Urban Scale Energy Demand Estimation in the Kinki region, Japan considering the Diversity of HVAC systems

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ABSTRACT

This paper reports a development of an urban scale energy demand model for the office building stock located in Keihanshin metropolitan area, Japan. In the model, we consider 15 kinds of HVAC system configurations. Detailed modelling was done for these HVAC systems in the design of archetype buildings. The share of the HVAC system configurations is also quantified. Based on the simulation result, we discuss how consideration of HVAC systems in urban scale modelling is important.

KEYWORDS

Archetype Engineering Model, Building Stock, Office Building, Urban-Scale Estimation, EnergyPlus

INTRODUCTION

Urban scale energy demand modelling can play an important role in policy design and technology development for energy conservation and energy management. One of the key issues in urban scale modelling is to address the diversity of buildings in models. This issue is especially important in the management of peak electricity demand of urban areas. While the electricity peak demand is observed at around 2 pm in the middle of summer in Japan, the electricity demand for cooling in the commercial building stock significantly contributes to the peak demand. In Japan, there are a wide variety of HVAC systems. The classification can be made mainly by the configuration of HVAC system (i.e. central system or distributed system), the energy source of heat source machines (e.g. electricity and city gas), and the adoption of advanced energy management system (e.g. thermal storage and combined heat and power). As each system has different energy consuming characteristics, the energy demand characteristics of the HVAC systems as well as their accumulation in the building stock must be comprehensively replicated in the model.

The archetype engineering modelling approach is a well-established methodology for urban scale modelling of energy demand of buildings (Swan and Ugursal 2009). In the approach, building stock is first classified into several stock categories according to the factors determining energy demand. Second, an archetype building is designed for each building category, which is used as a set of input data of building performance

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simulation. Third, building energy performance is simulated with the archetype buildings as input to estimate energy use intensity (EUI) of corresponding stock categories. Finally, total energy consumption of the entire building stock is quantified by adding up the energy consumption of each stock category by multiplying the EUI by total floor area. The diversity in the building physical characteristics such as building size and insulation performance has been well considered in the models that have been developed based on the approach. However, models considering the variety in the configuration of HVAC systems have not been well established.

Based on this background, the authors developed a database of the diffusion of HVAC systems utilized in office buildings and developed an archetype engineering model of the office building stock of Japanese urban area. In the remaining part of the paper, we first report the database development, and then the model development. As a case study using the developed model, estimated peak electricity demand in August is shown.

Table 1. *Sub-category classification of HVAC systems*

Type	*Case Name*	*Air Conditioning Unit*	*Heat Source Equipment*	
			Cooling	*Heating*
Distributed System	MUL	Multiple Indoor Unit	Variable Refrigerant Flow	
	PAC	Single Indoor Unit		
	GHP	Multiple Indoor Unit	Gas Engine driven Heat Pump	
Central System	FCU+TR	FCU	Turbo chiller	Gas Boiler
	FCU+AB		Absorption Chiller	Gas Boiler
	FCU+ABCH		Absorption Chiller-Heater	
	FCU+AHP		Air Source Heat Pump	
	CAV+TR	CAV	Turbo chiller	Gas Boiler
	CAV+AB		Absorption Chiller	Gas Boiler
	CAV+ABCH		Absorption Chiller-Heater	
	CAV+AHP		Air Source Heat Pump	
	VAV+TR	VAV	Turbo chiller	Gas Boiler
	VAV+AB		Absorption Chiller	Gas Boiler
	VAV+ABCH		Absorption Chiller-Heater	
	VAV+AHP		Air Source Heat Pump	

DEVELOPMENT OF HVAC SYSTEM DATABASE

SHASE (the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) published a database of the HVAC system adopted in newly constructed or renovated buildings in Japan since 1984. The data contains the usage, the physical property including total floor area, the number of floor of buildings, and the capacity and kind of heat source equipment of HVAC system stock. A database was developed based on this data. First, each sample was classified according to the configuration of HVAC system. Then the share of each configuration was counted in the data published from 1992 to 2012 in order to quantify the share of the HVAC system configurations.

SHASE data contains a list of heat source equipment adopted. Each of heat source equipment was labelled by purpose of operation: cooling, heating and dual operation heat source. Second, a kind of heat source equipment with the highest total capacity is selected for heating and cooling operation. Third, type of air conditioning unit is classified by Variable Refrigerant Flow (VRF), Constant Air Volume (CAV), Variable Air Volume (VAV) and Fan Coil Unit (FCU). Finally, by combining each heat source equipment and air conditioning unit, HVAC system is decided. Through this approach, sub-category of building stock by the configuration of HVAC system is developed. This paper reports the energy demand estimation result applying 15 types of HVAC system configuration shown in Table 1.

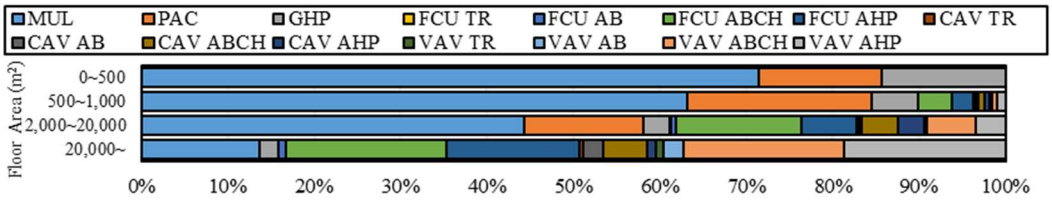

Figure 1. *Adoption ratio of HVAC systems to office buildings*

Adoption ratio of HVAC systems

By analysing database published by SHASE, the share of adopted HVAC systems can be estimated. This paper defines the share as 'adoption ratio' of HVAC system which shows different patterns depending on the building scale shown in Figure 1. According to Figure 1, it can be noticed that small building stock tends to have larger adoption ratio of distributed system. On the other hand, large scale of building stock tends to have greater adoption ratio of central systems. This adoption ratio will be applied to estimate EUI of each building category as explained later.

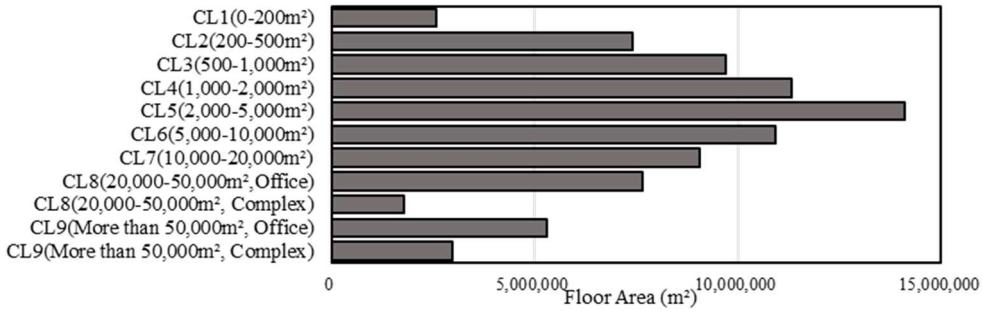

Figure 2. *Estimated total floor area of office buildings*

Table 2. *Architecture specification of representative archetypes of office buildings*

Category Name	*Usage*	*Range of Total Floor Area (m^2)*	*The Number of Floor*	*Total Floor Area (m^2)*	*Standard Floor Area (m^2)*	*Air Conditioning Area Ratio (%)*
CL1	Office	Smaller than 200	2	132	66	76
CL2	Office	200~500	3	349	116	75
CL3	Office	500~1,000	4	726	182	73
CL4	Office	1,000~2,000	5	1,447	289	72
CL5	Office	2,000~5,000	6	3,258	543	69
CL6	Office	5,000~10,000	7	7,089	1,013	66
CL7	Office	10,000~20,000	8	13,873	1,734	64
CL8	Office	20,000~50,000	11	31,238	2,840	63
CL8c	Complex	20,000~50,000	11	31,238	2,840	63
CL9	Office	50,000 or larger	29	190,202	6,559	63
CL9c	Complex	50,000 or larger	29	190,202	6,559	63

ARCHETYPE ENGINEERING MODELLING

Office building stock

Yamaguchi et al. (2014) classified office building stock into 11 categories by analysing the relation between building scale and energy use. Figure 2 shows the estimated total floor area of each stock category in the Keihanshin Metropolitan Area. On the basis of this classification, Matsuoka et al. (2014) proposed typological building specifications for each category by analysing survey data so as to model archetype engineering models. Table 2 shows the building specifications of the archetype engineering models for office building stock. Each category is classified depending on total floor area which is segmented into 9 ranges. Among the categories, it is supposed that both categories CL8 and CL9 (see Table 2) have complex facilities composed of

not only office but other usage such as retail, restaurants, defining them as CL8c for 20,000m^2~50,000m^2 and CL9c for 50,000m^2 or larger than 50,000m^2 respectively. Further, it is set that archetype models of CL8 and CL9 have a floor as OA centre which consumes 500W/m^2 of electric power for 24 hours every day. Common conditions of building specifications and internal activities for Archetype Engineering Model are shown in Table 3. The energy demand estimation model described in this paper is developed based on these building conditions as an input parameters of energy performance simulation.

Table 3. *Common conditions for archetype engineering model*

Categories	*Floor Height (m)*	*Ceiling Height (m)*	*Ventilation (m^3/m^2h)*	*Electric Equipment (W/m^2)*	*Occupants (person/m^2)*	*Lighting (W/m^2)*	*Window Area Ratio (%)*
CL1~CL7	3.8	2.6	5	OA:5.4, Base:3	0.1	15	25
CL8~CL9c							50

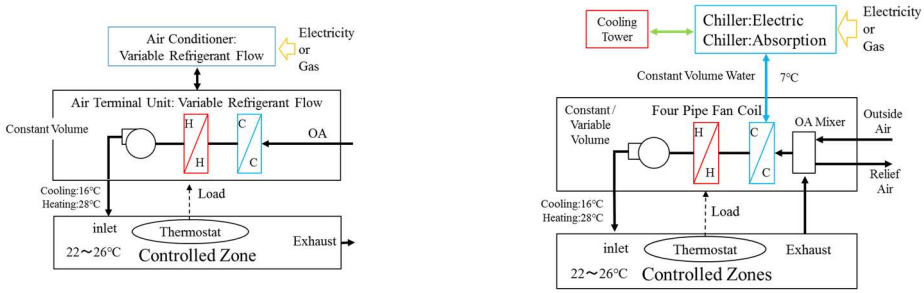

Figure 3. *Schematic system of HVAC systems(Left : Distributed system, Right : Central system)*

Table 4. *Adopted heat source equipment*

Heat Source Equipment	*COP (W/W)*		*Energy Source*	*Condenser Loop*
	Cooling	*Heating*		
VRF	2.77	3.41	Electricity	N
Gas Engine Driven Heat Pumps	0.95	1.19	Natural Gas	N
Turbo Chiller	5.50	-	Electricity	Y
Gas Boiler	-	0.83	Natural Gas	N
Absorption Chiller	1.06	-	Natural Gas	Y
Absorption Chiller-Heater	1.06	0.83	Natural Gas	Y
Air Source Heat Pump	3.05	3.21	Electricity	N

Building archetypes

On each category classified in the earlier step, archetype engineering models were designed by inputting building specifications into EnergyPlus. Total 137 archetype engineering models are designed by modelling 15 HVAC systems listed on Table 1 on each building size listed on Table 2. In this archetype modelling, central systems for small scale buildings from 0m^2 to 500m^2 (24 systems) and PAC of distributed systems for large scale buildings over 20,000m^2 (4 systems) are excluded because they have no adopted case as shown in Figure 1 earlier. In the following, archetype engineering modelling is described depending on the type of HVAC system. Figure 3 shows how each system is modelled in EnergyPlus schematically.

As mentioned earlier, 7 kinds of heat source equipment are considered in this model. Table 4 shows the type of heat source equipment adopted in this model and coefficient of performance (COP) of each heat source equipment. In system loop, heat source is installed in supply side producing heat. The heat is pumped to cooling/heating coils of

air conditioning unit in demand side of the loop. Figure 3 schematically shows how each type of air conditioning unit is input into EnergyPlus.

Okamoto et al. (2015) assumed the daily intensity of occupants for respective 11 building categories which are mentioned earlier in this paper. According to their results, larger scale buildings tend to be occupied for longer time than small scale buildings. Drawing from the daily intensity of occupants, simulation schedules for HVAC, lighting, electric equipment are set up.

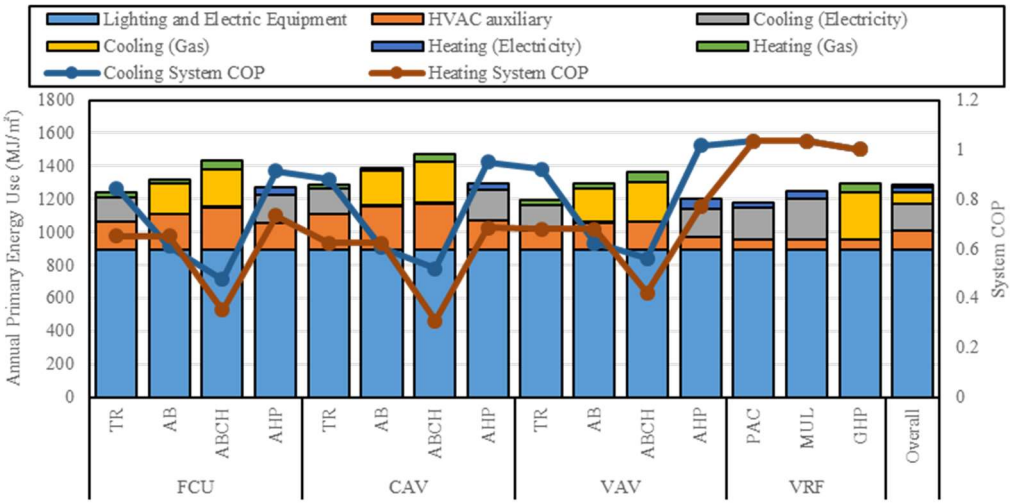

Figure 4. *The annual energy use intensity and system COP on each HVAC system (CL7)*

ESTIMATION RESULT

Simulation result of archetype engineering model

The overall energy use intensity of each category ($E_j, j = \mathrm{CL1}\sim\mathrm{9c}$) is calculated with applying adoption ratio figured in Figure 1, as in the equation below:

$$E_j = \sum_{i=1}^{n} (\lambda_i \times e_i) \tag{1}$$

where λ_i and e_i (i : HVAC system case listed in Table 1.) are the adoption ratio figured in Figure 1 and energy use of each archetype system model respectively. Figure 4 shows the annual primary energy use intensity on each HVAC system model and the overall energy use intensity of CL7. HVAC auxiliary in this Figure contains electricity consumption from fans, pumps and cooling tower. The systems with electricity driven heat source use less energy with higher efficiency, comparing to the systems with gas driven heat source. Central systems with VAV uses less energy from HVAC auxiliary equipment due to the less energy consumption from supply fan in Air Handling Unit. Distribution systems have high system efficiency in common because they do not require any equipment for plant side loop. From comparison the overall energy use intensity with the energy use intensity of each HVAC system, it can be noticed that the energy demand characteristics is strongly affected by the HVAC system and adoption ratio. The annual system COP from every HVAC system shows lower value than heat source equipment COP since systems are running under low part load conditions during spring and autumn period in spite of high part load conditions during summer and winter.

Every building category has this tendency on the estimation results in common, which effects on the electric demand on summer peak day (Figure 5). There is a tendency that systems equipped with electric driven heat source and central systems equipped with auxiliary equipment have greater electric consumption. Nevertheless, systems equipped with turbo chiller shows lower electric consumption. It is considered that it is due to the high COP of turbo chillers.

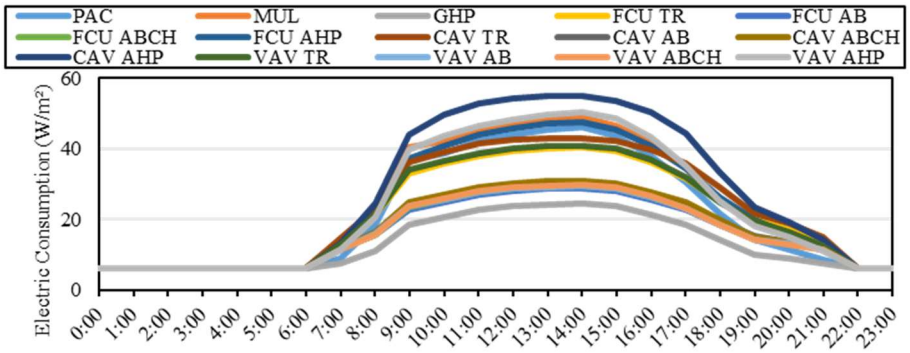

Figure 5. *Electric demand from diverse HVAC systems adopted to archetype engineering model (CL7) on summer peak day (2nd August)*

Figure 6 shows electric consumption by end use from archetype engineering model of CL7 with adoption ratio. The peak electricity is 63W/m^2 on 14:00. It is less than peak demand from HVAC systems which mainly consume electricity figured in Figure 4. This is because adoption ratio of HVAC systems equipped with gas driven heat source equipment shares approximately 29% of total. From this result, not only the diversity of HVAC system but also the adoption ratio of each system have a significant influence on urban energy demand.

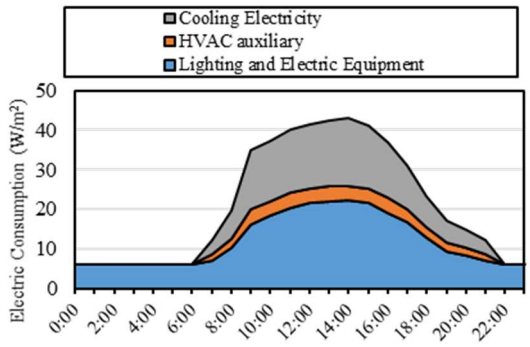

Figure 6. *Timely electric consumption from archetype engineering model of CL7 on summer peak day (2nd August)*

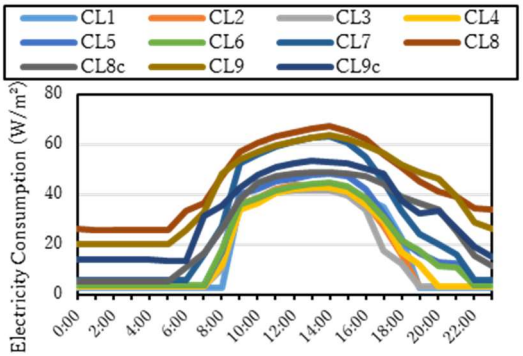

Figure 7. *Electric demand from building category on summer peak day*

Figure 7 shows the timely electric demand from archetype engineering model of specific building size (CL7) on summer peak day. The larger building categories have high electricity consumption because of electric power consumption from OA centre and their longer appliance operation schedule which are set as the simulation schedules, as mentioned earlier. There is a tendency that the larger scale of building has greater electric consumption.

Urban-scale estimation

By adding up simulation results (E_j) and total floor area of building stock (A_j), urban-scale energy demand from office buildings (E_o) is estimated, as in the equation below:

$$E_o = \sum_{j=1}^{n} (A_j \times E_j) \tag{2}$$

Figure 8 shows the urban energy demand from office buildings in Kinki region on every building category. Even if complex office facilities (CL8c and CL9c) have greater energy use, they consume less energy than middle-scale buildings, which means that total energy consumption is significantly affected by total floor area of building stock shown in Figure 2. In overall, it is estimated that approximately 120,000TJ of energy is consumed from total office buildings in Kinki region in a year.

Figure 9 shows urban scale timely electric demand of office buildings in Kinki region on summer peak day. It is estimated that the peak electric demand is 5900MW on 14:00. On the peak time, 52% of electric demand is from HVAC system related equipment, including cooling electricity and HVAC auxiliary equipment.

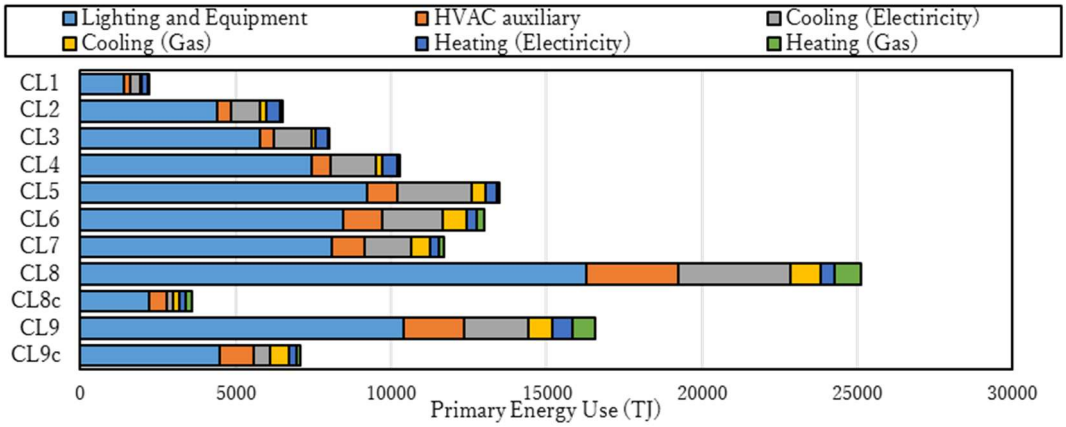

Figure 8. *The annual primary energy use from each category*

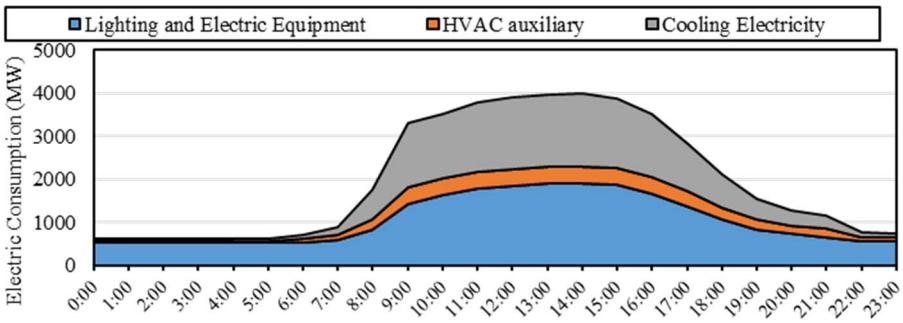

Figure 9*. Urban scale electricity demand from office buildings on summer peak day (2nd August)*

DISCUSSION

Even if there are several interests in studies on the urban scale energy modelling, this paper centres around two points of approach. The first focal point is the diversity of HVAC systems. As explained earlier in this paper, 15 kinds of HVAC system configurations are modelled and simulated so as to calculate EUI of office buildings.

From the simulation result, energy consumption pattern varies depending on the type of HVAC system. Second point is office building stock modelling such as scale category and adoption ratio. With stock modelling, urban scale energy estimation under building stock context is carried out. The estimation result applying adoption ratio and floor area shows that overall energy demand and energy demand composition are affected by office building stock. Consequently, in order to model the energy demand, this study tried to replicate the actual context of real building stock in simulation and bottom-up estimation.

CONCLUSION

This paper reports the development of urban-scale energy demand estimation model for the Kinki region, Japan. From this study, the authors found several conclusions as followings:

- The adoption ratio of HVAC system tends to have distributed systems for smaller buildings and central systems for larger buildings.
- Even though archetype buildings modelled in each category have common building specifications, the characteristics of energy consumption vary depending on the adopted HVAC systems.
- It is estimated that approximately 120,000TJ of energy is consumed from office buildings in Kinki region in a year from 94% and 6% of electricity and gas respectively.
- Applying building stock context both total floor area and system adoption ratio to energy estimation model influences on the result of urban scale energy demand estimation.

ACKNOWLEDGE

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