SIMULATION MODEL FOR MULTI-PURPOSE EVALUATION OF URBAN ENERGY SYSTEM

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ABSTRACT

Urban issues to be resolved concerning building energy systems involve not only global warming but also the heat island phenomenon, the planning of urban infrastructures for electricity generation and distribution, and water purification. It is important to find a solution by balancing the impacts of these issues domains with trade-offs in designing building energy systems.

In this paper, we propose a simulation model in which not only energy use and CO_2 emissions, but also anthropogenic heat release, peak power demand and water consumption are calculated in an integrated, bottom-up manner at the district level. We carried out case studies in order to evaluate measures, such as the large-scale introduction of distributed generators that could change the flow of energy and/or water in the district drastically on the abovementioned simulation outputs. The results of the case studies show that this simulation model can support the design of a suitable solution that balances the issue domains.

KEYWORDS

Urban energy system, global warming, heat island, commercial sector

INTRODUCTION

Buildings and building energy systems determine the characteristics of energy use and resultant emissions into the environment. The building sector currently contributes to global warming due to CO_2 emission. In the context of the mitigation of global warming, there has been growing interest in making drastic changes in the components of urban energy systems by, for example, technological advancement, dissemination of energy-saving technologies and local energy generation and distribution planning (Yamaguchi et al. 2007). The urban heat island phenomenon due to anthropogenic heat release from buildings in a densely constructed urban area has also been extensively studied in recent years (Chun-Ming Hsieh et al. 2007, Shobhakar Dhakal et al. 2002). In the mitigation of the urban heat island phenomenon, the reduction of energy used in buildings and the heat state, or sensible or latent heat, are the key domains. Thus, the mitigation of both global warming and the urban heat island phenomenon might result in undesirable effects on the urban infrastructures of electricity generation and the distribution and water purification if the actions are not properly considered. This is because the planning of electricity and water infrastructures heavily depends on the demand for electricity and water, respectively(Oda et al. 2005).

However, few models are capable of providing a function to analyze the interrelationship between these issue domains and the planning of a building’s energy system. Such a model would play an important role in the future, when a drastic change in the components of urban energy systems is demanded, by providing a comprehensive solution that multilaterally optimizes the abovementioned impact indexes and the cost for mitigation.

For example, the advancement of distributed generation technologies has generated widespread interest as a possible solution for mitigating global warming. Co-generation systems (CGSs) utilizing not only the generated electricity but also the exhaust heat from distributed generators has been gaining attention as a system configuration that would conserve energy(V.Dorer 2005) and reduce CO_2 emission. Dissemination of this technology would also reduce the peak demand of electricity during summer seasons(K.H.Khan et al. 2004). On the other hand, a large-scale introduction of distributed generators in an urban area might increase anthropogenic heat release to such a large extent that it would seriously contribute to the heat island phenomenon (Genchi et al. 2002). As another example, for mitigation of the urban heat island phenomenon, the substitution of air cooling for water cooling of heat-source systems is effective because it would decrease sensible anthropogenic heat release while increasing latent anthropogenic heat release(Kikegawa et al. 2003). However, this method increases water consumption and would have an impact on water infrastructure.

Table 1 Evaluation index

Influence	Index	Definition	Time scale
Resource depletion	annual primary energy consumption	This is a converted value of electricity and gas consumption. The primary energy consumption conversion factors are 9.83 MJ/kWh in electricity and 46.0 MJ/Nm^3 in gas. It is covered not only energy consumption of heat-source system but total energy consumption in buildings.	annual
Global warming	CO_2 emission reduction	CO_2 emission is calculated from electricity and gas consumption. The CO_2 emission conversion factors are 0.2384 kg- CO_2/kWh (average CO_2 emission rate) and 0.6839 kg- CO_2/kWh (marginal CO_2 emission rate) in electricity and 0.0724 kg- CO_2/MJ in gas (Simoda et al. 2002). It is calculated by comparison with base case.	annual
Heat island	anthropogenic heat release	The amount of anthropogenic heat release in the district when heat-source system supplies heat demand. It shows sensible waste heat.	in August
Urban utility	peak power demand	The peak value of electricity load for power plants.	—
	water consumption	The amount of tapped water for cooling towers. Tapped water means total water consumption for cooing towers including evaporative water, splash water and blow water.	annual

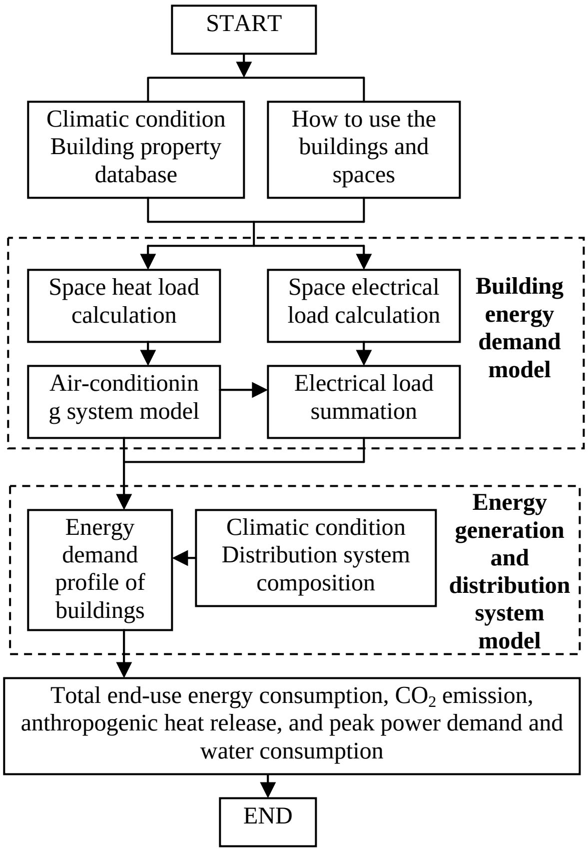

Figure 1 Simulation model

In this study, we developed a simulation model that is capable of quantifying energy use, that is, electricity and city gas, as well as CO_2 emission, and sensible and latent anthropogenic heat release in a particular area. This simulation model would serve as a tool to support decision-makers in the trans-boundary field, which includes the planning of buildings and building energy systems, mitigation of global warming and the urban heat island phenomenon, and the planning of electricity and water infrastructures.

In this paper, after a brief introduction of the model, we will describe simulations conducted through a case study on two commercial districts in Japan.

SIMULATION MODEL

Simulation model

Figure 1 illustrates the simulation model. This model is applied to a district consisting of a certain number of buildings in order to quantify the five indexes shown in Table 1. A detailed explanation of this model (about energy comsumption and CO_2 emission) is given elsewhere (Yamaguchi et al. 2003). This model can be divided into two sub-models, the building energy demand model, and the energy generation and distribution system model. In the building energy demand model, the heat and electricity demand profile for each building is simulated on an hourly basis. The total energy use in the district is then quantified by summing up the energy use of all the buildings and considering the configuration of the heat-source system of the buildings. In this process, electricity and city gas demands, sensible heat and latent anthropogenic heat release are quantified. In this paper, water consumption is calculated as the amount of tapped water for cooling towers, which is the total value of the evaporative water, splash water and blow water. The evaporative water is quantified based on the latent heat release.

In order to validate this simulation model, we carried out the following two validation studies on the consumption of energy and water.

Validation 1: Energy consumption

For the validation of the simulation model for energy consumption, we compared the predicted electricity and city gas consumption for 19 commercial sector

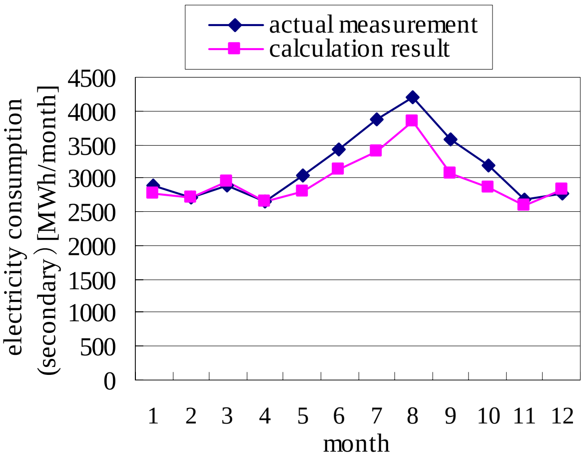

Figure 2 Comparison of calculation result with actual measurement of electricity

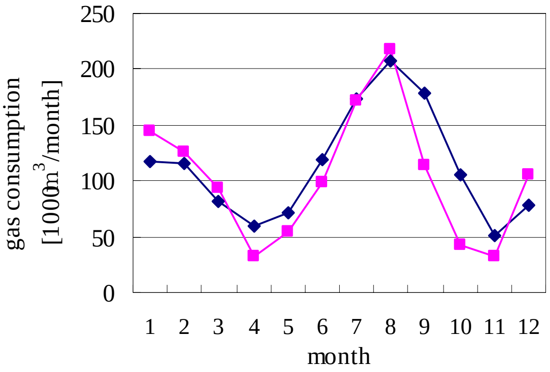

Figure 3 Comparison of calculation result with actual measurement of city gas

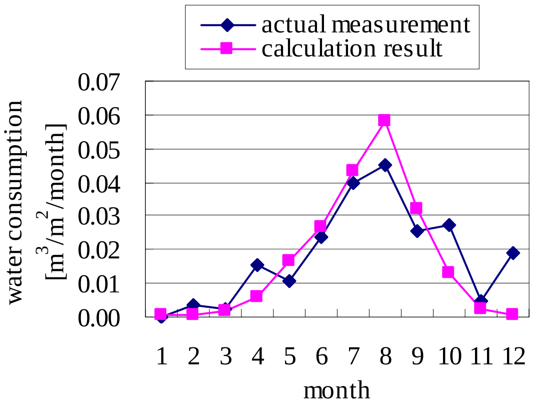

Figure 4 Comparison of calculation result with actual measurement of water consumption

Table 2 Compendium of targeted districts

Name of district	Total floor area and scale of the buildings	Ratio of the building use
Yodoyabashi	The gross floor-space ratio is from about 150% to about 350%. Different scale office buildings, from large-scale buildings of more than 30000 m^2 to small-scale buildings are here.	90% of the total floor area is used for offices.
Shinsaibashi	The gross floor-space ratio is from about 300% to about 600%. Middle and small-scale buildings for commercial are in high density.	Each of the total floor areas for office and commercial accounts for about 45%.

buildings in order to compare the predicted result and measured data. All 19 buildings are office buildings and the total floor area is 222000 m^2. We examined the main heat-source systems for each building and used the simulation result of the main heat-source system. CGS is not implemented in the 19 buildings. Figures 2 and 3 show the predicted and measured total electricity and city gas consumption for the 19 buildings, respectively. The estimated and measured values show good agreement for both electricity and city gas. Comparing annual values, the difference is -0.6% in electricity consumption and -0.9% in city gas. However, the simulation result of electricity consumption is smaller than the measured data during the summer season from May to September. For the gas consumption, the simulation result is smaller in both the spring and fall. These discrepancies in both electricity and city gas can mainly be attributed to variation in the input parameters of the model with those of actual buildings: for example, the room preset temperature and operating hours of air-conditioning systems, and limitations in accounting for physical and operational conditions of, for example, uncontrolled heat losses or gains from heating and cooling distribution systems (duct and pipes), and energy increases due to inappropriate design and operation of HVAC systems.

Validation 2: Water consumption

In order to validate the simulation model for water consumption, we applied the simulation model to 114 office buildings in the district of Yodoyabashi in Osaka, Japan. We compared the simulation results with measured water comsumption in 2001 provided by the Osaka City purification plant.

In the simulation model, we estimated the water consumption used through operation of the cooling towers. As the water consumption for cooling towers cannot be determined from the measured data, we assumed a fluctuation in water demand in January, when the water consumption is the lowest monthly quantity of the year.

Figure 4 shows the values predicted from the simulation and the actual values from the measured data. The simulation results are almost the same as the actual measurements, though the calculated simulation results are slightly larger than the actual measurement results for the summer. The total water consumption in the 114 buildings is estimated based

Table 3 Definition of heat-source systems

SYSTEM ALTERNATIVE	HEAT SOURCE			
	Cooling	Cooling COP	Heating	Heating COP
Absorption	Direct gas-fired absorption chiller	1.00	-	0.83
Turbo/boiler	Water-source turbo refrigerator	4.50	Boiler	0.83
AHP	Air-source heat pump driven by electricity	2.89	-	3.12
Individual	Individual air-conditioning system	2.60	-	3.20

Table 4 Building classification by total floor area

	Range of total floor area [m^2]		
CLUS-1	1000 m^2	-	3051 m^2
CLUS-2	3051 m^2	-	8188 m^2
CLUS-3	8188 m^2	-	19651 m^2
CLUS-4	19651 m^2	-	65536 m^2
CLUS-5	65536 m^2	-	

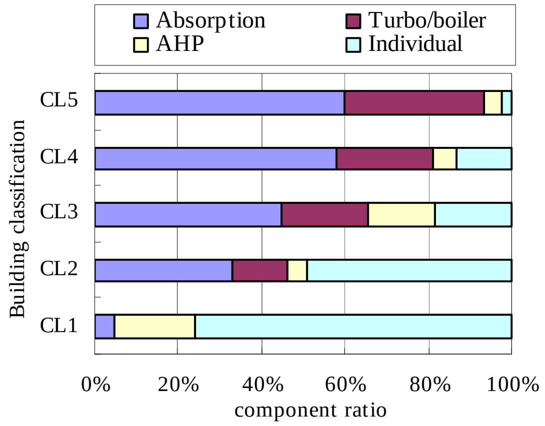

Figure 5 Share of heat-source systems

on the calculation results by assigning the rate of 10% (SHASE of Japan 1997) of the total water usage as the tapped water usage for the cooling towers. Comparing the estimated figure to the actual measurement, the difference is 21%; that is, the estimated figure is 1.62 [m^3/m^2/year] and the actual measurement is 2.02 [m^3/m^2/year]. Therefore, the calculation results are larger than the actual results in the summer.

CASE STUDY

Case study district

We carried out a case study in which the simulation model is applied to two districts in order to quantify the five indexes to demonstrate the capability of the simulation model.

The case study districts are "Yodoyabashi" and "Shinsaibashi" in Osaka, Japan. Yodoyabashi district is one of the central business districts in Osaka, and it is comprised of a number of large-scale office buildings. Shinsaibashi district is a commercial complex that has a high density of small-scale commercial buildings. Table 2 shows the characteristics of the two districts.

Table 5 The performance of targeted CGS

dispersed power system	gas engine cogeneration system
power generation efficiency	shown in Figure 6
generation capacity	50% of peak power demand
operating process	optimization of running cost

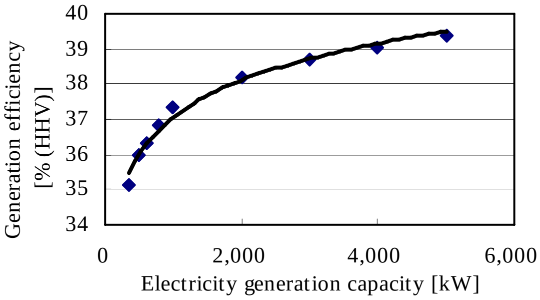

Figure 6 Generation efficiency of targeted CGS

Application of the model to the case study district

In order to apply the simulation model, we first distributed surveys to obtain information for the commercial buildings in both districts. We then developed a database of the configuration of all buildings with a total floor area of more than 1000 m^2. This database is used for modeling the demand profile of the heating, cooling, and electricity for each building in the two districts.

In the model, four types of heat-source systems are used in the buildings. Table 3 shows the configuration of heating and cooling and the efficiency of the heating and cooling system. An adoption ratio of the heat-source systems according to building scales and uses (JABMEE 2005) is used as the weighted average value of the simulation output to quantify the end-use energy consumption. As an example, Figure 5 shows the adoption ratios of the heat-source systems for office buildings. As shown in the figure, the scale of buildings is the principal element that determines the heat-source system utilized in buildings in the commercial sector in Japan.

In this study, buildings are classified into five categories according to the range of the total floor area based on statistical clustering of the existing building stock. The objective of clustering is to indicate connections between the scale of a building and configuration of its heat-source system, adopted energy-saving measures, and a strategy to manage

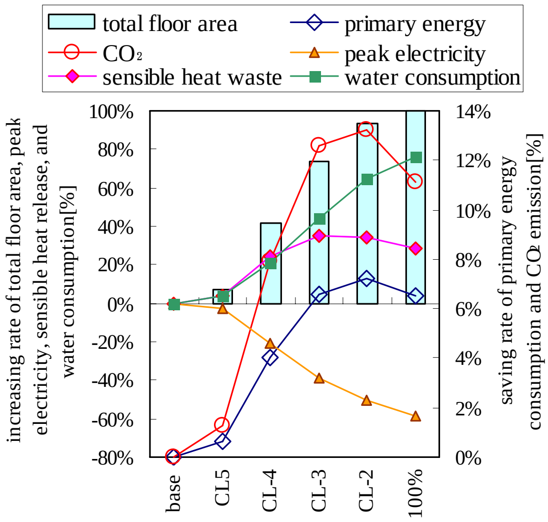

Figure 7 The increasing rates of five indexes by adopting CGS

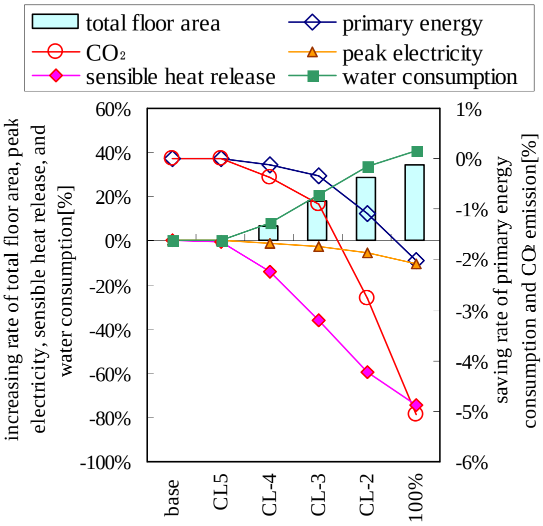

Figure 8 The increasing rates of five indexes by replacement water-cooling heat-source system

energy use. For an example, the office buildings are classified into five clusters depending on the set of scales shown in Table 4.

Simulation case

Using this model, we quantified the five indexes for the three cases of transition in the configuration of the heat-source systems. Case 1 assumes dissemination of CGS, as explained in the INTRODUCTION. Table 5 and Figure 6 show the gas engine system considered as the distributed generator of CGS in this study. We assumed that the exhaust heat recovered from the distributed generators is utilized so that it substitutes as energy input for heating and cooling energy generation. We also assumed that absorption chillers/heaters generate heating and cooling energy when the exhaust heat is not enough. There are currently no buildings that have adopted CGS in the district of Yodoyabashi.

Case 2 assumes substitution of the air-cooling heat-source system with the water-cooling heat-source system. In other words, we assumed that AHP (Air-source heat pump) and Individual are substituted with Turbo/boiler. When the heat-source system for cooling is changed to chillers, the heat-source system for heating is changed to boilers.

Case 3 assumes the spread of individual air-conditioning systems substituting for the central heat-source systems. Individual air-conditioning system consists of distributed heat-source systems with a small heat distribution system. This unit supplies heating and cooling energy for a small number of rooms and each unit is operable individually. While this system was recently widely adopted in small-scale buildings, as shown in Figure 5, it has become popular even in large-scale buildings, though the adoption ratio is still low. This trend can probably be accounted for by the flexibility provided for users in the operation of air-conditioning and for architects and building engineers in design and construction. Though this system is competitive in efficiency with the AHP system, the sensible heat release is larger than that for water-cooling systems. In this case, only the electric-driven systems (Turbo/boiler and AHP) are replaced with the individual air-conditioning systems.

According to the results of the five indexes, we compare the impact of measures in the district of Yodoyabashi. In a similar way we simulated the impact in the district of Shinsaibashi to examine the difference of the results due to the characteristics of the district.

Results

(Case 1) CGS

Figure 7 shows the increasing rates of three indexes (peak electricity, sensible heat waste and water consumption) in relation to the total floor area, and the saving rates of two indexes (primary energy consumption and CO_2 emission). It is assumed that CGS is adopted in all buildings in the order of the building-scale range, beginning with the base case (0%) and ending with 100% CGS. When the share of CGS reaches 100%, the anthropogenic sensible heat release increases by 29% in August, the primary energy consumption decreases by 6% and CO_2 emission decreases by 11%[1].

The largest change for primary energy consumption and CO_2 emission results from adopting CGS to buildings that are larger than CLUS-3 or CLUS-4. The increase in the saving rates of primary energy consumption and CO_2 emission becomes smaller

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[1] In Case 1, the change in primary energy consumption and CO_2 emission is less significant, even though we assumed that all the floor area was replaced by CGS. However, demand of electricity of a building would decrease while city gas would considerably increase. Thus, dissemination of CGS could have a significant impact on energy use.

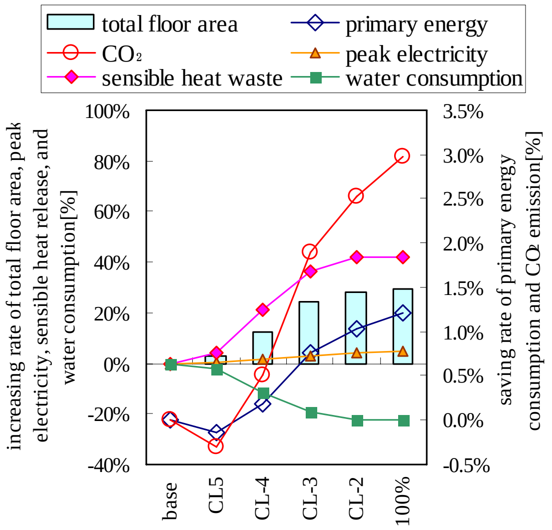

Figure 9 The increasing rates of five indexes by spreading individual air-conditioning systems

with saturation of the adoption rate of CGS. The saving rates even drop when CGS is adopted in buildings categorized into CLUS-1. This is due to the following two reasons. First, the generating efficiency of CGS is several percent higher in large-scale buildings than that in the small-scale buildings because of the advantage of scale in engine shown in Figure 6. Second, the energy saving gained by utilization of exhaust heat does not exceed the energy increase caused by substitution of heat-source systems. We assumed that Absorption is utilized in CGS instead of Individual that originally has a dominant share in small buildings as shown Figure 5. Because Individual has a higher energy efficiency for heating and cooling than Absorption, energy consumption of small buildings would increased if CGS is adoption.

Though it is not shown in Figure 7, the latent heat release keeps increasing when the buildings smaller than those in CLUS-3 adopt CGS. CGS leads to the replacement of the air-cooling heat-source system with the water-cooling heat-source system (Absorption). A depressed sensible heat release follows. Consequently, water consumption for cooling experiences a 76% increase in the case of 100% adoption of CGS.

(Case 2) Replacement of air-cooling heat-source system by water-cooling heat-source system

The percent changes of each influence in relation to the total floor areas are shown in Figure 8.

The adopted rate of the water-cooling heat-source system is about 65% for the base case in the district of Yodoyabashi. So, the increasing rate for the total floor area is 35% when water-cooling heat-source systems are adopted in all the buildings in the district. In this case, changing systems can reduce the sensible heat release by 74%, while the primary energy consumption increase by 2% and the CO_2 emission increases by 5%. Comparing the Individual system and the AHP system with the Turbo/boiler system in the rated cooling COP, the Turbo/boiler system is more efficient. However, the rated heating COP in the Turbo/boiler system is lower. If the Turbo/boiler system is adopted in the small-scale buildings, it is assumed the low-COP operating time increases in order that the heat demand per unit floor area is as much in the small-scale buildings as that in the large-scale buildings. Thus, primary energy consumption and CO_2 emission increase in the case of adopting the water-cooling heat-source system in the all buildings.

Table 6 Comparison of buildings with more floor area than CLUS-2 in the 2 districts

	Yodoyabashi	**Shinsaibashi**
The number of buildings (more than 1000 m^2)	113	185
The number of buildings (more than CLUS-2)	39 (35%)	19 (10%)
The total floor area (more than 1000 m^2)	988767	755742
The total floor area (more than CLUS-2)	728981 (74%)	421469 (56%)

* The building use expect offices are commercial and hotels. The “larger than CLUS-3” for the buildings using offices is equivalent of more than 8615 m^2 buildings for commercial and more than 13223 m^2 buildings for hotels.

(Case 3) Spreading individual air-conditioning systems

We simulated the case in which only the electric-driven systems (Turbo/boiler and AHP) are replaced with individual air-conditioning systems. In the district of Yodoyabashi, for the base case, the adopted rate of the individual air-conditioning systems is 25%; on the other hand, the rate of the direct gas-fired absorption chiller/heater systems is comparatively higher. Therefore, the increasing rate of the total floor area is 29% and the adopted rate is only 54%, even if all the electric systems are replaced with individual air-conditioning systems. The results of this case study are shown in Figure 9. The increasing rate according to the total floor area is comparatively smaller than the increasing rate in the previous two cases. But, in this case, the increasing amount of the sensible heat release for the increasing rate of the total floor area is larger than that in Case 1 (Figure 7). When the introduction rate achieves 100%, the sensible heat release increases 42%, however, the primary energy consumption is reduced by 1.2% and the CO_2 emission is reduced by 3%. Spreading individual air-conditioning systems contributes to saving energy, but we need to pay attention to the increase of the sensible heat release.

Table 7 The value per unit floor area and increasing amount

	Yodoyabashi	**Shinsaibashi**	**Yodoyabashi**	**Shinsaibashi**
	per unit floor area		**increasing amount**	
total floor area adopted measure ［m^2］	-	-	728981	421469
primary energy consumption [MJ/ m^2/year]	1773	2493	-125	-156
CO_2 emission reduction [kg-CO_2/m^2/year]	10	17	-7	-9
peak power demand [kW/m^2]	0	0	-31	-21
anthropogenic heat release [kJ/m^2/month]	73	92	19	19
water consumption [m^3/ m^2/year]	0.32	0.42	0.10	0.08

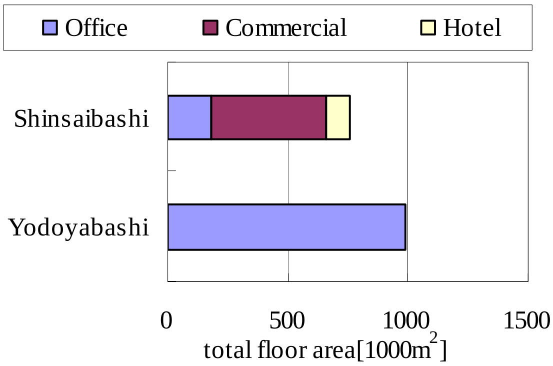

Figure 10 The total floor area by use in the two districts

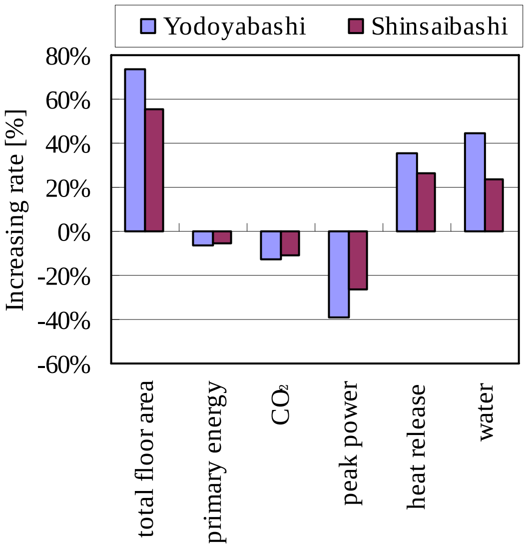

Figure 11 The increasing rate of each index

District comparison of impacts of the measures

We examined the impacts of the same measures in the districts of Yodoyabashi and Shinsaibashi, and quantitatively evaluated the differences of the impacts depending on the differences of each district. The adoption of CGSs was examined as the measures. Generally, CGSs are adopted in the large-scale buildings. Thus, it is unlikely that these systems are widely adopted in the small-scale buildings. In this section, we assume that the CGSs are adopted in buildings larger than CLUS-2 buildings. In this case, we compared the impacts of the introduction in the two districts. The differences for buildings larger than CLUS-2 buildings are shown in Figure 10 and Table 6. In Table 6, the ratio shown in parentheses is the share of the buildings larger than the CLUS-2 buildings compared to the total number of buildings in the district.

In comparing Shinsaibashi with Yodoyabashi, though the number of the buildings is large, the total floor area is small and the number of small-scale buildings is larger (shown in Table 6). All the target buildings in Yodoyabashi are used as offices, while 63% of all target buildings in Shinsaibashi are used as commercial buildings (shown in Figure 10). The number of commercial buildings in Shinsaibashi is 115. Of those, the number of buildings smaller than CLUS-3 buildings is 103. The percentages of total area of buildings larger than CLUS-2 buildings, in which the CGSs are adopted, in this case study are 74% in Yodoyabashi and 56% in Shinsaibashi. The value per unit floor area and increasing rate in each index are shown in Table 7 and Figure 11. In addition, the CO_2 emission in the baseline is calculated using the average emission rate (0.24t- CO_2/MWh), and the reduction of CO_2 emission is quantified using the marginal emission rate (0.68t- CO_2/MWh). The increasing rates show the percentage in relation to the values in the base case.

When we assume the same measures are introduced under same conditions, there are differences between the two districts (shown in Table 7). The percentage change of all five indexes in Yodoyabashi is larger than that in Shinsaibashi, and the impacts are large, considering that the total floor area in buildings larger than CLUS-2 buildings in Yodoyabashi is about 1.7 times greater than those in Shinsaibashi, as shown in Table 7. However, the reduction amounts of the primary energy and the reduction of CO_2 emission are larger in Shinsaibashi. The differences of the increasing rates of the two indexes are small between the two districts. On the other hand, the increasing amounts of the sensible heat release are almost same, though the increasing rate is larger in Yodoyabashi than in Shinsaibashi. The results show that the impacts of adopting CGSs to large-scale buildings based on the five indexes depend on the district characteristics, and the intensity of the impact on each index is different.

When we consider changes in energy systems as environmental measures, we should understand that the effects are different according to the district characteristics and that the intensity of impacts is different for each index. In other words, for the effects of each measure we evaluate, we should give much consideration to the impacts of district characteristics and the intensity differences between them.

CONCLUSION

In this study, we developed a simulation model that can quantitatively evaluate the impacts on energy consumption, CO_2 emission, heat island phenomenon, and urban infrastructure by changing the energy systems of buildings. We applied certain scenarios in two existing districts as the case studies. This study shows that changing the energy systems of buildings has influences on not only the energy consumption but also the urban environment and infrastructures. Also, it is shown that the influences are different according to the district characteristics and that the influences of the district characteristics are different for the evaluated indexes.

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