SIMULATION SUPPORT IN DESIGNING THE TRANSFORMATION OF URBAN BUILDING STOCK AND ENERGY INFRASTRUCTURE

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ABSTRACT

The transition of the urban building stock and infrastructure to sustainable forms is a key challenge in modern planning. The purpose of this paper is to propose a simulation model for energy use in the Japanese commercial sector. This model enables a user to consider a variety of energy-management concepts and discuss how urban building stock and infrastructure can be transformed over the coming decades. The model is characterized by having a bottom-up structure, which contributes to improving the reliability of the simulation results. Although the model is not yet complete, we present a case study to demonstrate the simulation capabilities of the model. The results of the case study indicate that the model can be used in support of a design to transform the urban building stock and infrastructure.

KEYWORDS

Urban building stock, Energy infrastructure, Transition, Commercial sector

INTRODUCTION

The Japanese government recently announced its goal of a 50% or higher reduction in CO_2 emissions by 2050 relative to 1990 levels. To achieve this emission target, we must transform the urban building stock and infrastructure to ensure that energy demand is significantly reduced and is fulfilled in a highly efficient manner compared to current levels. To design such a transformation from a long-term perspective, a backcasting approach would be useful (Breborg 1996). In backcasting, we first design long-term visions and then explore mid-term strategic goals as necessary steps for achieving the vision. Using this solution-driven approach, we can explore our options in terms of managing the energy use of the urban building stock and infrastructure such that a drastic change is realized. Each of the available options categorized in the following energy-management concepts must be fully considered.

- Improvement in the energy efficiency of energy-consuming equipment/appliances.
- The implementation of energy-saving measures for buildings, such as improvements in the insulation performance of building envelopes.
- Optimization of local energy generation and distribution systems, including the development of district heating and cooling systems and the adoption of renewable technologies at a local level.
- The management of land use and urban form that predetermines the proportion of energy consumption in the built environment.
- Improvement in the CO_2 emission factor of the electricity grid by improving the generation efficiencies of power plants, switching fuel, adopting CO_2 sequestration, and increasing the contribution of nuclear power generation and renewable energy sources.

Simulation models might potentially play an important role in the designing process of long-term visions of urban building stock and infrastructure. Simulation models enable us to predict a consequence arising from a specific change in the components of interest (Tweed 1998); however, existing simulation models commonly fail to accurately predict the consequence associated with extending the application from building simulation for a single building to building stock at the level of a district, city, or nation. In broadening the application, we usually have to simplify the simulation model and input information because of a lack of available data. This approach has the potential to adversely affect the reliability of the simulation results (Yamaguchi 2005).

In the present paper, we propose a simulation model that quantifies the energy use of building stock at the national scale. The model is designed to prevent a decline in the reliability of simulation results while maintaining the model's capability to consider the different options available in the energy-management concepts described above. We first review existing modeling approaches before introducing the new model. Although the model is not complete, we are able to demonstrate the simulation capability of the model using a case study. Finally, we discuss the simulation model in terms of its capability as a support tool in planning the transformation of a building stock in the Japanese commercial sector and the supporting infrastructure.

MODELING APPROACH

Building clustering modeling approach

Energy-saving measures are often analyzed in case studies that consider a specific building. Such an approach makes it difficult to quantify the extent to which the considered measures might contribute to a large-scale reduction in CO_2 emissions (e.g., at the city and national levels).

Previous studies established a methodology, herein termed the "building clustering modeling approach", that has been applied to quantify the energy consumed in building stock at scales ranging in size from a district to a nation (Haung et al. 1991, Jones et al. 2001, Clark et al. 2004, Shimoda et al. 2004). This methodology was designed to maintain the reliability of simulation results within acceptable levels. Using this methodology, we first design building prototypes, each representing a group of building stock with particular characteristics in terms of energy use. We then perform simulations using these building prototypes as input to a simulation model in order to predict the energy use in each building stock group. We finally obtain the total energy use by aggregating the amounts predicted for all of the building stock groups.

A model based on this approach is capable of dealing with a variety of energy-management options in an integrated manner. The influence of the energy-use options on energy use are considered to be relatively robust, although sufficient attention must be given to the simulation software being used. A model based on this approach, however, is incapable of considering district-level energy generation and distribution systems, such as a district heating and cooling (DHC) system. This limitation arises because the methodology ignores how buildings form the building stock in the studied area.

District clustering modeling approach

We previously proposed a modeling approach termed the "district clustering modeling approach" (Yamaguchi et al., 2007a, b). A simulation model based on this approach is capable of dealing with district-level energy generation and distribution systems, in addition to the measurements that can be

Table 1 Procedure followed to develop a model based on the building and district clustering modeling approaches

Process	Modeling approach	
	Building clustering modeling approach	*District clustering modeling approach*
Clustering process	Clustering of building stock into several building stock categories *The elements considered in clustering the building stock are as follows:* *- building use (e.g., office, retail, hotel, hospital)* *- size* *- zoning of the floor plan* *- adopted heat source system*	Clustering of the districts represented by the grid cell dataset into several district categories *Elements considered in the clustering of districts, or grid cell dataset:* *- total floor area for each building use (office, retail, hotel, hospital)* *- gross floor area* *- average number of floors in the buildings* *- number of buildings*
	Design of the prototypical building models, each representing a building stock category	Selection of representative districts for each district category and subsequent field investigations
Simulations undertaken to calculate the representativ e end-use energy consumption	Performing simulations using these prototypical building models as input: 1. *Performing simulations of energy demand in buildings for space heating and cooling, hot water, and electricity on an hourly basis* 2. *Performing simulations of energy generation and distribution systems to quantify end-use energy consumption (i.e., electricity and city gas) in prototypical building models*	Performing simulations with the district-level energy system simulation model using building information databases, as developed from the field investigations in the previous step: 1. *Performing simulations of energy demand for space heating and cooling, hot water, and electricity for each building in the representative districts on an hourly basis* 2. *Performing simulations of energy generation and distribution systems to quantify total end-use energy consumption in the representative districts*
	Calculation of representative end-use energy consumption per unit floor area for each building stock category	Calculation of representative end-use energy consumption per unit floor area for each district category (each district category has only one representative end-use energy consumption per unit floor area, regardless of building use)
Aggregating process	Aggregate the total end-use energy consumption by summing the products of the total floor area and the representative end-use energy consumption for each building stock category	Aggregate the total end-use energy consumption by summing the products of the total floor area and the representative end-use energy consumption for each district category

considered in a model based on the building clustering modeling approach. This approach is similar to the building clustering modeling approach in terms of the procedure used to quantify energy use. Table 1 describes the procedure followed in the district clustering modeling approach compared with the building clustering modeling approach. While the building clustering modeling approach considers a building as a unit, the district clustering modeling approach considers a district as a unit. The clustering of districts aims to identify connections between the form of the building stock and a strategy employed to manage energy use and CO_2 emissions. Using this methodology, we first classify districts in a studied area according to how buildings form the building stock. We then select a representative district for each district category, rather than selecting a building prototype as undertaken in the building clustering modeling approach. We then perform simulations using a database of buildings in the representative districts as input to a simulation model to predict the end-use energy consumption per unit floor area; the results are then used in quantifying the total end-use energy consumption of the district category. We finally obtain the total energy use by aggregating the amounts predicted for all of the district categories.

The bottom-up structure of the model means that we can seamlessly model the performance of energy-consuming appliances/equipment, building systems, and local energy generation and distribution systems, as well as the form of building stock. Thus, we can evaluate a variety of options available in the energy-management concepts listed above. We are also able to obtain a concrete image of what the assumption considered in the study means in reality.

Despite these advantages, this modeling approach requires the development of a detailed database of information on how buildings form the building stock at the neighborhood level; consequently, it would be difficult to apply this approach to all of the regions in Japan, but it can be applied to large cities in which the building stock is concentrated and for which statistical data on the building stock are relatively well developed.

Proposal of a simulation model for the Japanese commercial sector

In developing a simulation model for the building stock of the Japanese commercial sector, we combine the two modeling approaches described above. Figure 1 shows the procedure to be followed in developing the model.

1) Division of Japan according to climate conditions

The Japanese Archipelago extends more than 3,000 km from north to south, thereby experiencing a great diversity in climate. The Japanese Law Concerning the Rational Use of Energy, which was established to enhance energy management, takes into consideration six different climate zones (Figure 2), according to the characteristics of the local climate, to promote heat insulation of the outer walls and roofs. To take into account the characteristics of the local climate, we use this climate division in the model.

1. Division of Japan according to climate conditions
   We divided Japan into six climate zones, as shown in Figure 2.

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2. Development of building stock database that contains information on building stock for each climate zone

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3. Classification of districts in each climate zone
   - We used the district clustering modeling approach to construct dense districts in the cities designated by government ordinance and the 23 special wards of Tokyo
   - The building clustering modeling approach was applied to other districts in the cities
   - The building clustering modeling approach was applied to districts in other cities

↓

4. Development of databases of factors with a significant influence on energy use in buildings and that are dependent on climate conditions and local socio-economic conditions such as access to the city's gas infrastructure
   - Heat source system database
   - Energy-saving measures database

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5. Application of district and building clustering modeling approaches to all districts in Japan to quantify energy use in buildings in the commercial sector

Figure 1 Procedure followed in developing the simulation model in the context of building stock in the Japanese commercial sector

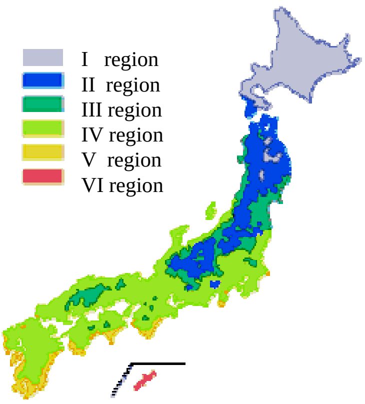

Figure 2 Climate zones in Japan

2) Development of a building stock database that contains information on building stock in each climate zone

To take into account the distribution of building stock in each climate zone, the building stock database is developed for each climate zone. The database contains the distribution of the size and configuration of buildings for each type of use in the commercial sector. These data are gathered for all principal uses (e.g., office, retail, hotels, hospitals, and schools).

A more specific database is also developed for the cities designated by government ordinance and the 23 special wards of Tokyo (Table 2). The building stock is concentrated in these areas, and statistical data on the building stock is well developed. For a city such as Osaka City and cities within Tokyo, a detailed database is available that contains building size, number of floors, principal use, and other specific information for all existing buildings. For other cities, we use the grid cell dataset that contains the total floor area for each building use within 500 × 500 m (or 1 × 1 km) grid cells.

Table 2 Cities designated by government ordinance and the 23 special wards of Tokyo

Region	Prefecture	City	Population [thousands]
Hokkaido	Hokkaido	Sapporo	1,821
Tohoku	Miyagi	Sendai	1,090
Kanto	Tokyo	The 23 special wards of Tokyo	11,125
	Saitama	Saitama	933
	Chiba	Chiba	859
	Kanagawa	Yokohama	3,091
		Kawasaki	1,097
Tyubu	Shizuoka	Shizuoka	738
	Aichi	Nagoya	2,515
Kinki	Kyoto	Kyoto	1,585
	Osaka	Osaka	3,664
		Sakai	770
	Hyogo	Kobe	1,537
Tyugoku	Hiroshima	Hiroshima	1,163
Kyusyu	Fukuoka	Kitakyusyu	1,045
		Fukuoka	1,531

3) Classification of districts in each climate zone

By using the grid cell dataset for the cities designated by government ordinance and the 23 special wards of Tokyo, as established in the previous process, we selected districts with a gross floor area of more than 100%. For these districts, we apply the district clustering modeling approach such that we can examine the development of district-level energy generation and distribution systems. For other areas in Japan, we apply the building clustering modeling approach.

4) Development of heat source systems and energy-saving measures

To precisely estimate the energy use of buildings and avoid an overestimation of the reductions in CO_2 emissions gained by introducing energy-management measures, it is important to make appropriate assumptions regarding the type and number of heat source systems and the energy-saving measures adopted in the analyzed buildings. This generally depends on the size and use of buildings in Japan. We developed databases of the heat source system and energy-saving measures for each climate zone. We also developed these databases for the cities designated by government ordinance and the 23 special wards of Tokyo.

The heat source system database contains the share of the heat source systems adopted in buildings along with the building use and ranges in building sizes. The energy-saving measures database contains measures that are generally widely adopted in existing buildings. In quantifying end-use energy consumption, we perform simulations under the assumption of all types of heat source systems for each building. The total end-use energy consumption of the building is then quantified as a weighted-averaged value of the energy use quantified for each heat source system according to the share of the different heat source systems.

5) Quantification of energy use and consideration of the incorporation of energy-management measures

We divide the land within Japan according to the procedures 1), 2) and 3) listed above. We then perform simulations based on the building or district clustering modeling approach, as determined in procedure 3), to estimate the energy use of the building stock in each divided area. The total energy use is then quantified by aggregating these results.

Simulation capability of the model

To improve the reliability of the simulation results, we increase the number of divisions of building stock according to the characteristics of climate, building size, and use; we also develop improved databases of building stock, heat source systems, and energy-saving measures by making use of available statistical data.

The bottom-up structure of the building and district clustering modeling approaches means that the model is able to seamlessly connect the characteristics of the building stock, efficiency of energy-consuming appliances and machines, energy-saving measures and heat source systems, and local infrastructure in an integrated manner. Thus, the model is capable of taking into account the options available in the variety of energy-management concepts listed in the Introduction.

CASE STUDY

To demonstrate the simulation capability of the model described above, we present a case study in which we applied the building and district clustering modeling approaches to the commercial sector of Osaka City, Japan.

Table 3 Prototypical building models and building stock included in the building stock categories

Building use	Indicator	Classes in building size				
		Class 1	Class 2	Class 3	Class 4	Class 5
Office	Floor area of floor plan [m^2] †	279	633	1,194	2,736	4,509
	Total floor area [m^2] †	1,671	4,432	11,944	27,357	103,716
	Number of floors	6	7	10	10	23
	Proportion of total office building stock	19.3%	25.9%	23.0%	20.6%	11.1%
	Range in total floor area for each class	less than 3,051 m^2	3,051 to 8,188 m^2	8,188 to 19,651 m^2	19,651 to 65,536 m^2	greater than 65,536 m^2
Retail	Floor area of floor plan [m^2] †	358	2,633	5,643	6,410	-
	Total floor area [m^2] †	1,432	15,797	33,857	96,148	-
	Number of floors	4	6	6	15	-
	Proportion of total retail building stock	65.2%	10.2%	6.2%	18.5%	-
	Range in total floor area for each class	less than 8,615 m^2	8,615 to 24,827 m^2	24,827 to 65,003 m^2	greater than 65,003 m^2	-
Hotel	Floor area of floor plan [m^2] †	451	1,462	2,519	3,721	-
	Total floor area [m^2] †	4,508	21,937	65,498	137,669	-
	Number of floors	10	15	26	37	-
	Proportion of total hotel building stock	7.7%	21.5%	48.2%	22.5%	-
	Range in total floor area for each class	less than 13,223 m^2	13,223 to 43,718 m^2	43,718 to 101,583 m^2	greater than 101,583 m^2	-
Hospital	Floor area of floor plan [m^2] †	1,092	3,309	5,559	5,635	-
	Total floor area [m^2] †	6,553	26,476	55,589	90,160	-
	Number of floors	6	8	10	16	-
	Proportion of total hospital building stock	7.8%	30.0%	29.9%	32.3%	-
	Range in total floor area for each class	less than 16,514 m^2	16,514 to 41,032 m^2	41,032 to 72,874 m^2	more than 72,874 m^2	-

† These data are for prototypical building models

Building clustering modeling approach

According to the building clustering modeling approach, we designed 612 prototypical-building models in the clustering process of the procedure outlined in Table 1. We recognized four building uses (office, retail, hotel, and hospital), four or five ranges in building size (five ranges of building size for office buildings and four ranges for other buildings, as shown in Table 3), nine zoning and configuration patterns, and four types of heat source systems. Each prototypical-building model is constructed based on statistical data on the HVAC equipment within newly constructed buildings.

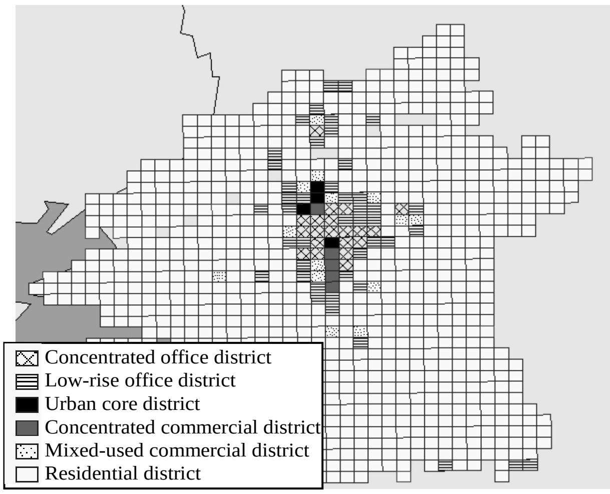

Figure 3 Result of the grid cell classification

The demand profiles of space heating and cooling, hot water, and electricity for each building are simulated on an hourly basis. The energy use of the prototypical buildings is then simulated to quantify the energy use. A detailed description of the simulation model is given elsewhere (Yamaguchi et al. 2007a), as is a validation study of the simulation software used in the present study (Hashimoto et al. 2007).

District clustering modeling approach

1) Classification of districts

We also developed a model according to the district clustering modeling approach. We first developed the grid cell dataset within 500 × 500 m grid cells for the elements of total floor area for each building use, gross floor area, average number of building stories, and total number of buildings. The grid cells were then classified into six district categories (as shown in Figure 3) based on clustering that employed all the elements of the grid cell dataset. Figure 4 shows the total floor area for different uses, which was

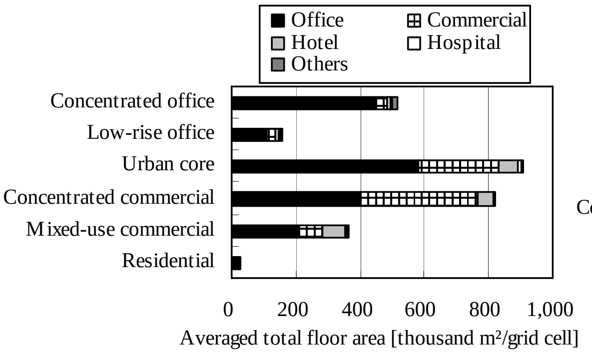

Figure 4 Total floor area for different uses averaged for each district category

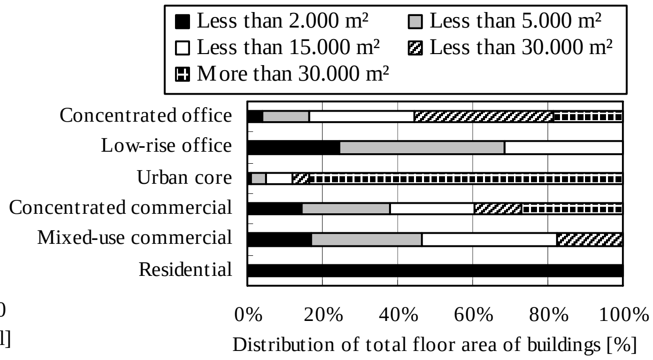

Figure 5 Distribution of the total floor area of buildings in each representative district

Table 6 Description of energy-management scenarios

	Management Concept	**Description**
Case 1	Advancement in technology	We ignore efforts to save energy at the building- to city-scale levels. Table 7 shows the efficiencies of the technologies considered for the baseline estimation and those assumed for the year 2050.
Case 2	Dissemination of energy-saving measures	Available energy-saving measures at the building level are fully incorporated into buildings. We assumed the available energy-saving measures to consist of improvements in insulation performance, advanced lighting control and outdoor air intake, and variable speed control in heat distribution systems.
Case 3	Optimization of heat source systems	Heat source systems are replaced by systems that minimize CO_2 emissions by using available heat source systems. We assume the introduction of district heating and cooling systems in districts with a gross floor area of more than 100%. For districts with a gross floor area less than 100%, we assume that optimization leads to heat source systems being replaced with those using heat pumps (air-source heat pumps and room-air conditioner for the commercial buildings listed in Table 7) running on electricity.

averaged for all the grid cells categorized into each district category. We then selected a representative district for the district categories with a gross floor area over 100%. All buildings in the representative districts were surveyed to grasp how buildings form the district at the neighborhood level for each district category. Figure 5 shows the distribution of the total floor area of buildings in each representative district.

2) Quantification of end-use energy consumption per unit floor area

The district-level energy system simulation model (Yamaguchi et al. 2007a) developed in the present research was applied to the representative districts to quantify the annual end-use energy consumption per unit floor area. The total end-use energy consumption in each building was simulated considering the configuration of the employed systems of energy generation and distribution. The end-use energy consumption per unit floor area was then quantified by dividing the total end-use energy consumption of all the buildings by the total floor area. The total end-use energy consumption and CO_2 emissions from the commercial sector of Osaka City were quantified by multiplying the total floor area of the building stock in the districts categorized into each district category by the end-use energy consumption per unit floor area calculated for each representative district.

Total end-use energy consumption predicted for the commercial sector of Osaka City

Figure 6 shows the predicted total end-use energy consumption—a secondary energy-based value—of the commercial sector of Osaka City. The simulation results, based on both the building and district clustering modeling approach, reveal smaller values than the statistical values obtained in the total end-use energy consumption of electricity and city gas. Given that the results estimated according to the district and building clustering modeling approaches are similar, the discrepancy between the estimated results and statistical values is not due to the modeling approaches. The discrepancy is mainly attributed to the fact that the simulation model does

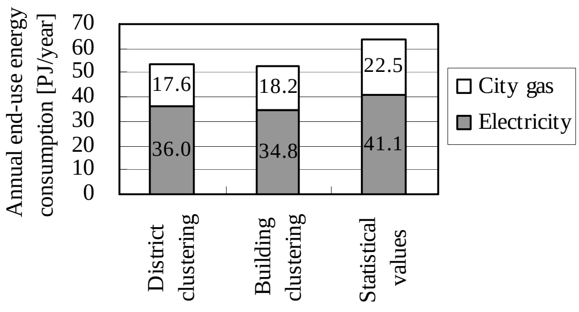

Figure 6 Predicted total end-use energy consumption for the commercial sector in Osaka City

Table 7 Efficiencies arising from lighting, office equipment, and heat source equipment

Technologies		Baseline	Year 2050	Note
Lighting	Technology Luminous efficiency	Fluorescent 70 [lm/W]	LED 150 [lm/W]	
Improvement in the energy efficiency of office equipment (electric load compared to current condition [%])		100%	60%	
Absorption chiller [HHV]	Cooling COP	1.00	1.65	
Compression chiller	Cooling COP	4.5	8.0	Inverter technology will be introduced to improve part-load operation
Air-source heat pump	Cooling COP	2.9	5.0	
	Heating COP	3.1	5.4	
Room air-conditioner for commercial buildings	Cooling COP	2.6	4.0	
	Heating COP	3.1	5.0	

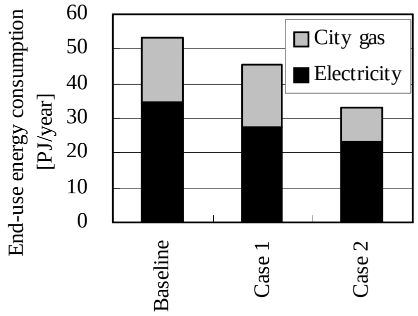

Figure 7 Predicted total annual end-use energy consumption

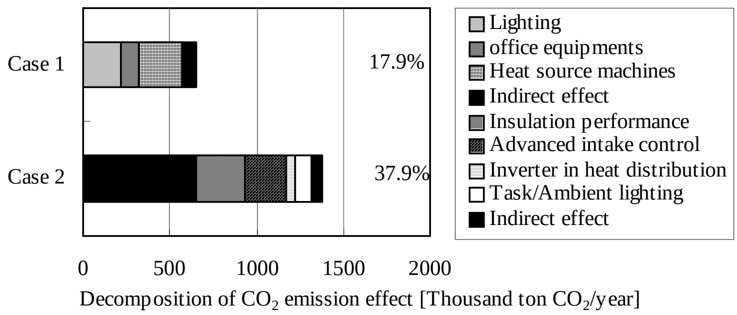

Figure 8 Decomposition of reductions in CO_2 emissions

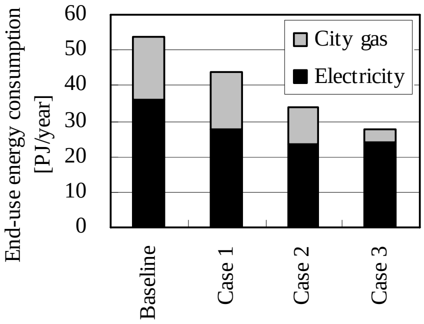

Figure 9 Predicted total annual end-use energy consumption

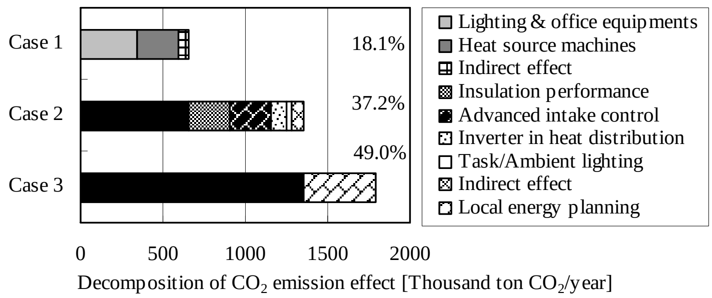

Figure 10 Decomposition of reductions in CO_2 emissions

not take into account a number of energy demands. For example, we ignored energy demand for cooking in buildings of all use types, demand for hot water in offices and commercial buildings, and demand for sterilization procedures employed in hospitals. We also ignored unreasonable energy use (e.g., the infiltration of outside air through an entrance that is always left open while the building is open for use).

Use of the building clustering modeling approach to evaluate the dissemination of advanced technologies and energy-saving measures

Figure 7 shows the predicted total annual end-use energy consumption for the commercial sector of Osaka City for the baseline, Case 1, and Case 2 listed in Table 6. Figure 8 shows the decomposition of reductions in CO_2 emissions; the numbers within the bar graph indicate the percentage reduction in CO_2 emissions relative to the baseline emissions.

Use of the district clustering modeling approach to evaluate district energy generation and distribution systems

Figure 9 shows the predicted total annual end-use energy consumption, while Figure 10 shows a breakdown of reductions in CO_2 emissions and percentage reductions.

Simulation capability of the simulation model based on a combination of the building and district clustering modeling approaches

By applying the building clustering modeling approach to the entire building stock of the Japanese commercial sector (as outlined in Figure 1), the proposed model is capable of quantifying the potential reduction in energy use and CO_2 emissions achieved by technological advances and the dissemination of energy-saving measures, as demonstrated for Osaka City.

By applying the district clustering modeling approach to cities with a high density of building stock, the developed model is capable of quantifying the potential reduction in energy use achieved by the planning of local energy generation and distribution systems, as demonstrated for Osaka City. Such energy savings will become even more important if advances are made in energy-generation technologies such as solid oxide fuel cells and highly efficient compression chillers.

The model proposed in Figure 1 combines the building and district clustering modeling approaches, thereby giving it the combined advantages of the two modeling approaches. The model is capable of quantifying energy use at the national scale by considering a variety of options available in energy-management concepts involving advances in technology: the dissemination of energy-saving measures into buildings, the planning of local energy generation and distribution, management of the spatial pattern of building stock, and improvements in the CO_2 emission factor of the electricity grid. Thus, in using the model, the user is able to study the extent to which a particular change in building stock and infrastructure alters the energy use and CO_2 emission, as calculated based on a number of factors assumed by the user. This process will be of use in designing visions to achieve sustainability.

The model also considers elements with a potentially significant impact on energy use and CO_2 emissions, such as climate, technology, and the lifestyle of occupants, all of which may vary significantly over the coming decades. The model makes it possible to study the influence of possible changes in these elements. Such a simulation capability is important in discussing future urban sustainability, both in Japan and other rapidly growing countries in East Asia.

CONCLUSION

This paper proposed a simulation model that quantifies the energy use of the Japanese commercial sector at the national scale. This model combines two different modeling approaches (the building clustering modeling approach and district clustering modeling approach) to avoid any reduction in the reliability of the simulation results. We carried out a case study on the commercial sector of Osaka City to demonstrate the simulation capability of the modeling approaches. The results generally showed that the employed combination of the building and district clustering modeling approaches enables the development of a simulation model for the Japanese commercial sector that is capable of considering various options available in energy-management concepts arising from advances in technology, including the dissemination of energy-saving measures into buildings, the planning of local energy generation and distribution, management of urban form, and improvements in the CO_2 emission factor of the electricity grid. The model also provides the user with a clear image of the future building stock and supporting infrastructure. Such a model will prove to be useful in designing future visions of building stock and infrastructure.

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