Urban Scale Energy Demand Modelling of Commercial Building Stock Considering the Variety of HVAC System Configuration

Shun Kimura, Yohei Yamaguchi, Bumjoon Kim, Yusuke Miyachi,
Yumei Kou and Yoshiyuki Shimoda

Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University, M3 Building, 2-1 Yamadaoka, Suita, Osaka, 565-0871, Japan,
yohei@see.eng.osaka-u.ac.jp

Abstract

This paper reports a development of an urban scale energy demand model of the commercial building stock in Japan using building archetypes. In this model, we consider 23 types of HVAC system configurations which consist of 7 kinds of air supply system and 6 kinds of heat source system. Detailed modelling is carried out for these HVAC system configurations in the design of archetype buildings and energy system simulation using EnergyPlus. The developed model is used to evaluate how the assumption in the share of HVAC system configurations affects simulation results of energy demand and peak electricity demand of the sector.

Introduction

The archetype engineering modelling approach is a well-established methodology for urban scale modelling of energy demand of buildings (Swan and Ugursal 2009).

This paper presents a preliminary study on an application of the archetype engineering modelling approach to the commercial building stock in Japan to estimate time-series electricity demand and its flexibility that can be used to improve the performance of the electric power system. In the archetype engineering modelling approach, building stock is first classified into several stock categories according to 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 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. Due to the bottom-up structure, developed models can reflect the structure in which energy demand is determined in a building and the composition of the building stock in the modelled area. This is a clear advantage in urban-scale modelling.

One of the key issues in urban scale modelling is to address the diversity of buildings. Although building physical characteristics and insulation performance have been well addressed in the previously developed models. For example, Korolija et al. (2013) have developed archetype simulation models for energy demand estimation of office buildings in UK. The authors parameterized general architectural characteristics such as floor plan, insulation and internal/external gains which substantially vary among office building stock and also affect the thermal loads with maintaining occupants thermal comfort. The parameters are modeled to represent the architectural complexity and diversity of office building stock and can be variably configured. However, these models incorporate only physical characteristics and insulation performance but lack in energy consumption characteristics performed by various HVAC system configurations. Shahrestani et al. (2013) quantified how the system configuration of centralized HVAC systems characterizes energy consumption of office building in UK. The authors classified HVAC systems according to 3 types of primary and 12 types of secondary system characterizing energy performance and energy consuming characteristics of buildings. The classification adopted in Shahrestani et al. cannot be simply applied to Japanese context. This is because the HVAC system configuration adopted in Japan is more diverse as cooling has been recognized as taken-for-granted while heating and cooling have been fields in which a variety of technical innovations have taken place. HVAC systems can be characterized 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, there is a need to consider the stock of HVAC systems and their energy consuming characteristics in the model. Its consideration is important to model time-series electricity demand and its flexibility that can be provided by the sector. For example, 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.

Based on this background, the authors developed a database of the diffusion of HVAC systems utilized in the commercial buildings and developed an archetype engineering model of the commercial building stock. The developed model is used to evaluate how the assumption in the share of HVAC system configurations affects simulation results of energy demand and time-series electricity demand of the sector to clarify the importance of the HVAC system database.

Development of Commercial Buildings Database

Yamaguchi et al. (2014) collected energy use intensity (EUI), which is defined as primary energy consumption per floor area, from approximately five thousands of retail facilities in Japan and found that each retail category such as general merchandise store and food supermarket, consumes energy in different way. This is because there is a certain tendency among buildings in each retail category in determinants of energy demand such as building size and geometry as well as the composition, specification and operation of equipment and appliances (Matsuoka et al. 2014).

In our study, we focused on the business category to develop the classification of building stock. The business category was described by the main building usage, i.e. office, hotel, hospital, school and restaurant in this paper, as well as building size as shown in Table 1. The building size was divided into nine classifications for office, hotel and hospital. The reason why we considered building size is not only that the geometry of buildings significantly alters thermal demand of buildings, but also that the operation hour of buildings, internal activities on floors, as listed in Table 2, and HVAC systems are characterized by the building size (discussed further below).

In the fourth step of the model development in the archetype engineering modelling, the total floor area of each building stock category is required. For office, hotel and small hospital, the data was developed based on the corporations survey on land and buildings of Japan conducted by the Ministry of Land, Infrastructure, Transport, and Tourism of Japan. For large hospitals and schools, GIS data which contains usage, building coverage and height of individual buildings is utilized. For restaurant, a database containing the business category and address was used to quantify the total floor of restaurant with distinction regarding building location between urban and the other area, since the business hour is different. The climate condition was also taken into account by using the prefectural boarder.

The estimated floor area shown in Appendix C. for each building stock category was further divided by the HVAC system according to the adoption ratio mentioned in the next chapter.

Development of HVAC System Configurations Classification

SHASE (the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) contains the kind of heat source equipment and specifications of HVAC systems adopted in newly constructed or renovated buildings. Each sample was divided into centralized and distributed

Table 1 Business categories used in the building stock category

Building usage	Business categories	Size and other attributes
Office	General office	< 20,000 m^2
	Compound office	≥ 20,000 m^2
Hotel	Commercial hotel	< 5,000 m^2
	Commercial hotel, multi-function hotel	≥ 5,000, < 20,000 m^2
	Multi-function hotel	≥ 20,000 m^2
Hospital	Small medical office	< 1,000 m^2
	Middle scale medical office	≥ 1,000 m^2, < 5,000 m^2
	General hospital	≥ 5,000, < 20,000 m^2
	Large hospital	≥ 20,000 m^2
School	Elementary school	
	Junior high school	
	High school	
Restaurant	Bar	Urban
		Suburban
	Café	Urban
		Suburban
	Restaurant	Urban
		Suburban

Table 2 Characteristics in building operation and internal activity on floors

Building usage	Characteristics
Office	Operating hours increases with an increase in total floor area including Saturday and Sunday
Hotel	There are two kinds of hotels, namely commercial hotel for accommodation only and multi-functional hotel. With an increase in total floor area, the proportion of multi-functional hotel increases.
Hospital	EUI increases with an increase in building floor area. Small health clinic has small energy demand during night, while it is large in large hospital as medical facilities are operated. In addition to this, large hospital has a more space for advanced medical equipment, such as major surgery room, intensive care unit (ICU) and emergency room, with a high EUI.
School	EUI is approximately 200 to 500 MJ/m^2.
Restaurant	Kitchen area ratio of restaurants is larger than pub and café. In addition to this, operation hour is different among the categories.

Table 3 Adopted HVAC system

Type	Case name	Air conditioning unit
Distributed System	MUL, GHP	Multiple Indoor Unit
	PAC	Single Indoor Unit
Central System	FCU	Fan Coil Unit
	CAV	Constant Air Volume
	VAV	Variable Air Volume
	CAV + FCU	CAV in interior zone, FCU in perimeter zone
	VAV + FCU	VAV in interior zone, FCU in perimeter zone

Table 4 Adopted heat source equipment

Case name	Heat source equipment	COP		Energy source	Condenser Loop
		Cooling	Heating		
MUL, PAC	Variable Refrigerant Flow	2.77	3.41	Electricity	N
GHP	Gas Engine Driven Heat Pumps	0.95	1.19	Natural Gas	N
TB	Turbo Chiller + Gas Boiler	5.50	0.83	Electricity, Natural Gas	Y
AB	Absorption Chiller + Gas Boiler	1.06	0.83	Natural Gas	Y
ABCH	Absorption Chiller-Heater	1.06	0.83	Natural Gas	Y
AHP	Air Source Heat Pump	3.05	3.21	Electricity	N

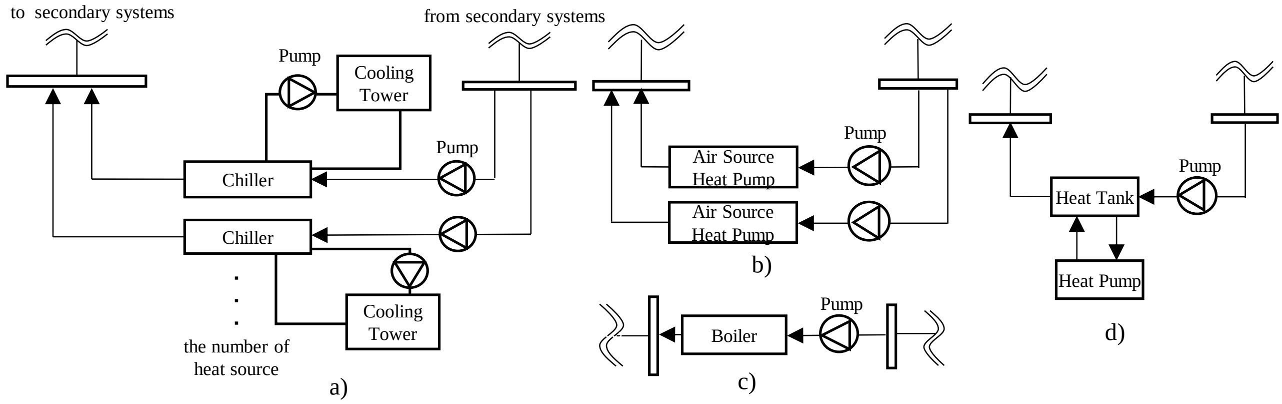

Figure 1 Primary systems (a) Chilled water loop and condenser loop (b)Chiller water loop with air cooled chiller (c) Hot water loop with gas boiler (d) Hot water loop with heat pump

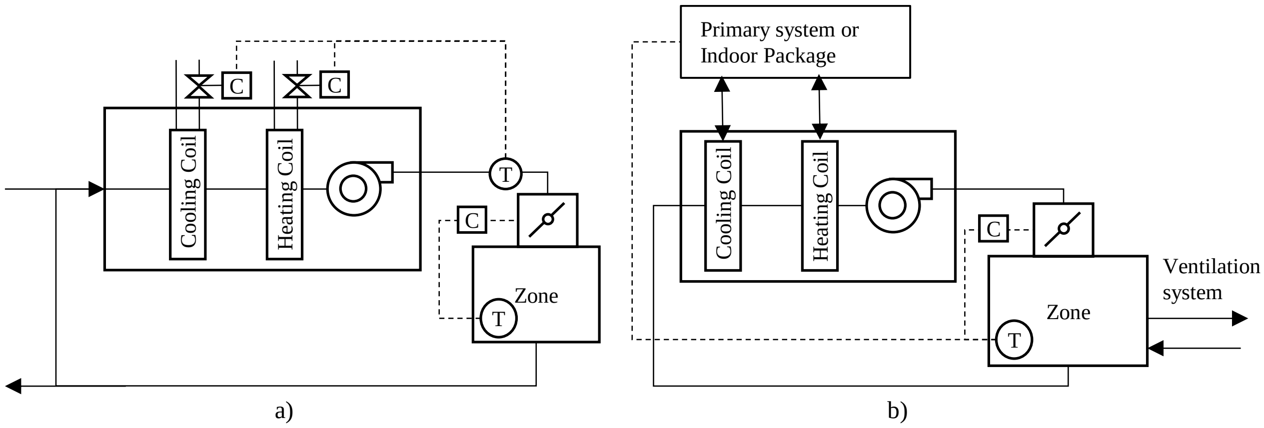

Figure 2 Secondary systems (a) CAV and VAV (b) FCU and Distributed system

systems and were further classified according to the composition of heat source machines for cooling and heating (Table 5 and Table 6). The adoption ratio of the developed HVAC system configurations was estimated for each region. Appendix B. shows the share of the heat source category in each area. The variable refrigerant flow (MUL or PAC) accounted for the most part in the small-scale buildings. In the middle-scale building, the variable refrigerant flow or absorption chiller-heater (ABCH) accounted for the largest proportion. In the large-scale building, ABCH accounted for the largest proportion, followed by large the compression chiller and boiler (TB). According to regional results, Hokkaido and Tohoku region had more gas driven systems such as gas engine driven heat pump (GHP) and absorption chiller and gas boiler (AB) than in any other regions.

In every building usage, single indoor unit packaged air-conditioner (PAC) occupies about 40%, while multiple indoor unit (MUL) does about 60%. In the central system, CAV and VAV accounted for the most parts in the office buildings and large-scale hospital. In the hotel and middle-scale hospital, FCU accounted for the most parts.

Building Archetypes

On each category classified in the earlier step, the archetype models were designed to be inputted into EnergyPlus. Total floor area, floor plan, zoning, number of stories and floor usage were designed on each building archetype according to the dataset collected to quantify total floor area of each building stock category and some additional references so that the building archetypes represent each category. Appendix A. lists the conditions given to the building archetypes. We assumed specific conditions on the density of occupants, lighting intensity, appliance intensity, volume of outdoor intake for each floor space usage as listed in Table 7. We assumed that lighting and HVAC systems are operated while one or more occupants is using the floor. Appliances whose usage is shared by a number of occupants, the same operation setting was applied. For appliances that is used personally, the operation schedule is assumed to be same as the occupancy schedule.

An archetype is developed for each HVAC system configuration. Figure 1 and Figure 2 shows the schematic model of primary and secondary loop of HVAC system modelled in EnergyPlus respectively. In addition, the COP and the number of the heat source machines on each building model were decided based on technical references and the SHASE database mentioned above. Table 4 lists the rated COP of the simulated heat source machines. The part load characteristics and dependency on the condensing conditions were also considered.

The detail of pipes, ducts, coils and other thermal properties in archetypes were determined by using the ideal loads calculation function of EnergyPlus. In the ideal loads calculation, energy transfer rate to treat thermal loads is calculated without any limitation in the thermal capacity of coils. The cooling and heating capacity of coils is determined so as to satisfy the peak the peak cooling and heating loads. other system parameters such as chilled or hot water volume, air flow volume etc. are calculated based on the cooling and heating capacity.

The weather data were given from the EPW files of Tokyo, Osaka, Hokkaido, Kagoshima provided by EnergyPlus developers.

Simulation Result of HVAC System

Figure 3 shows the annual primary energy consumption for heating and cooling of the archetypes of office, hotel and hospital with a total floor area between 20,000 and 50,000 m^2. The energy consumption of the electricity driven chillers and heat pumps is smaller compared to those using gas driven ones. The energy consumption in air source heat pump is smaller than any other central system in the hotel and the hospital model because of absence of the condenser loop. On the other hand, AHP uses more energy than TB, which is caused by higher COP of TB as listed in Table 4 even though AHP uses less energy from pumps. The VAV system consumes less energy for HVAC auxiliary equipment due to inverter control of fans. However, VAV system has the highest energy consumption of cooling heat source, because VAV system treats more latent heat loads. The energy consumption of heating heat source is also the largest due

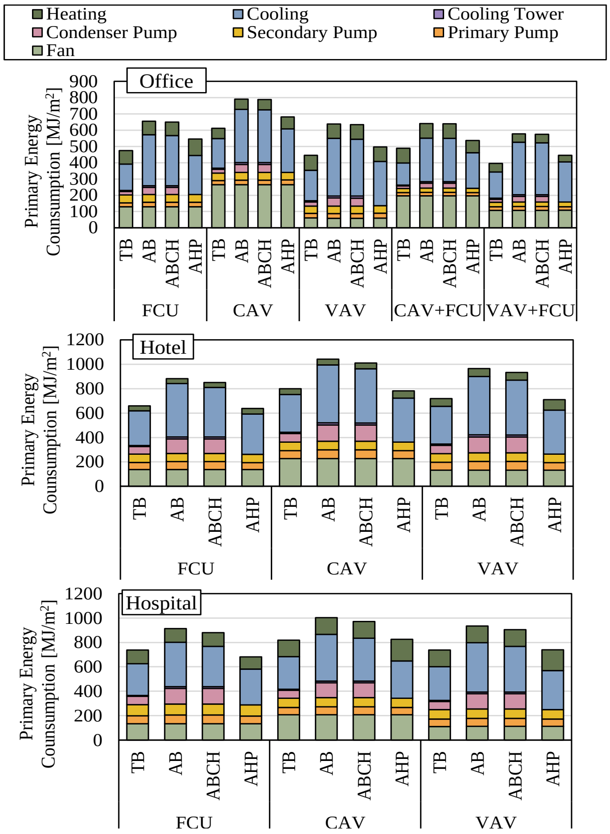

Figure 3 Primary energy consumption on each central system of CL8

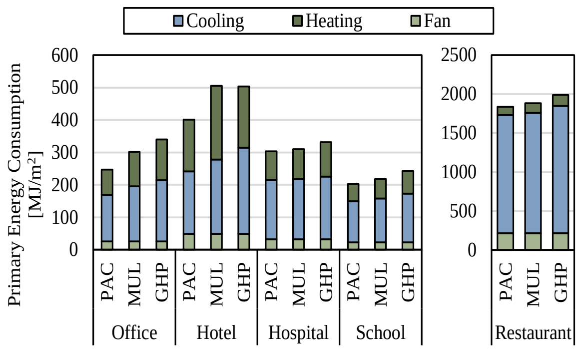

Figure 4 Primary energy consumption on each distributed system of CL2, school and restaurant

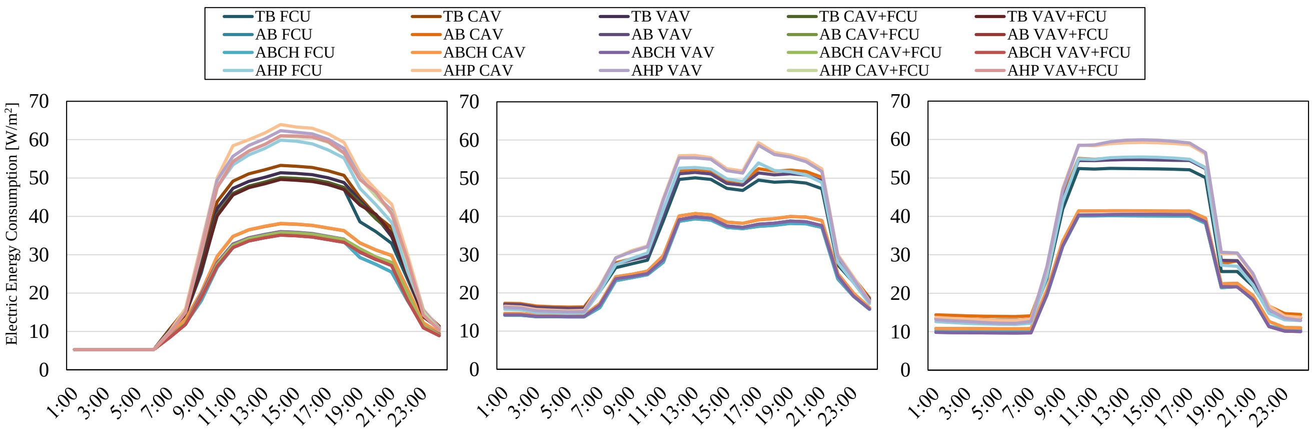

Figure 5 Electric peak demand on each HVAC system configurations

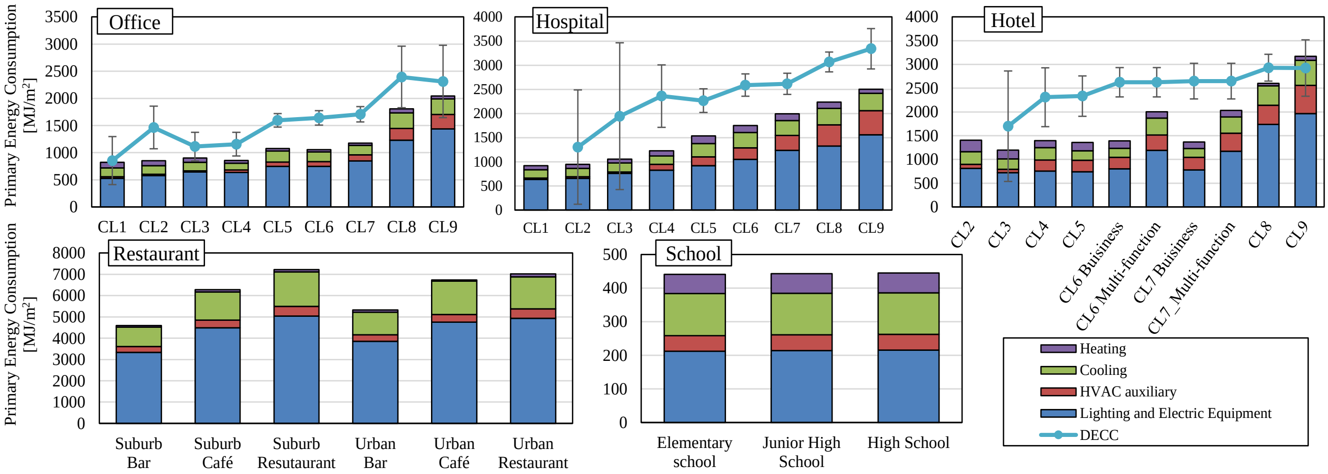

Figure 6 Primary energy consumption of each building model

to its minimum heat gain from fans. CAV+FCU and VAV+FCU models showed a smaller pump energy consumption than any other system. This is caused by less water flow rates, which is determined based on heat load calculation different from other system.

Figure 4 shows the simulation result of the distributed HVAC systems assumed to be installed in archetypes with total floor area between 200 – 500 m^2. The distributed system consumes less energy for HVAC auxiliary than the central systems because the refrigerant delivers heat between indoor and outdoor units. It should be noted that the energy consumptions shown in Figure 3 and Figure 4 cannot be simply comparable because the building size and activity conducted in the buildings were assumed to be different.

These figures show that the HVAC system configuration significantly affects primary energy consumption. It is also true for the time-series electricity demand. Figure 5 shows hourly peak electricity demand. Electricity demand peaks are at 2 pm in the office building, at 1 pm or 5 pm in the hotel and at 12 am – 2 pm in the hospital. Electricity demand is mainly characterized by the primary system. There is a tendency that systems equipped with electric driven heat source, such as the compression chillers and air source heat pumps, have larger electricity demand compared to those using gas driven ones. Electricity demand of compression chillers is smaller than that of air source heat pump due to its higher COP.

Evaluation of energy demand simulation result using the archetypes

Figure 6 shows the estimated annual primary energy consumption of each building usage and size located in Kinki region. The result for each HVAC system configuration was weighted-averaged according to the share of the configurations. The result is compared with the average annual primary energy consumption by the database of existing commercial building (Matsuoka et al. 2014). The simulated energy consumption in each building usage is much smaller than DECC data, especially among the middle-scale models.

In order to confirm the cause of underestimation, Figure 7 shows the estimated electricity and heat demands compared with a reference value (SHASE 2015). The electricity demand in Figure 7 includes the pumps and fans electric demand excluding the heat source. The estimated electricity demand for office is 9% larger than the reference. Cooling demand is 21% larger and heating demand is 22% larger than the reference. This result implies that the HVAC system configurations in the archetype model are more efficient than the building stock. This might be due to that the conditions assumed in the archetypes are too ideal. The assumption on the internal activity (see Table 2) might deviate from the reality, because a typical operation schedule was assumed. For the hotel and hospital archetypes, the cooling demands were overestimated, while the heating demands were underestimated. This result implies that the assumption of internal heat activity is inaccurate. Thus, the assumption of the building archetypes such as occupancy schedule, building envelop and system efficiency should be updated.

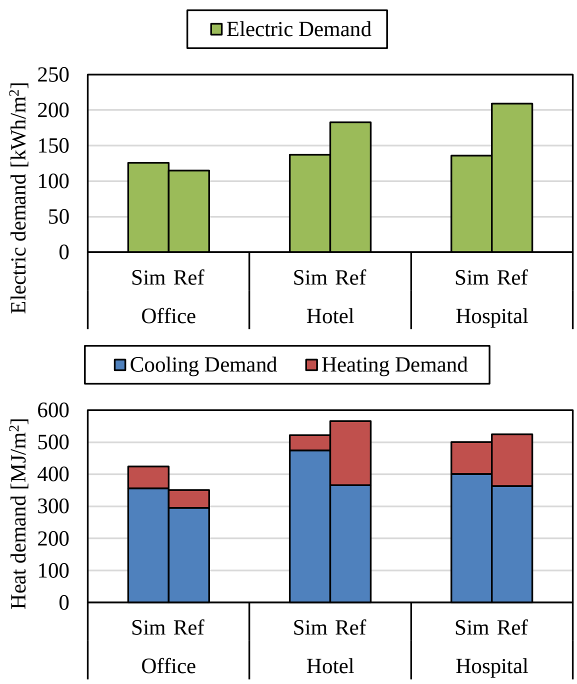

Figure 7 Comparison of electric and heat demand

Total electricity demand of the building stock

Figure 8 shows the estimated total hourly electricity demand on the day on which the peak electricity demand was observed during summer of the simulated year. The estimated peak electricity demand was 4.5 GW in Hokkaido and Tohoku, 31 GW in Kanto and Chubu, 15 GW in Kinki, Chubu and Shikoku and 6.9 GW in Kyushu and Okinawa. Kanto and Chubu has the largest peak demand, because they have the largest building stock. Hokkaido and Tohoku has the smallest peak demand per floor area, because it has relatively cooler climate than the other regions. The office building has the maximum contribution for the peak demand in every region.

Although there is no data available to evaluate the accuracy of the electricity demand, according to our knowledge, the demand during evening and night was underestimated. This is due to the assumption in the occupancy and operation schedule of building equipment. We have confirmed that realistic occupancy schedule improves the accuracy of energy demand model (Kou 2016).

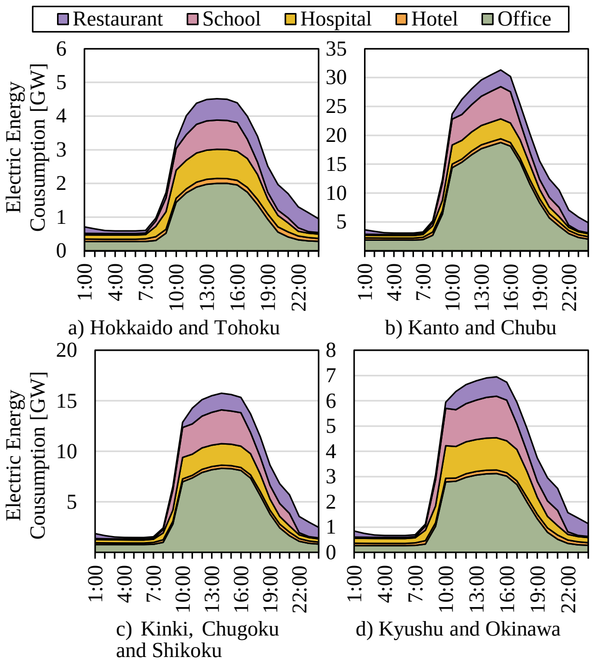

Figure 8 Hourly electricity demand in each region

Discussion

In order to examine the significance of considering diversity of HVAC system configurations, a case study was carried out. Electricity demand was quantified with an assumption in which only one HVAC system configuration with the highest share in each building size is adopted (see Figure 10 and Figure 11). This case is referred to as Typical configuration case. Figure 9 shows the difference in the hourly electricity demand on the peak day in Kinki, Chugoku and Shikoku region between the original model and Typical configuration case. The result shows that the assumption using typical HVAC system configurations underestimates electricity demand for office and hotel and overestimates for hospital, school and restaurant. The differences can be attributed to the share of the HVAC system configurations. Large buildings have a relatively large share of gas-driven systems. Electricity demand consumed by electricity driven systems is ignored in Typical configuration case, which resulted in the overestimation. For education building and restaurant, only MUL or PAC, which are electricity driven systems, is assumed in Typical configuration case. This resulted in the overestimation because a part of electricity consumption is avoided by those using gas-driven systems, GHP and ABCH, which are not taken into account in Typical configuration case. The office has the largest gap between the original case and the typical case, which was approximately 0.8 GW. This result implies the necessity of considering the diversity of HVAC system in order to estimate time-series electricity demand.

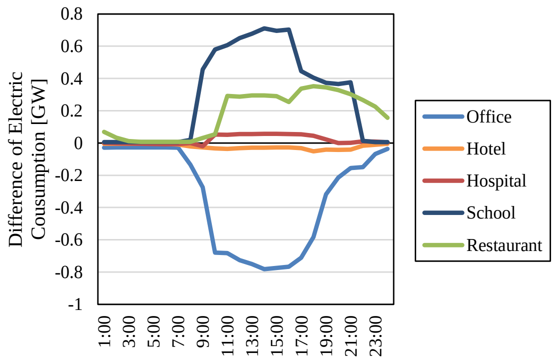

Figure 9 Comparison between developed model and typical case

Table 5 Defined Typical Case

Building Usage	Size and other attributes	HVAC system configurations
Office	<1,000 m^2	MUL
	≥1,000 m^2, <20,000m^2	MUL and ABCH VAV
	≥20,000 m^2	ABCH VAV+FCU
Hotel	<1,000 m^2	MUL
	≥1,000 m^2, <20,000m^2	MUL and ABCH VAV
	≥20,000 m^2	ABCH VAV
Hospital	<1,000 m^2	MUL
	≥1,000 m^2, <20,000m^2	MUL and ABCH VAV
	≥20,000 m^2	ABCH VAV
School	All configurations	MUL
Restaurant	All configurations	MUL

Conclusion

This paper reports a development of urban-scale energy demand model for the Japanese commercial building stock. We assumed 3 types of distributed system and 20 types of centralized system as archetype. This paper generally revealed that the consideration of the diversity in the HVAC system configurations is significantly important to replicate time-series electricity demand of the sector. However, the model underestimated the primary energy consumption. This is because typical parameters and occupants' behavior are assumed in develop archetypes. In order to solve these problems, database reflecting the actual conditions must be developed.

Appendix A. Building stock category

Table 6 and Table 7 shows the building stock category used in the energy demand model.

Appendix B. Share of HVAC system configurations

Figure 10 and Figure 11 shows the estimated share of HVAC system configurations considered in the study.

Appendix C. Commercial building stock

Figure 12 shows the total floor area of each building usages.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number JP16H04463 and by JST CREST Grant Number JPMJCR15K4, Japan.

Reference

Committee for Data-base for Energy Consumption of Commercial Building, Japan Sustainable Building Consortium. DECC-Data-base for Energy Consumption of Commercial Building http://www.jsbc.or.jp/decc/

DOE, Weather Data | EnergyPlus, 2016, https://energy plus.net/weather (accessed 11.1)

Koh Y et al. 2016. Simulation based analysis on the influence of occupants' presence on energy consumption of office buildings, Proceedings of 3rd Asia conference of International Building Performance Simulation Association (ASim2016), South Korea, November 2016

Korolija I et al. 2013. UK office buildings archetypal model as methodological approach in development of regression models for predicting building enrgy consumption from heating and cooling demands. *Energy and Buildings 60*, 152-162

Matsuoka A et al. 2014. Energy Demand Modelling of the Commercial Sector of Kinki Region Considering the Variety of Commercial Building Stock. *Proceedings of the 30th Conference on Energy, Economy, and Environment*. 561-566 (In Japanese)

Ministry of land, infrastructure, transport and tourism, Corporations survey on land and buildings, http://www.e-stat.go.jp/SG1/estat/eStatTopPortal.do

Shahrestani M et al. 2013. Characterising the energy performance of centralized HVAC&R systems in the UK. *Energy and Buildings 62*, 239-247

Swan L and Ugursal V. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews, Vol. 13*, 1819-1835

Yamaguchi Y et al. 2014. Classification of Commercial Building Stock Based on DECC database. *Proceedings of the 43th Academic Conference of Kinki Chapter of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan*. 341-344 (In Japanese)

Table 6 Design of building archetypes

Building use	Attributes	CL1	CL2	CL3	CL4	CL5	CL6	CL7	CL8	CL9
Office	Total floor area [m^2]	132	349	726	1,447	3,258	7,089	13,873	31,238	190,202
	Building coverage [m^2]	66	116	182	289	543	1,013	1,734	2,840	6,559
	Number of stairs	2	3	4	5	6	7	8	11	29
	Floor usage	office							Office, meeting room, restaurant, retail shop	
Hotel	Total floor area [m^2]	137	364	744	1,444	3,200	7,611	15,083	34,528	177,850
	Building coverage [m^2]	69	121	186	289	457	846	1,160	2,877	6,587
	Number of stairs	2	3	4	5	7	9	13	12	27
	Floor usage	Room clerk, lobby			Room clerk, Lobby, restaurant			Room clerk, Lobby, restaurant , banquet hall		
Hospital	Total floor area [m^2]	136	330	701	1,455	3,238	7,597	14,696	31,309	104,835
	Building coverage [m^2]	68	110	234	364	648	1,266	2,449	4,473	6,989
	Number of stairs	2	3	3	4	5	6	6	7	15
	Floor usage	Clinic, waiting room, lobby, inspection office			Clinic, waiting room, lobby, inspection office, bedroom		Clinic, waiting room, lobby, inspection office, bedroom, operating room		Clinic, waiting room, lobby, operating room, ICU, inspection office, bedroom	
School	Total floor area [m^2]	3,000			1,500			Note: we assumed that elementary school, junior high school and high school consist of two buildings listed on the left.		
	Building coverage [m^2]	1,000			500					
	Number of stairs	3			3					
	Floor usage	Classroom, special classroom, management room			Classroom, special classroom, management room					
Restau-rant	Total floor area [m^2]	150						Note: we assumed one building geometry for all of the restaurant/pub/café.		
	Building coverage [m^2]	150								
	Number of stairs	1								
	Floor usage	Restaurant customer seat, restaurant kitchen, bar customer seat, bar kitchen, café customer seat, café kitchen								

Table 7 Setting of internal activity

Building use	Floor usage	Lighting [W/m^2]	Appliance [W/m^2]	Occupants [$person/m^2$]	Quantity of outdoor air intake [$m^3/(m^2\cdot h)$]
Office	Office room	12	12	0.1	5
	Meeting room	10	2	0.25	5
Hotel	Room clerk	15	4	0.07	4
	Lobby	20	5.2	0.1	2.5
	Banquet hall	50	0.5	0.7	5
Hospital	Clinic	20	15	0.2	5
	Waiting room/lobby	6.7	10	0.1	6
	Inspection office	20	30	0.1	6
	Operating room	60	50	0.15	6
	Sickroom	12	3	0.08	4
	ICU	20	30	0.1	4
School	classroom	8.0	0.2	0.45	0
	Special classroom	8.0	0.2	0.45	0
	Management rooms	8.0	11	0.10	5
	Liberal arts laboratory	8.0	5.5	0.1	3.0
	Physical science laboratory	8.0	11.5	0.1	3.0
	Lecture hall	8.0	2	0.3	0.0
Restaurant	Restaurant customer seat	30	30	0.5	5.0
	Restaurant kitchen	15	50	0.1	12.5
	Pub customer seat	25	30	0.5	5.0
	Pub kitchen	15	50	0.1	12.5
	Café customer seat	30	30	0.4	5.0
	Café kitchen	15	33	0.1	12.5

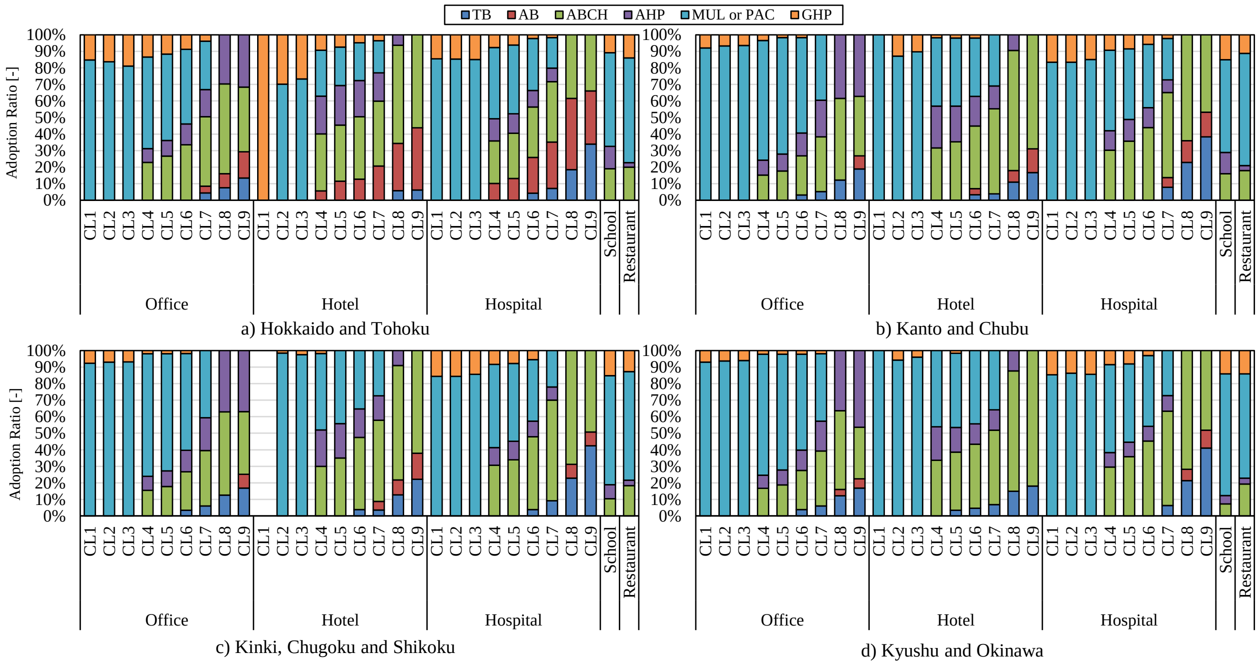

Figure 10 Adoption ratio of the heat source systems on each region

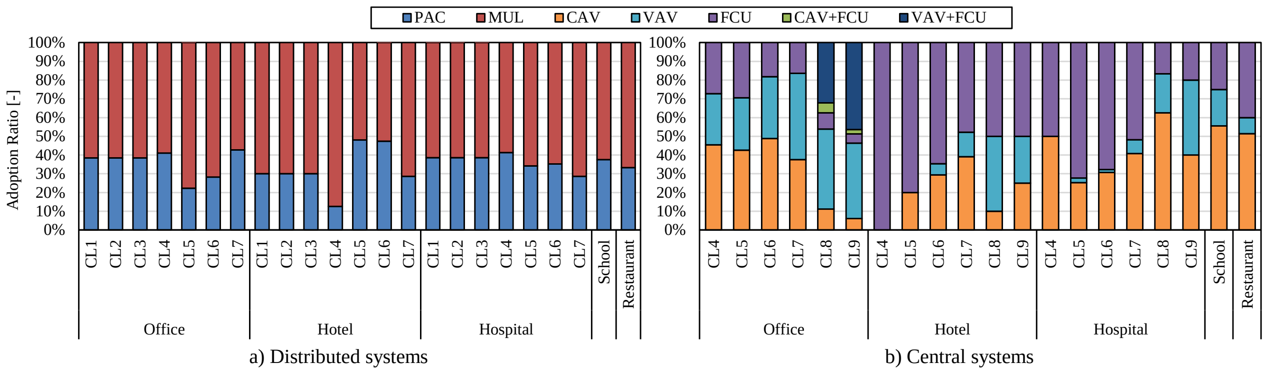

Figure 11 Adoption ratio of the HVAC systems

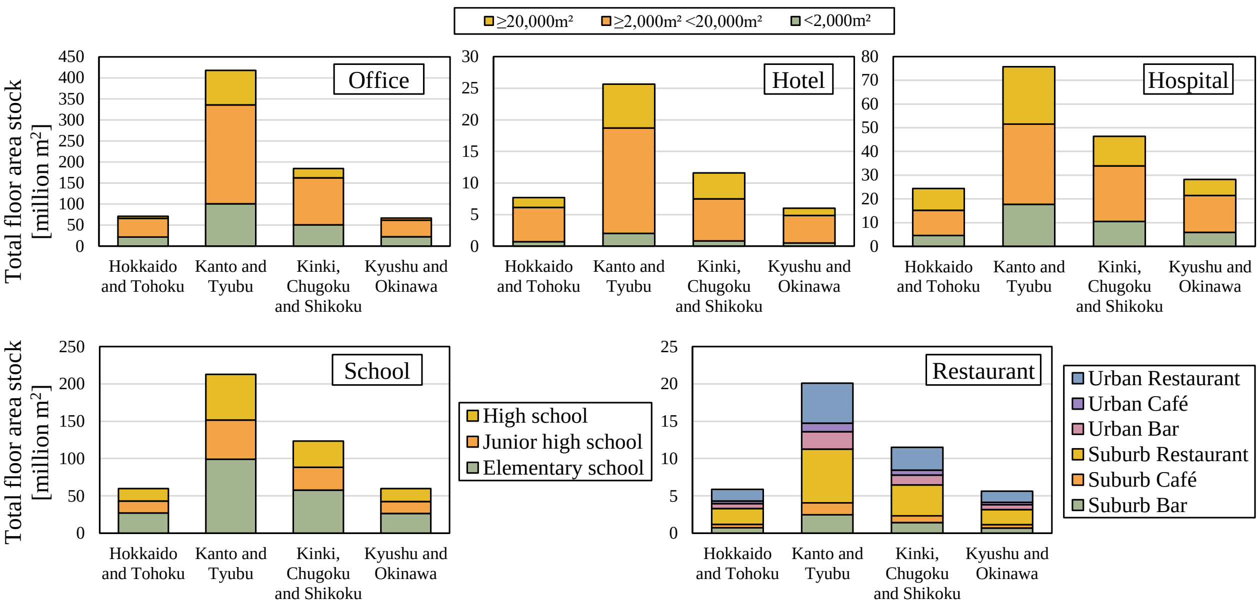

Figure 12 Total floor area stock of each building