# DEVELOPMENT OF DISTRICT ENERGY SYSTEM SIMULATION MODEL BASED ON DETAILED ENERGY DEMAND MODEL

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## ABSTRACT

This paper presents a district energy system simulation model in which the energy flow of a district is modeled as the sum of total energy flow in each building. By using this model, various kinds of energy supply systems can be evaluated taking into account the relationship among performance of energy supply systems, available technologies, and conditions of targeted districts, such as characteristics of energy demand, size and arrangement of buildings. In the last part of this paper, results of a case study, which evaluates two types of energy supply systems utilizing CGS are presented.

## INTRODUCTION

Recently, there has been growing interest in energy saving technologies in the building industry. Various energy saving measures that could considerably reduce energy consumption of a building have been proposed. In total, however, the net energy consumption at city/district level is still increasing. In order to curb this upward trend and to reduce energy consumption, strategies to improve energy system should be better imposed.

Figure 1 shows the characteristics of a typical building energy supply system with two axes. The vertical axis represents grid electricity dependency. Advancement in the distributed generation technologies allows an energy system to be partially or completely independent from grid electricity (Mathew et al, 1999). Due to the fact that these technologies could considerably change the energy flow of a district, grid electricity dependency is a vital factor for the evaluation of a district energy system.

The other axis shows different combination of buildings in the installation of energy supply systems. Advancement in distributed generation technologies could contribute not only to self-sustenance in electricity but also realize various types of heat and electricity supply systems in a district. For example, a small scale Waste Heat Network (WHN), which is at the right-hand side of the horizontal axis, may be a flexible and effective system. In this system, a number of closely located buildings share the heat and power generated from one or more cogeneration

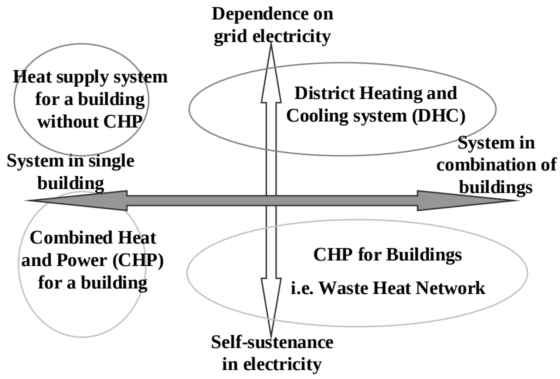



*Figure 1 Characteristics of energy supply systems*

systems installed in one or more buildings. This system will be realized when the distributed generation technologies achieve sufficient advancement. Further development of these technologies, however, could lead to complete self-sustenance of each building by decrease in heat power ratio of cogeneration systems. If this situation occurs, cooperation with neighboring buildings would be unnecessary. As combination of building energy demand profile alters the heat and electrical load of energy supply systems in pattern and scale, combination of buildings in sharing an energy supply system is also a significant factor in evaluating the effectiveness of a district energy system.

As can be seen in the example of distributed generation technologies given earlier, the development of technologies utilized in energy supply systems could change the choice of energy supply system and affect the energy flow of a district. Similarly, the circumstances of buildings' renewal are also significant in choosing suitable energy supply systems. For example, if a number of neighboring buildings are renewed simultaneously, an energy supply system with combination of buildings could be relatively easily installed. On the contrary, if the renewal of each building occurs separately, a system with combination of buildings could not be implemented simultaneously; thus, its installation is uneconomical due to the longer pay back period. Therefore, in order to employ effective strategies to improve a district energy system, a framework that is able to evaluate various energy supply systems by taking into account uncertainties such as technology development and buildings' renewal is required.

During investigations on the performance of energy supply systems in the commercial sector, energy demand profiles of buildings have been traditionally assumed as a fixed demand per unit floor area (IBEC 1985 etc.). Although this is very convenient, it shows limited ability to achieve accurate estimation. Huang et al. (1991) and some other researchers have provided prototypical input information of various commercial buildings for energy demand simulation. The output of this simulation allows users to estimate the effectiveness of energy supply system considering the effect of energy saving measures and climatic conditions. Both methods generalize energy demand profiles to acquire generalized effectiveness of energy supply systems. In reality, however, the performance of energy supply systems utilizing distributed generators varies with the changing pattern of building energy demand profiles (Yanagi et al, 2002). The performance of systems connecting a small number of buildings such as a WHN system could also be affected by differences of energy demand in each building. For this reason, in order to evaluate various energy supply systems at a district level, the relationship between the performance of energy supply systems and energy demand profiles of buildings should be taken into account even if the buildings are of the same function.

Thus, in order to evaluate various energy supply systems considering the relationship among the performance of energy supply systems, characteristics of energy demand of buildings, and available technologies, we developed a district energy system simulation model which contains a detailed energy demand model. This model adopted the bottom up approach in which the energy flow of a district is modeled as the sum of total energy input and output of each building. In this model, heat and power demands of each building are simultaneously calculated considering climatic conditions, occupant behaviors, use of appliances, adoption of energy saving measures, and etc. In this paper, we present the structure of the simulation model and the result of evaluation of the two systems, which are CHP for a single building and WHN for two buildings.

## MODELING DISTRICT ENERGY SYSTEMS

Figure 2 illustrates the calculation procedure of the district energy system simulation model. This model consists of three basic components, an occupant behavior model, a building energy demand model and district energy supply system model. Firstly, based on occupant behavior, the heat and electrical load generated from the use of energy consuming appliances by each occupant are simulated in the occupant behavior model. Then, heat and electrical demand profiles of each building are calculated. Finally, the total energy flow of a district is quantified.

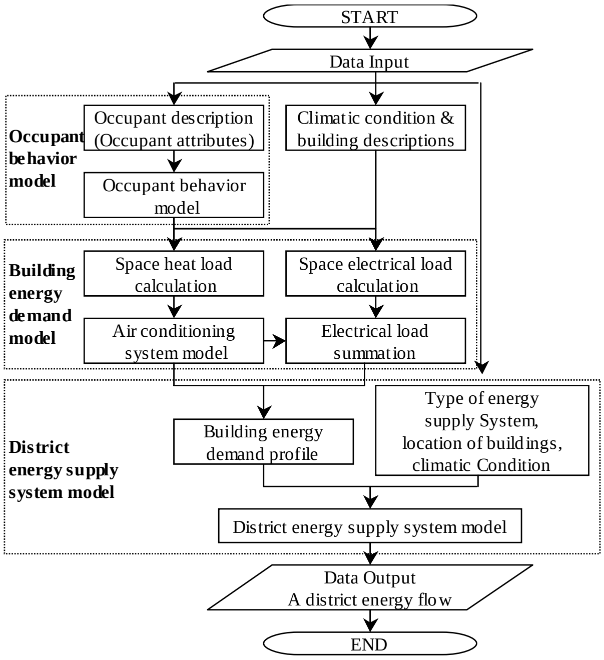



*Figure 2 Flow chart of the district energy system simulation model*

The remaining part of this section presents descriptions of each sub-model.

### *Occupant behavior model*

The purpose of this model is to reflect the practical operational condition of a building and also energy consuming appliances in energy demand profiles. These operational conditions of many prototypical buildings have been modeled as fixed conditions as stated previously. In reality, however, there are differences in those conditions among buildings. Particularly, energy-consuming appliances vary in number, specification and operational conditions. These real conditions could change the energy demand profiles and also the energy saving potential of active energy saving measures such as the adoption of low-power consuming appliances and improvement of these operational conditions. Then, it could further affect the performance of energy supply systems. Thus, to account for these influences, we developed the occupant behavior model stochastically simulating the practical operational condition of energy consuming appliances and occupant schedule, resembling as much as possible the real world condition.

#### Stochastic model for occupant behavior

Figure 3 illustrates the flow chart of the occupant behavior model. The model adopted a transaction approach in which the behavior of each occupant is simulated.

Firstly, working hours of each occupant are decided base on the distribution functions of $T_1$~$T_4$ as defined in Table 1.

Then, the working state of each occupant during working hours are decided. There are limited kinds of working states for office building occupants that can be roughly divided as in Table 2. Firstly, we assume random mobility among working states. Secondly, the duration in each working state is assumed to be occupant's attribute-dependent. Based on the first assumption, the transition of states can be modeled as a Markovian process. In a Markovian process, the next state will depend only on the present state. Additionally, the second assumption allows transition probabilities to depend only on occupant attributes. The occupant attributes are data that can be easily obtained for each building, such as type of job and ages. In this paper, only the type of job is considered as occupant attributes.

In Markovian process, Markov matrices define the transition of states, which its elements are transition probabilities from a present state to another. Markov matrices are generated corresponding to the occupant attributes. To generate these matrices, two kinds of data are required. One is the average duration of each occupant in a state $i$ (=1, 2,.., n where n is the number of states). From this information, the probability ($r_i$) of transition occurrence from a state $i$ to other states is decided. The other data required is the percentage distribution ($s_j$) of working states $j$ (=1, 2,.., n) for building occupants with different attribution. From these data, the transition probabilities from the present state $i$ to another state $j$ ($p_{ij}$) of Markov matrices for each occupant attribute are decided by formula (1).

$$p_{ij} = 1 - r_i + r_i \cdot s_j \quad (i = j) \qquad (1a)$$

$$p_{ij} = r_i \cdot s_j \quad (i \neq j) \qquad (1b)$$

Using the inverse function method (R. Fritsch et at, 1990) with these Markov matrices, the working states of occupant can be simulated. Although probabilities $r_i$ and $s_j$ should be given by measured data, we assumed the values of $r_i$ as given in Table 3 and each $s_j$ can be decided at a constant 6.25% for all states and all attributes, which means that the expectation of state transitions is 1.5h base on a 5-minute time step used in the occupant behavior model.

Finally, the calculation results of working states of each occupant are translated into occupant schedule and power consumption and heat release from appliances controlled by each occupant. By inputting these data into the building energy demand model, occupant behaviors are thus integrated into the energy demand profiles of a building.

***Building energy demand model***

The building energy demand model calculates the hourly heat and electrical demand profiles of each building simultaneously.

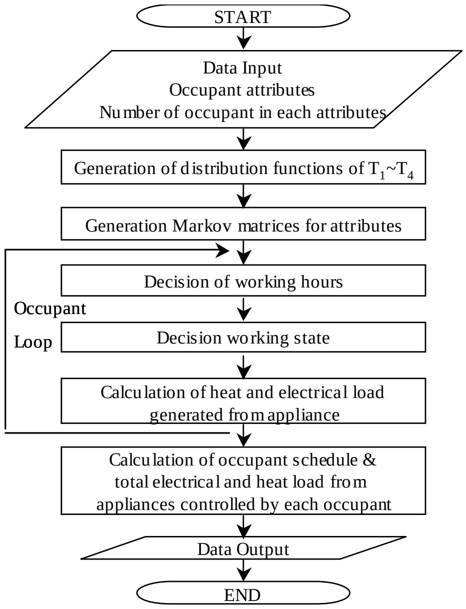



*Figure 3 Flow chart for the occupant behavior model*

The space heat load is calculated using the weighting factor method. Then, the air conditioning system model translates the space heat loads into the cold and hot water coil loads. It is assumed that an air conditioning system is installed in each story. The load of the heat supply system is then defined as the sum of all cold and hot water coil loads.

The electrical demand of a building is calculated by summing the electrical loads shown in Table 4. Table 4 also shows the calculation method of each electrical load. The capacity of each appliance is calculated considering its number and specifications. Electrical load for conveyance, emergency, sanitary, security and etc. are also calculated by the total capacity of 31.2W/m$^2$ and the schedule showed in Figure 4. The value of total capacity is taken from statistical data (Japan Building Mechanical and

*Table 1 Definition of $T_1$~$T_4$*

| Time | Definition |
|---|---|
| $T_1$ | Time when occupant starts work |
| $T_2$ | Time when occupant finishes work |
| $T_3$ | Time when occupant leaves for lunch break |
| $T_4$ | Time when occupant comes back from lunch break |

*Table 2 Working states of building occupants*

| State | Definition | Location | Load source of appliances |
|---|---|---|---|
| A | Using PC | Seat | 1 PC + 1 monitor |
| B | Not using PC | Seat | Stand-by power of 1 PC and monitor |
| C | Being out | Outside of office | Stand-by power of 1 PC and monitor |
| D | Using two PC | Seat | 2 PCs + 2 monitors |

*Table 3 Percentage distribution of working states for building occupants at different positions*

| State | Position | | | |
|---|---|---|---|---|
| | Manager | Clerk | Sales | Engineer |
| A | 30 | 60 | 20 | 30 |
| B | 30 | 20 | 20 | 20 |
| C | 40 | 20 | 60 | 20 |
| D | 0 | 0 | 0 | 30 |

*Table 4 Electrical load*

| Term | Example | Load calculation mothod |
|---|---|---|
| Lighting | - | Capacity * Schedule |
| Appliance controlled by single occupant | PC, Moniter | Input from occupant behavior model |
| Appliance controlled by ocupants group | Copy machines | Capacity * Schedule |
| Appliance always switched on | Network servers | Capacity * Schedule |
| Fan for ventilation | - | Input from secondary system model |
| Fan for air supply | - | Input from secondary system model |
| Other Electrical loads | Conveyance<br>Emergency<br>Sanitary<br>Security | Capacity (31.2W/m$^2$)* Schedule<br>(Schedule is shown in Figure 4) |

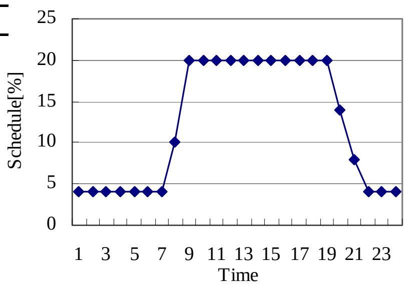


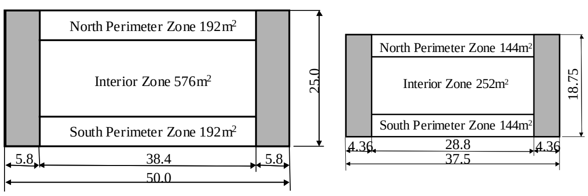

*Figure 4 Schedule for other electrical load in Table 4*

Electrical Engineers Association 1994). The schedule pattern is decided with reference to the IBEC electrical demand profiles (IBEC 1986).

***District Energy supply system model***

The district energy supply system model calculates the total energy flow of a targeted district. The input information is the energy demand profiles of all buildings, climatic conditions, types of energy supply system, and location of the buildings, which is required for the design of heat supply pipelines

The district energy supply system model is able to deal with systems for a single building and for a number of buildings. The inner and outer diameters of pipelines and its insulator are designed from the peak heating or cooling demand of each building. The part-load characteristic is assumed in the calculation for all components of the energy supply system. For refrigerators, in addition to the part-load characteristics, the COP modeled from its rated COP and its regression with chilled water temperature as well as condenser water temperature.




Large office building
16,250m$^2$ (1,250m$^2$/story)
12 stories 1 basement

Medium office building
6,327m$^2$ (703m$^2$/story)
9 stories

| | |
|---|---|
| Location | Osaka |
| Percentage of glass in wall | 40% |
| Occupancy rate | 0.1 person/m$^2$ |
| Light | 20 W/m$^2$ |
| Appliances | 19 W/m$^2$ |

*Figure 5 Illustration and description of buildings in case study*

*Table 5 Definition of the combination of buildings*

| Combination | Description of building combination |
|---|---|
| C1 | Two large office buildings |
| C2 | One large office building and One medium size office building |

## CASE STUDY

In this case study, the effectiveness of two types of energy supply systems utilizing cogeneration systems (CGS) is evaluated for two different combinations of closely located buildings shown in Table 5. One combination (C1) is of two large office buildings with a total floor area of 16,250m$^2$ (1,250m$^2$ per story). The other (C2) is the combination of a large building and the medium office building with a total floor area of 6,325m$^2$ (about 703m$^2$ per story). The illustrations of these buildings are shown in Figure 5. In addition, distance between the two buildings is assumed to be 50m for calculations of the heat supply pipelines.

*Description of Energy Supply Systems Utilizing CGS*

Three types of energy supply systems were assumed in this case study. Figure 6 illustrates the basic energy supply system to be compared with systems utilizing CGS.

Figure 7 illustrates the first type of energy supply system utilizing CGS for a single building. In this system, all generated electricity and exhaust-heat are used only in the building itself. In this system, utilization of gas engine cogenerations is assumed. Exhaust-heat is recovered in hot water and steam. The hot water and steam are converted into heating energy using heat exchangers, then to cooling energy using exhaust-heat gas absorption chiller/heaters (EGAR). Finally, the surplus of the recovered hot water is discharged from cooling towers. However, it should be noted that there is an upper limit of the exhaust-heat utilization. A maximum of 30% of EGAR cooling capacity could be supplied by exhaust-heat utilization.

Figure 8 illustrates the second type of energy supply system, the Waste Heat Network (WHN) for two buildings. In this system, CGS is installed in one building (the CGS building). This system also adopts gas engine cogenerations. In the CGS building, the recovered hot water and steam are used similarly as those in CHP for a single building. Then, the surplus electricity and steam are supplied to the neighboring building (the demand side building). In the demand side building, the supplied steam is used for heating, then for cooling using double effect absorption

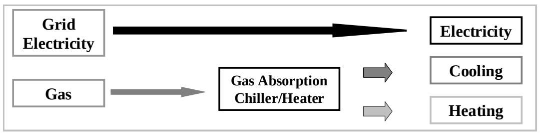



*Figure 6 Schematic of the basic energy supply system*

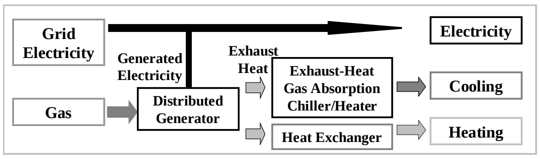



*Figure 7 Schematic of CHP for a single building*

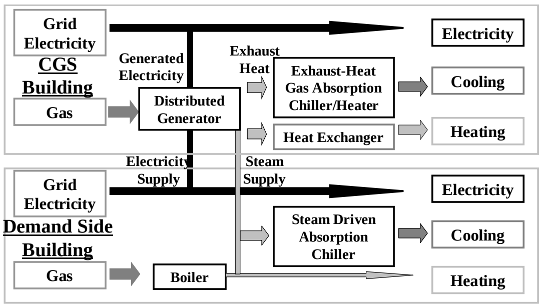



*Figure 8 Schematic of WHN for two buildings*

chillers (AR). The steam supplied to the demand side building enhances the utilization ratio of exhausted heat. The electricity supply to demand side building contributes to increase the full-load operating hours of CGS.

The power generation efficiency, steam and water recovery efficiencies of gas engine cogeneration utilized in these two systems are shown in Figure 9 considering part-load operating condition. Basically, the efficiency in Figure 9 will be used in this case study. We describe this CGS as high efficiency CGS. In the last part of this case study, we examined a different efficiency of CGS, the medium efficiency CGS. The respective efficiencies of the medium efficiency CGS are shown in Figure 10. Values in Figure 9 and Figure 10 are based on lower heating value of fuel (city gas).

We would like to point out that any heat storage facilities are not considered in this case study. Thus,

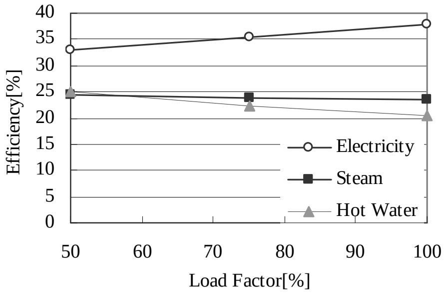



*Figure 9 Efficiency of the high efficiency CGS*

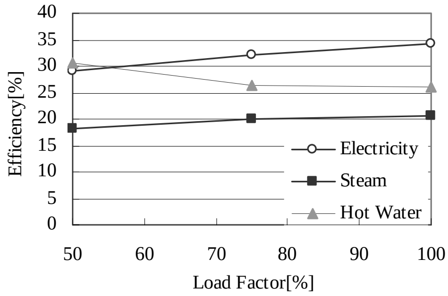



*Figure 10 Efficiency of the medium efficiency CGS*

the performance of the energy supply systems could be heavily depending on energy demand patterns. In order to better understand the performance of energy supply systems utilizing CGS, further study considering energy storage facilities will be carried out.

*Alternatives of energy saving measures*

Table 6 shows the alternatives of energy saving measures for two buildings. These alternatives are combinations of two types of energy supply systems utilizing CGS described above and energy saving measures shown in Table 7.

Energy consumption, cost and amount of waste heat produced will be focused in this study. We defined these values as the summation of these of two buildings in the targeted building combinations.

### *Simulation Result*

*Impact of operational condition of CGS*

For each system utilizing CGS, two operational

*Table 6 Alternatives for energy saving systems*

| Alternative | Description |
|---|---|
| Case 1 | No measures |
| Case 2 | Energy saving measures in Table 7 |
| Case 3 | One CHP for each building |
| Case 4 | WHN shared by two buildings |
| Case 5 | Energy saving measures in Table 7 + One CHP for each building |
| Case 6 | Energy saving measures in Table 7 + WHN shared by two buildings |

*Table 7 Energy saving measures*

| Item | Standard condition | With energy saving measure |
|---|---|---|
| Window | Solar reflecting glass | Pair glass |
| Light | 20[W/m2] | 15[W/m2] |
| Set point of room temperature | Cooling:26[$^{o}$C], Heating:22[$^{o}$C] | Cooling:28[$^{o}$C], Heating:20[$^{o}$C] |
| Total heat exchanger | Assume unused | Use, and efficiency 30[%] |

conditions for CGS are defined as follows.

1) Energy minimum operation

With this operational condition, CGS is operated to minimize the primary energy consumption for each time step. The optimum capacity for energy minimum operation of CGS is calculated from the value of minimum primary energy consumption of two buildings.

2) Cost minimum operation

With this operational condition, CGS is operated to minimize the operational cost each time step. The optimum capacity for cost minimum operation of CGS is calculated from the value of minimum annual depreciation and operation expenses. The operation expenses include standing charge and unit commodity charge for electricity and city gas.

Usually, energy supply systems are operated to minimize total cost. This operational condition may differ with the operational condition in which systems achieve the maximum energy conservation potential. Thus, clarifying the degree of the difference is important to improve the effectiveness of energy supply systems. Figure 11 shows the annual primary energy consumption at optimum capacity of CGS for energy minimum operation. Figure 12 shows these values at cost minimum operation. Both figures show the total energy consumption of two buildings in the building combination C1 as defined in Table 5. Percentage at the end of bar graph shows the energy saving ratio of each case.

At the energy minimum operation, the energy saving ratio of Case 2 is 19.3%. This value is larger than those of Case 3 and Case 4 where energy saving measures are not implemented. As can be seen in Figure 11, the energy saving ratios in Case 5 and Case 6 are about 25% with the difference of 0.7%. At the cost minimum operation, however, a greater difference, which reaches 3.5% in the energy saving ratios between Case 5 and Case 6 are obtained. Figure 13 and Figure 14 can account for this difference. Figure 13 shows the transition of energy saving ratio of Case 5 and Case 6 at cost minimum operation for different CGS capacities. Figure 14 shows the annual depreciation and operation expenses in the same condition. In Case 6, the optimum capacities of CGS for the maximum energy saving ratio (Figure 13) and for the smallest annual depreciation and operation expenses (Figure 14) almost conform. On the contrary in Case 5, there is discrepancy between these capacities of CGS. The difference in degree of reduction of energy conservation efficiency between Case 5 and Case 6 is the consequence of this discrepancy.

In addition to this, Figure 13 and 14 shows higher energy and economical performance of Case 6. In Case 6, the demand side building utilizes exhaust-heat without limitation. This means that a larger amount of exhaust-heat utilization can be achieved, thus leading to higher energy saving ratio compared to Case 5. Furthermore, the energy saving

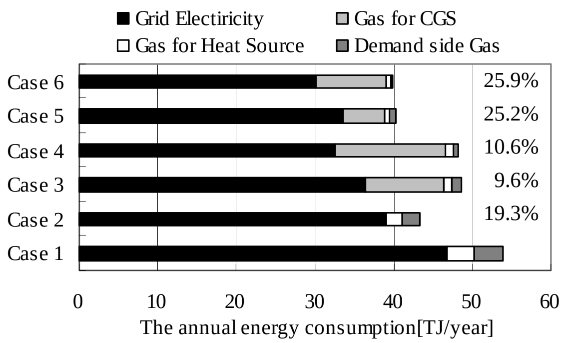



*Figure 11 Annual primary energy consumption and energy saving ratio [%] at energy minimum operation*

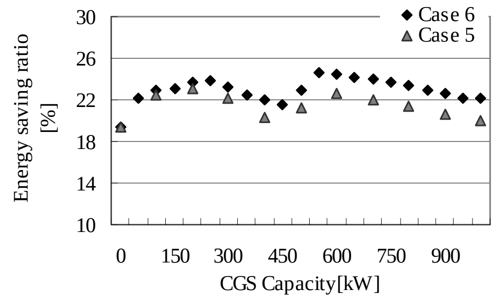



*Figure 13 Transition of energy saving ratio of Case 5 and Case 6 at cost minimum operation*

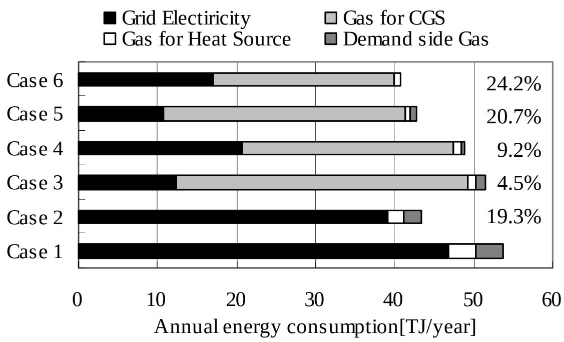



*Figure 12 Annual primary energy consumption and energy saving ratio [%] at cost minimum operation*

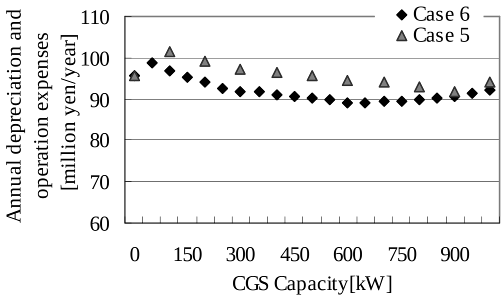



*Figure 14 Transition of the annual depreciation and operation expenses of Case 5 and Case6 at cost minimum operation*

ratio in Figure 13 shows two maxima. The energy saving ratio declines after the first peak as CGS operates without exhaust-heat utilization during unconditioned hours. During these hours, with low CGS capacity, the electricity is supplied by CGS operation thus resulting in energy cost reduction. However, with larger CGS capacity after the local dip in Figure 13, the CGS operation during unconditioned hours (low load factors) becomes uneconomical due to the fall in CGS power generation efficiency. Thus, the CGS operation during these hours is ceased; resulting in the rise to the second peak of the energy saving ratio. Furthermore, the scale merit of the CGS initial cost with the lower standing charge and unit commodity charge for gas utilization together account for the economical merit shown in Figure 14.

*Impact of type of energy supply system utilizing CGS*

Figure 15 shows the annual depreciation and operation expenses at optimum capacity of CGS at cost minimum operation. The numbers in Figure 15 shows simple pay back periods for each case. As can be seen in Figure 15, although Case 2 provides the shortest simple pay back period, the least annual depreciation and operation expenses occurs in Case 6 which also provides the highest energy saving ratio. These results demonstrate feasibility of Case 6.

Figure 16 shows the annual amount of waste heat produced for each case in the same operating condition. As can be seen in Figure 16, although introduction of CGS increases waste heat from these buildings, the waste heat produced in Case 6 is less than those in Case 5.

*Impact of building size*

In existing city centers, various types of office buildings have been densely constructed. Thus, in order to achieve sufficient energy conservation, we could not ignore various types of combinations of buildings. With regard to building size, smaller buildings have relatively more difficulties in adopting energy saving measures as it usually requires large initial investment (i.e. the introduction of CGS), though these buildings usually make up a large portion of existing city centers. In this section, the case study is executed for the building combination C2 as defined in Table 5 to study the effect of building size on the effectiveness of energy supply systems.

Figure 17 and Figure 18 shows the annual energy consumption and the annual depreciation and operation expenses at the cost minimum operation respectively. In Case 5, the CHP system for the medium size office building is unsuitable due to the higher annual depreciation and operation expenses than those without CGS. Thus, for Case 5, the most suitable installation criteria were found to be only a CHP in the larger building. On the contrary, Case 6 achieved the highest energy saving ratio of 23.3% from these two buildings without increasing the annual depreciation and operation expenses. However, the simple pay back period of Case 6 increased to 7.6 years from the 5.5 years in the building combination C1.

*Impact of the efficiency of CGS*

In energy supply systems using CGS, the total effectiveness of the system may be critically affected

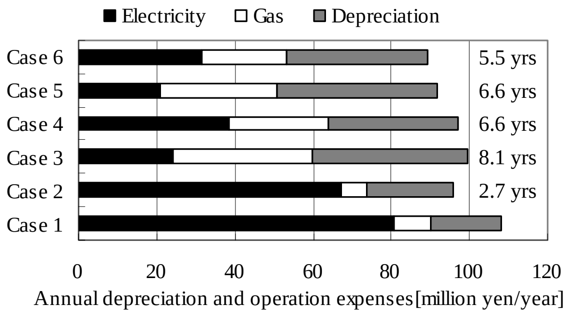



*Figure 15 Annual depreciation and operation expenses and simple pay back period [yrs] at cost minimum operation*

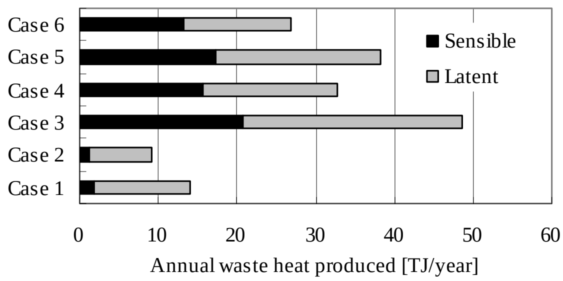



*Figure 16 Annual waste heat produced at cost minimum operation*

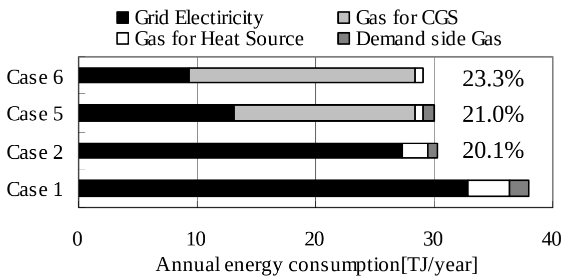



*Figure 17 Annual energy consumption and energy saving ratio [%]*

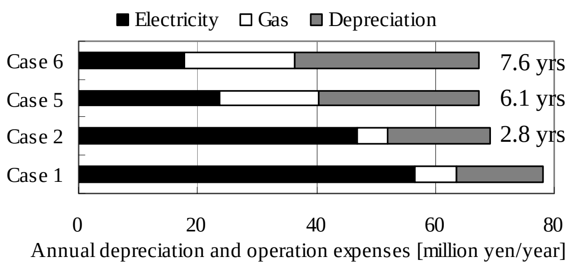



*Figure 18 Annual depreciation and operation expenses and simple pay back period [yrs]*

by the efficiency of CGS. In this section, in order to investigate this sensitivity, the comparison between cases utilizing high and medium efficiency CGS is presented. Figure 19 and Figure 20 shows the annual energy consumption and the annual depreciation and operation expenses respectively for both high and medium efficiency CGS. Here, the building combination C1 is assumed. Both figures show results of Case 5 and Case 6 where systems with medium efficiency CGS are indicated with an apostrophe (i.e. Case 6').

As can be seen in Figure 19, the deterioration of efficiency of CGS leads to the increment of total energy consumption, though the cost performance changes slightly for both cases. From this, the largest energy saving rate occurs in Case 2 when the lower efficiency CGS is utilized. Thus, in order to achieve adequate energy conservation by utilizing CGS, sufficient development of CGS is essential as well as the adoption of high efficiency equipments and suitable maintenance.

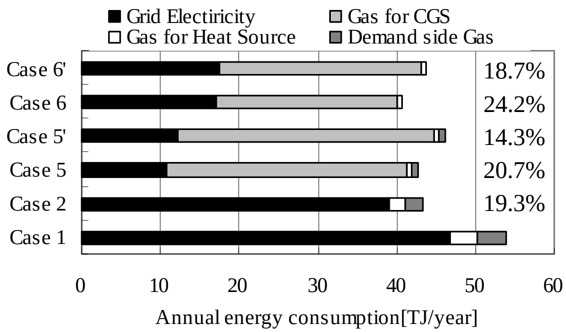



*Figure 19 Annual energy consumption and energy saving ratio [%]*

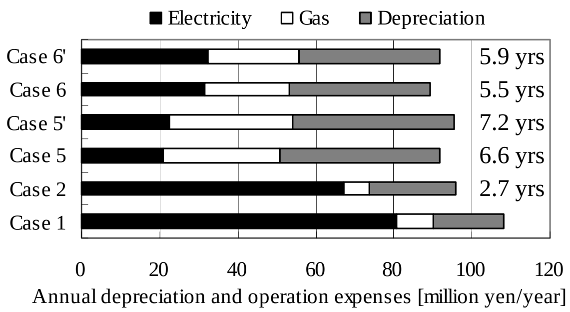



*Figure 20 Annual depreciation and operation expenses and simple pay back period [yrs]*

## CONCLUSION

This paper described a district energy system simulation model that adopted a bottom up approach. In this model, the energy flow of a district is modeled as the sum of total energy input and output of each building. By using this model, six alternatives comprising various energy saving measures and utilization of CGS were examined in the case study. The combination of energy saving options and WHN achieved the highest energy saving ratio and the lowest annual depreciation and operation expenses for the examined two combinations of office buildings. Particularly important was the finding that WHN was more effective than CHP for a single building in energy conservation, cost, and waste heat produced. This result implies that utilizing CGS in a combination of buildings is more appropriate to achieve energy saving potential than installing CGS for every building respectively. Additionally, for medium size buildings where it is usually not economical to install a CGS, the WHN proves to be a solution with lesser cost. Thus, WHN is an effective energy supply system to reduce energy consumption of a district. On top of that, as the efficiency of CGS critically influences the effectiveness of energy supply systems, adoption of high efficiency equipment and suitable maintenance are essential.

In our future work, combination of various case studies in actual districts with higher variability of building combinations will be carried out, taking into account the uncertainties in technology development of distributed generation systems. Other improvements of the model will include shorter time-step, consideration of facilities maintenance cost and etc.

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