decreased. The main portion of the EMR is provided by air-conditioner that was quantified by the difference in power consumption between Mode1 and Mode2 (see Table 5). Most of EMR which can be decreased is provided at morning and evening at which air-conditioner is often operated. The data in the positive region shows EMR that can be increased by using these appliances. EMR varies over time because of the operation condition of these appliances driven by occupants' behavior. Refrigerator has EMR all through the day, while the other appliances, especially dishwasher, have most of EMR during night. That is because the operation of defrosting is flexible independently of occupants' behavior, unlikely as the other appliances. In August, the highest EMR was observed to be 110W from 21h00 to 7h00. The highest EMR in

February was to be 180W, which was higher than August due to the increase in EMR given by refrigerator whose consumption during normal operation increases with an increase in ambient temperature. It should be noted that we ignored change in electricity consumption for refrigerator's defrosting that should be observed when defrosting span is changed. Table 7 shows the averaged total amount of EMR per day among households. While interruptible load of refrigerator accounts for 40 to 80% of EMR on weekdays as mentioned earlier, thermal load of air-conditioner accounts for the largest portion of the total amount of EMR.

Table 6. *Distribution in* house archetypes and family compositions

Family compositions	2L DK	3L DK	4L DK	Family compositions	2L DK	3L DK	4L DK
Working couple	0	12	6	Working mother and 2 children	0	4	2
Couple	0	12	6	Mother and 2 children	0	5	2
Working mother and child	0	8	4	Working couple and 2 children	0	20	11
Mother and child	0	10	5	Couple and 2 children	0	24	14
Working couple and child	1	18	9	Working couple and 3 children	0	5	4
Couple and child	1	22	11	Couple and 3 children	0	6	4

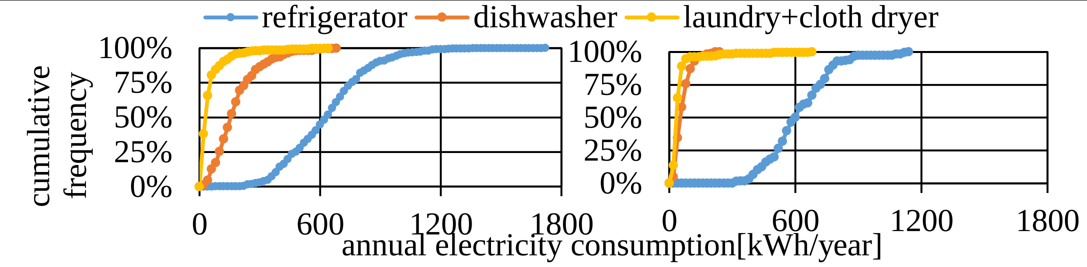

Figure 4. *Cumulative frequency of annual* electricity consumption *of appliances (left: measured data, right: simulation result)*

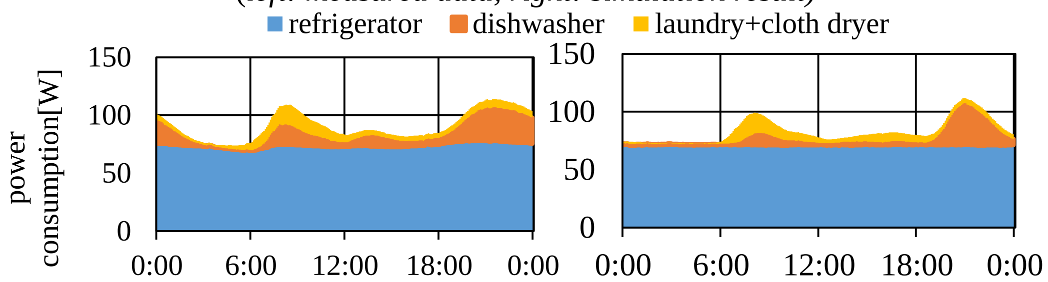

Figure 5. *Average power consumption among households on weekdays (left: measured data, right: simulation result)*

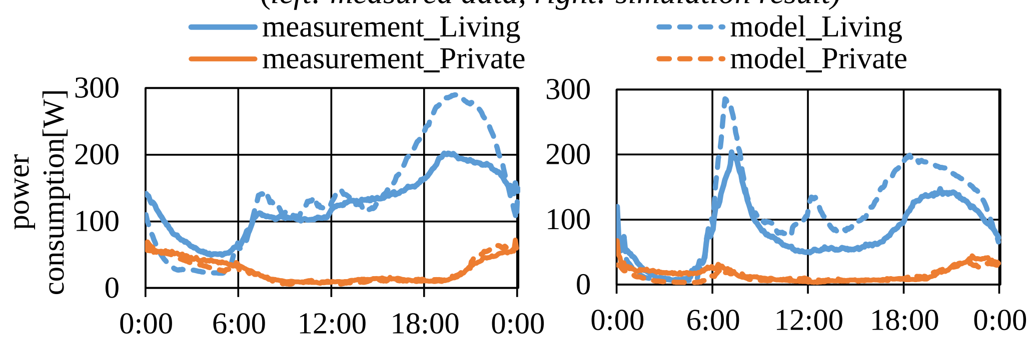

Figure 6. *Average power consumption of air-conditioner among households on weekdays* (*left: cooling, right: heating)*

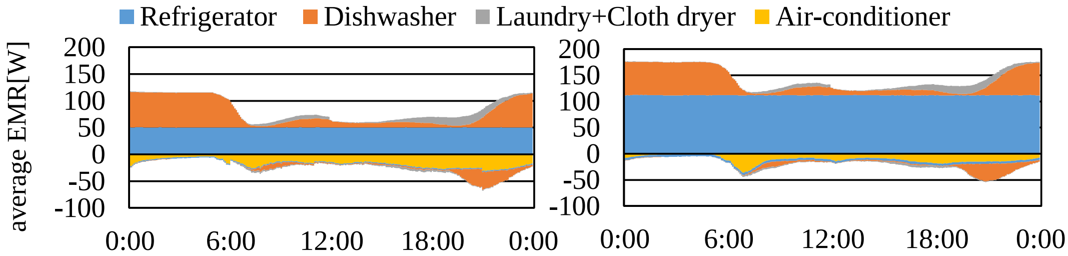

Figure 7. *Monthly-averaged EMR per household on weekdays (left: August, right: February)*

Table 7. *Averaged total amount of EMR per day among households*

[Wh/household]	Refrigerator	Dishwasher	Laundry + Cloth dryer	Air-conditioner
August	46	127	32	409
February	99	125	31	267

CONCLUSION AND IMPLICATIONS

This paper presented a model to estimate energy demand of residential buildings. This model was applied to estimate energy management resource (EMR) that can be provided by refrigerator, dishwasher, laundry, cloth dryer and air-conditioner. To realistically simulate EMR, we developed a database on power consumption and operation condition of these appliances. The simulation result showed that the scale of EMR per household was 70W during daytime and 110W during night in August. The shift of defrosting timing of refrigerators accounts for a half of EMR and is available all through the day, since refrigerator can conduct defrosting independently from occupants' behavior. On the contrary, the duration of defrosting operation is short and power consumption is not so large, the total amount of EMR is smaller than that of air-conditioner. More importantly, EMR provided by air-conditioner and the other appliances except refrigerator varies over time depending on occupants' behavior in home. It should be noted that the developed model have several weaknesses. For example, the model did not generate the operation of appliances during late night and the model did not generate realistic operation of air-conditioners. This weakness is due to the modelling methodology of occupants' behavior and operation of appliances.

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