Estimation of time series urban energy demand and Examination of optimal energy supply system

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Abstract. From the background of the liberalization of electricity and city gas retail market, it is considered that in the future Japan will move to a distributed supply form from each building and household. In order to properly place and operate this decentralized supply facility in the city, knowledge of time-series demand fluctuation in urban scale is necessary, but since there is no data or estimation method corresponding to this, it is necessary to develop one.

In this research, we first developed a program to estimate the energy demand fluctuation at five-minute intervals of non-residential buildings in urban scale into four energy applications (electricity, cooling, heating, and hot water supply). First, we acquire the building information (usage, extended floor, and coordinates) of the target city by GIS (Geographic Information System) data. Based on this data, we predict the demand fluctuation by building as a reference. By distributing the value, using probability density based on statistical and measurement data, we reproduced the variation of demand due to the difference of building characteristics which cannot be obtained via GIS data. We estimate the demand fluctuation for a city by integrating the building-specific demand fluctuation estimation values.

In this paper, the calculation was carried out using a program for Fukuoka city, Tenjin and Hakata districts, and the estimation result was compared and verified.

Based on the data obtained by the urban energy demand estimation program, we will consider optimal placement and operation methods of distributed supply equipment typified by PV panel, cogeneration, and storage battery. By flagging the presence or absence of equipment for each building and calculating it, we compared and examined the amount of energy reduction in each pattern.

1. Introduction

Conventionally, the method of supplying energy to cities in Japan was via wide-area energy supply form grid electric power and gas piping. In the future, however, it is expected that it will transform into distributed energy supply from each building and each house in the city. In order to effectively deploy distributed energy supply facilities in the city and to operate it, it is necessary to predict the demand for each energy use for each building, considering operation technology such as accommodation and energy management, studies on scale are necessary.

Therefore, in this research, our purpose is to construct a method to establish a time series estimation method of energy supply form of cities incorporating renewable energy by demand
fluctuation estimation based on building information and geographical information of buildings. In this paper, we developed a time series energy demand estimation program for non-residential buildings and analysed the estimation result when using this for an actual city. Subsequently, based on this, we set up an energy supply facility and developed a method to operate it.

2. Non-Residential energy demand estimation program

In estimating urban energy demand fluctuation, we created a program to calculate demand fluctuation based on information on each non-residential building owned by that city. Building information is acquired by GIS (Geographic Information System) data. Demand fluctuation by energy use (electricity, air conditioning, heating and hot water supply) by utilizing the building floor area of the building and the building use classified into six non-residential sectors (hospitals, hotels, offices, commerce, restaurants and schools).

2.1. Program flow

![Program Flow Diagram]

Figure 1 Program Flow
The calculation flow of the developed estimation method is shown in Fig. 1. The demand fluctuation is estimated by determining the annual standard demand intensity unit from the total floor area of each building and reproducing the necessary fluctuation of demand for each energy application; followed by accumulating demand fluctuation by building, and estimates for demand fluctuation as a district.

2.2. Annual demand unit intensity

In preparing the annual energy demand intensity unit for each type of business to be given to each building, the annual demand intensity unit described in bibliog. 1 for four industries (hospital, hotel, office, and commercial) was adopted. In this document, there is no description about offices, commercial hot-water supply applications, restaurants, and schools. Therefore, in the former case, the ratio of the thermal demand described in bibliog. 2 and the calculated value by multiplying the annual demand unit for the air conditioning application of bibliog. 1 are taken as the annual demand intensity unit for the demand estimation method in bibliog. 1, the annual demand for each application is calculated based on the model used for the Model Building Method using BEST3) (Building Energy Simulation Tool). Table 1 shows the annual demand intensity for each industry.

| Demand Intensity Unit per year | Hospital | Hotel | Office | Commercial | Restaurant | School |
|--------------------------------|----------|-------|--------|------------|------------|--------|
| Electric Power Demand [kWh/m²] | 209      | 183   | 115    | 284        | 206        | 64     |
| Cooling [MJ/m²]               | 363      | 366   | 295    | 627        | 432        | 246    |
| Heating [MJ/m²]               | 162      | 200   | 55     | 188        | 322        | 67     |
| Hot Water Supply [MJ/m²]      | 270      | 423   | 8      | 117        | 1305       | 77     |

2.3. Correction of annual demand by total floor space

Building attributes considered to influence building demand can be considered as the number of rooms, the number of floors, the number of users, the number of years of use, and opening hours. This paper focused on these areas.

The natural logarithm of the function of the annual primary energy consumption intensity in the same temperature classification (six areas) and the total floor area of the same industry building using public data of the environment related database of non-residential buildings are hereinafter referred to as DECC data. For this, we assumed that the rate of change in the primary energy consumption intensity unit based on the total floor area is equal to the rate of change in the annual demand intensity per unit area, and this function was taken as the change formula of the annual demand intensity per unit area. Table 2 shows a list of coefficients and coefficient of determination for the function. For restaurant and school industries, the number of data per area classification is small, and since it is considered that there are few large-scale buildings in restaurants, the magnification of both industries was set as a constant.

| Coefficient and Coefficient of Determination of Approximate Expression | Hospital | Hotel | Office | Commercial | Restaurant | School |
|------------------------------------------------------------------------|---------|-------|--------|------------|------------|--------|
| Common Logarithm Coefficient                                           | 8.46    | 6.9   | 6.14   | -17.71     | 0          | 0      |
| Constant Term                                                          | 104     | 28.8  | 39.24  | 281.3      | 540        | 26     |
| Coefficient of Determination (R²)                                      | 0.94    | 0.96  | 0.86   | 0.94       | -          | -      |
2.4. Reproduce the variation of annual demand using random numbers

In reality, energy demand is considered to be different between two buildings of the same industry and the same extended floor area. As this factor, building information represented by the number of users mentioned above can be considered, but it is difficult to analyse the individual influences on them. Therefore, in this paper, in addition to the above-mentioned procedure, the annual demand intensities are further changed by using the probability distribution, and the annual demand intensity unit specific to each building is set.

When creating the probability distribution for each industry, we created the frequency distribution of each industry from each industry type in the sixth region in DECC data and each industry. All the frequency distributions showed a shape close to the normal distribution. Therefore, we grasp the tendency of each industry type and set each individual variance. The width of the magnification was determined by a normal distribution with variance of this value and an average of 100%. The set dispersion is shown in table 3. By applying the random number set for each building to this normal distribution, the magnification to be applied to the annual demand is determined.

Table 3. Standard Deviation of Normal Distribution to Annual Demand

|          | Hospital | Hotel | Office | Commercial | Restaurant | School |
|----------|----------|-------|--------|------------|------------|--------|
|          | 22.67    | 19.67 | 26.33  | 30.33      | 29.00      | 11.67  |

2.5. Demand rate by month and time

Estimation of energy demand fluctuation by time is done at five-minute intervals. Therefore, time-specific demand ratios for each five-minute interval for the annual demand unit were created. In order to create this five-minute interval energy demand ratio, we first created hourly demand rates at one hour intervals. As with the annual demand intensity unit, the values of four non-residential industries (hospital, hotel, office and commercial) are described in bibliog. 1 and bibliog. 2, and restaurants and schools are based on the calculated values of BEST, created by month, day of the week classifications (weekdays, Saturdays, Sundays and holidays). Based on the hourly energy demand ratio for this one hour interval, we set the demand rate at five-minute intervals via the following procedure.

1. Demand rate for each one hour divided by 12 created values for five-minute intervals within the base time
2. Based on the data in (1), a moving average is taken in 13 section

The created five-minute interval time demand ratio is the ratio of the total value in each day of the week of each month. Therefore, to calculate the daily value, it is necessary to divide this value by the total number of days of each day in each month. Since the number of days is different between the four industries created based on bibliog. 1 and the two industries created based on BEST, the corresponding day number data was prepared and used for calculation.

2.6. Demand fluctuation by power time zone

Demand fluctuations of electric power greatly fluctuate at each time according to the usage situation. Moreover, this blur is thought to be different for each of the four time zones of closing, going to work, sales and leaving. Analysis was conducted with the business hours. The probability density of the magnification to the average value was created for each of these time zones, and it was regarded as an almost normal distribution. Therefore, standard deviation for each time zone was set based on this, and it was used for reproduction of the blur. Table 4 shows the standard deviation for each time zone type. Demand fluctuation by time is reproduced by the magnification obtained by giving different random numbers at each time to the normal distribution with the standard deviation of Table 4 and an average of 100%.

Table 4. Standard Deviation of power demand by time

|        | Closing | Attendance | Open | Leaving |
|--------|---------|------------|------|---------|
|        | 7.0     | 13.0       | 10.0 | 8.0     |
2.7. Correction by air temperature of cooling and heating demand
It seems that the demand for cooling and heating is strongly influenced by the outside temperature. Based on the measured data, we analysed the difference between the average outside air temperature at each time of cooling and heating and the ratio of the demand by time to the monthly average demand, respectively. The results are shown in Fig. 2. It can be approximated by a linear function passing through a point where the difference from the average outside air temperature is zero and cooling can be seen to have a large blur with respect to the approximate expression. Therefore, when the probability density of the demand ratio was created for each difference of the outside air temperature, it showed the normal distribution form with almost the same standard deviation, so we used this to reproduce this blur. Table 5 shows the coefficients of the cooling and heating and the standard deviation of the normal distribution.

Table 5. Air-conditioning demand coefficient and standard deviation

|         | Cooling  | Heating |
|---------|----------|---------|
| Coefficient | 0.0647   | -0.0697 |
| Standard Deviation | 0.23     | 0.20    |

2.8. Reproduce dispersion of business hours
It seems that the office and the commercial facility are greatly different in opening hours for each building. Therefore, a method to reproduce the difference in demand fluctuation accompanying this was constructed.

The office, a subdivision of the office industry classified by the total floor area was stochastically applied based on biblog. 3, based on the average monthly working hours of each industry obtained from biblog. 3 documents for each subdivided industry type, set office hours and reproduction of business hours.

For commercial facilities, subdivision of industries was first conducted, and the proportion of these industries to all commercial facilities was set based on biblog. 4. By applying it stochastically, we assigned detailed industries to each commercial building. Next, the probability of opening time and closing time for each one hour interval of each of these subdivided industries was obtained from biblog. 4 and stochastically given the opening hours of each building by using it. As a result, the opening time can be reproduced from 5:00 to 11:00 and the closing time can be reproduced at one hour intervals in the range from 16:00 to 22:00.

In incorporating the business hours obtained by the above into the program, calculations were made in the following process.
(1) Demand fluctuation in the target time zone is shifted by the difference from the reference based on the starting time and the closing time that have caused variation.

(2) Supplementing the demand at the time of the non-operating time zone and business hours due to the movement of demand fluctuation by referring to the value before or after the movement amount.

2.9. Correction of hot water supply demand in commercial facilities

Figure. 3 shows the rate of change in demand for hot water supply for commercial use. Although it shows a demand fluctuation trend with three peak times in one day, this is seen in commercial facilities involving cooking such as supermarkets. In the buildings of commercial industry without cooking represented by the apparel industry, it is assumed that such a trend of change will not be shown. Therefore, in order to reproduce this, it is determined whether cooking is accompanied with each sub category of commercial industry used to reproduce the variation of business hours, and for industries not involved, the rate of change in hot water supply demand of the office building. We decided to adapt the annual demand intensity unit.

3. Demand estimation results for the Tenjin and Hakata areas

By using the non-residential buildings demand estimation program developed this time, we estimate the energy demand fluctuation in the area unit of the real city group buildings and analysed the result.

3.1. Target area summary

The calculation target area covers the Tenjin and Hakata areas of Fukuoka City, Fukuoka prefecture. Due to the characteristic that both districts are the central business district of Fukuoka city there are few residential buildings, and many offices and commercial buildings are dotted. In addition, Hakata district has a lot of hotels from the characteristics of the station front. Table 6 shows the number of cases for each type of building industry and the total floor area. Based on these characteristics, it can be said that this area is suitable for utilizing the developed non-residential demand estimation program.

| Table 6. Owned building information of the calculation target area |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Tenjin          | Hospital        | Hotel           | Office          | Commercial      | Restaurant      | School          | Total           |
| Number of buildings | 8               | 1               | 249             | 260             | 31              | 4               | 553             |
| Total floor space[ha] | 3.33            | 1.05            | 89.78           | 121.14          | 0.73            | 0.53            | 216.4           |
| Total floor area ratio[%] | 1.5             | 0.5             | 41.5            | 56.0            | 0.3             | 0.2             | 100.0           |
| Hakata          | Hospital        | Hotel           | Office          | Commercial      | Restaurant      | School          | Total           |
| Number of buildings | 6               | 31              | 255             | 151             | 32              | 13              | 488             |
| Total floor space[ha] | 1.31            | 21.0            | 57.25           | 60.28           | 0.67            | 4.21            | 144.7           |
| Total floor area ratio[%] | 0.9             | 14.5            | 39.6            | 41.6            | 0.5             | 2.7             | 100.0           |
3.2. Demand estimation results for Tenjin and Hakata area

After calculating demand fluctuation for all the non-residential buildings in Tenjin and Hakata districts in Fukuoka city, we calculated demand fluctuation as the whole district by integrating these for each time. Figures. 4 to fig. 7 shows the data for one week of the representative month in the calculation results.

In both districts, we see that the influence of the proportion of the building industry possessed is clearly reflected in the demand fluctuation of the entire district. In the Tenjin district where the influence of offices and commercial facilities is common, the Hakata district, which has many hotels, has a string demand for heating demand and hot water supply demand, the time when the demand peaks for each building industry is different, the peak time of the entire district is expected to change greatly depending on the owned building industry. Demand fluctuation at each time is smaller as compared to when looking at electric power demand, cooling and heating demand by building alone. This is considered to be due to the levelling of the district as a whole due to the accumulation of the demands of building demand. From this, it turns out that the more buildings in the area, the more prominent from the standards, the higher the demand or the probability that the demand will decline. The fluctuation tendency of the electricity demand of the commercial facility is in a staircase shape because the result of giving the hourly variation in business hours appeared in this way. It was confirmed that the demand for cooling and heating is greatly influenced by the outside temperature and has an influence on demand. As for heating demand, the peak zone of demand is different depending on the building application, so the overall demand peak time zone fluctuates greatly depending on the building composition of the district. Since the demand for hot water supply did not reproduce the fluctuation of demand at each time and reproduce the blur in business hours, it was confirmed that the demand fluctuates as it is with the monthly overlap of the standard demand fluctuation.

![Figure 4](image1.png)

**Figure 4** Summer electric power demand fluctuation (Upper:Tenjin Lower:Hakata)[MWh]

![Figure 5](image2.png)

**Figure 5** Summer cooling demand fluctuation (Upper:Tenjin Lower:Hakata)[GJ]
4. Energy supply equipment response

As an energy supply facility for non-residential construction, we will provide optional equipment from among three categories: cogeneration system (CHP), solar panel (PV), storage battery, building multi air conditioning (hereinafter referred to as air conditioning equipment), hot water storage tank an hot-water supply boiler (hereinafter hot-water supply equipment) was installed in each non-residential building in the target area and a method to calculate the response of each facility at five-5 minute intervals was developed. Details of each procedure and usage data in the calculation flow of this method are described.

4.1. Data input

First, enter the building industry of each non-residential building, the total floor area, presence/absence of installation of hot-water supply equipment, operation method and the amount of solar radiation every five-minutes to PV from external data. Then, enter the loop calculation for each building at intervals of five-minutes, input the target time, the electric power demand of the target building obtained by the demand estimation, the heat demand for heating, cooling and hot water supply at the beginning of the loop.

4.2. CHP power generation

In the CHP power generation, when the sum of the electric power demand five-minutes before the CHP installation building and the current chargeable state of the storage battery in the country at present is 50% or more of the CHP rated generation amount, the CHP generation amount, load rate, power generation efficiency, and gas consumption are calculated using some equations respectively. The values used for the formulas and calculations (Table 7) were set with reference to existing
programs5) and previous studies6). The number of units to be operated was set to be second operation, and third operation, respectively, when the electric power demand became 150% or more five-minutes before the CHP rated generation amount.

Table 7 Value used for calculation of CHP power generation

| Item                                                      | Value |
|-----------------------------------------------------------|-------|
| Rated power generation efficiency                          | 0.45  |
| Second order coefficient of power generation efficiency curve | 7.2   |
| First order coefficient of power generation efficiency curve | 8.2   |
| Constant term of power generation efficiency curve         | 84.6  |
| Ratio of real value to catalog value of power generation   | 0.99  |
| Ratio excluding consumption by auxiliary machinery of power generation | 0.95  |

4.3. CHP waste heat

In the case of CHP waste heat, when CHP generates electricity, it supplies each heat demand by using generated waste heat. Supply priority ranked in the order of air conditioning, heating, and hot water supply. In addition, the cooling was set to be supplied to each demand via the heat exchanger 1 (exchange efficiency: 1.0[-1]) and the heating and hot water supply waste heat input type absorption cooler/heater (hereinafter RHA: Recovered Heat-Driven Absorption Cooler) heating and hot water supply. The values used for these formulas and calculation (Table 8, Table 9) were also set with reference to existing programs5) and previous studies6).

Table 8 CHP value used for calculation of waste heat

| Item                                                      | Value |
|-----------------------------------------------------------|-------|
| Rated overall efficiency                                  | 0.85  |
| Second order coefficient of total efficiency curve        | -14.4 |
| First order coefficient of total efficiency curve         | 43.6  |
| Constant term of total efficiency curve                   | 70.8  |
| Proportion of waste heat piping excluding heat loss       | 0.97  |

Table 9 RHA instantaneous rating capability intensity unitMJ/h•㎡

| Building industry     | Hospital | Hotel | Office | Commercial | Restaurant | School |
|-----------------------|----------|-------|--------|------------|------------|--------|
| Unit consumption      | 33.05    | 26.57 | 28.99  | 35.17      | 45.13      | 26.49  |

4.4. Operate air conditioning equipment

In air conditioner operation, air conditioning heat demand remaining after CHP operation is processed by air conditioning equipment and added to electric power demand. The heating efficiency and the cooling efficiency were set to be constant (heating: 3.4[-1], cooling: 3.2[-1]) regardless of the load factor of the air conditioning equipment.

4.5. PV power generation

For PV power generation, the PV power generation amount is calculated from solar radiation amount at target time and it is supplied to power demand of PV installation building. The calculation formula is based on the Japan Industrial Standard7).

4.6. Rechargeable battery charge and discharge

In storage battery charging and discharging, charging the storage battery and discharge from the storage battery are performed based on the power demand of the target building, CHP and PV generation amount. The storage battery is assumed to be a lithium-ion battery, and is composed of a storage battery main body and a power conditioner (PCS). In this paper, the power loss by PCS and storage battery body at charge and discharge is calculated based on the formula set with reference to the previous studies8). In addition, the equipment specifications are shown in Table 10.
Table 10 Equipment specification of storage battery

| Item                                      | Value |
|-------------------------------------------|-------|
| PCS rated charge / discharge C rate       | 0.3   |
| Discharge stop lower limit adequacy ratio | 0.5   |
| Charging stop lower limit adequacy ratio  | 1.0   |
| Efficiency of lithium ion battery         | 0.957 |
| Natural electricity per day               | 0.05  |

4.7. Hot water supply equipment operation

The hot water supply equipment goes out from the hot water storage tank or heats the boiler according to the hot water supply demand of the building. Table 11 shows the capacity consumption unit for each building's use of the hot water storage tank. These were prepared based on biblio. 9. Hot water supply is carried out using only the hot water supply boiler without setting the hot water storage tank in the office building. Also, the hot water storage tank was set so that the effective hot water storage amount was 70% of the hot water storage tank capacity, and when the effective hot water storage amount became zero, hot water was supplied to the tank using a heater.

Table 11 Hot water storage tank capacity consumption unit [MJ/m²]

| Building industry | Hospital | Hotel | Office | Commercial | Restaurant | School |
|-------------------|----------|-------|--------|------------|------------|--------|
| Unit consumption  | 8.78     | 13.26 | 0      | 3.29       | 40.60      | 3.36   |

4.8. Primary energy consumption calculation

The primary energy consumption is calculated from the electric power demand after the building’s energy supply facilities are supplied and from the gas usage amount of each facility. In addition, the primary energy conversion coefficient of electricity demand was 9.97 in the daytime (8:00 to 22:00) and 9.28 in the night time (22:00 to 8:00).

5. Consideration of optimum equipment placement

We introduced energy supply facilities in the Tenjin and Hakata districts where the energy demand estimation was made using the developed method. The optimum capacity and its effect were analysed while changing the capacity of each supply facility. We targeted the Tenjin and Hakata areas for demand estimation.

5.1. Capacity setting for each energy supply facility

Table 12 summarizes the examination cases of capacity and number of each facility. The rated generation capacity of CHP was set to 3 cases, and the capacity of each case was changed according to the total floor area of the building. In addition, PV was uniformly installed on the roof of all non-residential buildings and half of the roof area was used for installation. The installation angle of PV was set to 26.1° from the annual optimum system shooting angle set by the NEDO solar radiation database browsing system (10). For each building, we examined a total of 48 cases of CHP capacity, 3 cases x 4 pieces of cases x 4 storage cases of storage batteries, and cases where the primary annual energy consumption was the smallest are summarized for each region as a BEST case.

Table 12 Capacity of each supply facility, cases with number

| Case | CHP capacity <20000 m² | CHP capacity ≥ 20000 m² | CHP | Storage battery capacity [kW] |
|------|------------------------|--------------------------|-----|-----------------------------|
| 1    | 5                      | 100                      | 1   | 5                           |
| 2    | 35                     | 700                      | 2   | 50                          |
| 3    | 100                    | 1200                     | 4   | 200                         |
| 4    | -                      | -                        | 8   | -                           |
5.2. Best Case calculation result in each region
The annual primary energy consumption reduction rate of BEST case was calculated for each region. In the case of optimizing the capacity of supply facilities in each building, the primary energy consumption in each region was reduced by about 23% annually.

5.3. Calculation of optimum capacity unit consumption in each region
By dividing the total capacity of the supply facilities in the BEST case of each region by the total value of the non-residential building total floor are in each region, the optimal capacity basic unit of CHP and storage battery in each region was calculated. While the annual primary energy consumption reduction rate has been collected at around 23% in every region, the optimum capacity of the area was variable among CHP and storage batteries. Slight differences in building size and composition in each region are thought to cause large variations in the optimal capacity basic unit of both supply facilities.

6. Conclusion
By dividing the total capacity of the supply facilities in the BEST case of each region by the total value of the non-residential building total floor area in each region, the optimal capacity basic unit of CHP and storage battery in each region was calculated. While the annual primary energy consumption reduction rate has been collected at around 23% in every region, the optimum capacity of the area was variable among CHP and storage batteries. Slight differences in building size and composition in each region are thought to cause large variations in the optimal capacity basic unit of both supply facilities.

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