Energy and carbon management system for a city and a nation

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Abstract

A digital twin model for energy and carbon management of the building sector, both nationally and at the city level, is developed. The model consists of the following three tools: 1) a bottom-up, end-use energy simulation model that replicates the energy demand determination mechanism, 2) individual statistical data that explain the relationships between household/building characteristics and appliance ownership/energy-saving behavior, which enables the model to consider the heterogeneity of households and buildings, and 3) smart meter data that can be used to analyse the energy efficiency progress of households and buildings. The concept of an energy/carbon management system is introduced and the progress of the Japanese Plan for Global Warming Countermeasures (PGWC) is assessed. A distinctive feature of the Japanese PGWC is that it clearly identifies the target diffusion amounts for each countermeasure technology. To simulate Japan's residential sector, a representative sample of 0.03 % of Japanese households is randomly selected, and various characteristics, including the number and attributes of household occupants, the thermal performance of the residential building, occupant ownership and use of home appliances, and the type of water heater and space heating equipment, are used to accurately reflect population heterogeneity. With these data, together with weather data for the target years, the annual energy demand of the Japanese residential and non-residential sectors is simulated for 2013–2019. In the residential sector, the impact of differences in weather conditions is found to be substantial, reaching a maximum of 50 %. For the non-residential sector, the effect of weather differences is relatively small. The effect of the government's energy efficiency measures as estimated by the simulation is smaller than the government estimates for both the residential and non-residential sectors, and is well below the government's 2019 target.

Introduction

JAPANESE GLOBAL WARMING MITIGATION POLICY

In 2015, in response to the Paris Agreement, the Japanese government submitted its Nationally Determined Contribution (NDC), which stated that Japan would reduce its GHG emissions by 26 % by 2030 relative to the country's 2013 level. Based on the NDC, the Japanese Cabinet established its Plan for Global Warming Countermeasures (PGWC) in May 2016. For the residential sector, the PGWC targeted a 79 Mt-CO_2 reduction in emissions, representing an ambitious 39 % reduction from the 2013 level of 201 Mt-CO_2. Similarly, the non-residential sector was required to reduce CO_2 emissions by 40 % from the 2013 level.

In 2021, the Japanese Prime Minister announced that the overall 2030 reduction target would be raised to 46 %, resulting in a revision of the PGWC. In the new PGWC, reductions of 66 % and 51 % were required for the residential and non-residential sectors, respectively. Under the revised plan, the new targets will be met primarily by the increased use of renewable power sources, while the end-use energy reduction targets remain relatively unchanged.

OUTLINE OF LONG-TERM ENERGY SUPPLY AND DEMAND OUTLOOK

Energy-derived CO_2 accounts for more than 90 % of all greenhouse gases in Japan. As the basis for its PGWC, the Japanese government has published the Long-term Energy Supply and Demand Outlook (LESDO), which projects Japan's power source composition and energy demand in 2030. A special feature of LESDO is that it shows the energy demand reduction targets in bottom-up form, specifying the target dissemination ratio of each countermeasure and its effect. Table 1 shows the countermeasures and their estimated energy demand reduction effect relative to the 2030 business-as-usual (BAU) case described in the 2015 LESDO for the residential sector, which served as the basis of the 2016 version of the PGWC.

PROGRESS MANAGEMENT OF THE PLAN FOR GLOBAL WARMING COUNTERMEASURE

The progress of PGWC is evaluated annually by a joint council of the Ministry of the Environment and the Ministry of Economy, Trade and Industry. The evaluation is done in two ways: One is an evaluation based on national energy and CO_2 emission statistics; the other is an evaluation of the progress of each of the measures shown in Table 1. From the evaluation of progress in FY(Fiscal Year)2019, the results in the building sector were as follows:

- According to national energy statistics, CO_2 emissions in FY2019 decreased by 23.7 % for the non-residential sector relative to FY2013. These reductions indicate progress at a faster pace than planned. However, these reductions were in part due to the decarbonization of electricity arising from the dissemination of renewable energy and the restart of nuclear power. In fact, energy consumption in the residential sector decreased by 13.1 %; in the non-residential sector, the decrease was 6.6 %. Nevertheless, these values are faster than the rate of energy consumption reduction planned by LESDO for 2030.
- Based on the progress of the countermeasures listed in LESDO, it appears that approximately half of the countermeasures were behind the plan and that the progress of the PGWC was, as a whole, not favorable.

As noted above, the results of the evaluation by the two methods do not match. The following factors can be considered the reason:

- Actual CO_2 emissions and energy consumption are affected by various factors such as weather and socio-economic activities.
- LESDO's measures indicate the amount of reduction from the 2030 BAU case, but the BAU case estimation itself is inaccurate.
- In LESDO, the effect of a measure is estimated as the product of the amount of dissemination and the effect per unit. However, in reality, the effect varies according to household (Taniguchi-Matsuoka et al. 2020) and building characteristics.

Concept of digital twin model for energy and carbon management

OVERVIEW OF THE DIGITAL TWIN MODEL

To resolve the problems of the present progress evaluation system, we propose a new energy and carbon management system for cities and the nation, one that is better suited to a modern digital society. An overview of the system is shown in Figure 1. The proposed system is a so-called "digital twin model" which reproduces in cyberspace the actual energy consumption occurring in the real world (physical space). The model consists of the following three tools: 1) a bottom-up, end-use energy simulation model that can replicate the energy demand determination mechanism for a city or a country, 2) individual statistical data that explain the relationships between household/ building characteristics and energy consumption, appliance ownership status, and the energy-saving behavior of a building's occupants in order to account for the heterogeneity of households/buildings, and 3) smart meter data that can be used to analyse the energy efficiency progress of households/ buildings. By combining these three tools, it is possible to assess the present situation regarding energy consumption and CO_2 emissions in the residential and non-residential sectors, evaluate the progress of the energy efficiency program currently in place, and plan for new energy efficiency measures.

RESIDENTIAL ENERGY END-USE SIMULATION MODEL

To conduct an end-use energy simulation for the residential sector, the authors developed the TREES (Total Residential End-use Energy Simulation) model. TREES is a bottom-up engineering model based on the time use schedule of building occupants and a heating/cooling load calculation model, making it possible to reproduce the electricity load curve and fuel consumption, and to seamlessly evaluate various levels of mitigation measures such as human behavioural changes, improved appliance efficiency, and the enhancement of building efficiency. TREES has previously been used to evaluate the Japanese PGWC up to 2030 (Taniguchi-Matsuoka et al. 2020), carbon neutrality in 2050 (Shimoda et al. 2021), summer peak demand reduction potential (Taniguchi et al. 2016) and the effect of telecommuting on energy demand (Shimoda et al. 2007).

As shown in Figure 2, the TREES model consists of various data preparation models and an end-use energy model. In this study, 16,000 (0.03 %) of Japan's 53 million households were randomly selected as representative households. Household attributes were randomly assigned to each representative household according to the census. The input data for the simulation were determined from statistics, as described in the "Use of individual statistical data" section. The attributes used in the simulation included the number of occupants in the household, household income, and the age, gender, and employment/ school type of each family member, together with the construction period for the building, floor area, and type of building (apartment or detached house). Distribution of insulation level of buildings is determined from share of insulation level for each construction period.

NON-RESIDENTIAL ENERGY END-USE SIMULATION MODEL

The energy model for non-residential building stock uses an approach similar to the TREES model, as shown in Figure 3. The model consists of thousands of reference building models that represent a building stock segment, classified by weather condition, building business category and size, insulation performance, system configuration for space heating and cooling and water heating, and energy conservation measures. The reference building models were used to conduct an EnergyPlus simulation that would allow a quantification of energy use

Table 1. Countermeasures for the residential sector listed in the Long-term Energy Supply and Demand Outlook (LESDO) formulated in 2015.

Countermeasures		2013	2030	Estimated Energy Demand Reduction [PJ]		
				Total	Electricity	Fuel
Energy saving standards for newly built houses		6%*	30%*	121.8	30.5	91.3
Insulation retrofitting of existing houses				16.5	4.3	12.2
Installation of high-efficiency water heaters [units]	Electric HP water heater	4,220,000	14,000,000	104.1	-10.2	114.3
	Condensing gas/oil water heater	4,480,000	27,000,000			
	Fuel cell cogeneration	55,000	5,300,000			
Installation of high-efficiency lighting devices		9%	Approximately 100%	77.9	77.9	0.0
Improvement in appliance energy efficiency by the top-runner Standard		–	–	51.7	40.6	11.1
Energy management by HEMS and smart meters		0.2%	Approximately 100%	69.1	69.1	0.0
Efforts by citizens (Cool Biz/Warm Biz [1 °C relaxation of set temperature] , promotion of appliance replacement, home energy auditing)		–	–	8.7	4.1	4.5
Total				449.8	216.4	238.5

** These values indicate the percentage of houses that meet the latest energy efficiency standard relative to the total housing stock.*

Table 2. Progress evaluation by national energy statistics.

		2013	2019	2030 Target (2016 version of PGWC)
CO$_2$ emission [10^6t-CO$_2$]	Residential	208	159	122
	Non-residential	238	192	168
End-use energy consumption* [PJ]	Residential	1919	1668	1402
	Non-residential	2395	2239	2064

**Electricity consumption is converted by 1kWh=3600kJ*

Table 3. Progress evaluation by progress of countermeasures. The percentage shows the ratio of the estimated energy demand reduction of each countermeasure.

	Residential	Non-Residential
A: Measures that have already achieved the 2030 target	24%	0%
B: Measures progressing at a pace that exceeds the target.	0%	25%
C: Measures progressing at the target pace	32%	23%
D: Measures behind the target	43%	51%
Estimated progress of energy demand reduction (ratio to target)	138PJ (30.8%)	160PJ (33.7%)

intensity (EUI) per floor area. Total energy consumption was quantified by summing the products of the EUI and total floor area for all the building stock segments. The model covers the Japanese office, hotel, medical, retail and school building stock and is validated in Yamaguchi et al. (2022). The model's most notable feature is that a probabilistic method is employed to consider the heterogeneity and time series change in the composition of building stock in terms of adopted technologies for building insulation, lighting, heating, ventilating, and air-conditioning (HVAC) systems. The model was updated to consider the yearly change in building stock in order to quantify the yearly change in CO$_2$ emissions.

USE OF INDIVIDUAL STATISTICAL DATA

The results of large-scale official surveys provided individual statistical data for our bottom-up simulation, which enabled us to reproduce the heterogeneity of actual household energy use. For Japan's residential sector, the Survey on Carbon Dioxide Emissions from Residential Sector (Household CO_2 Statistics), published annually by the Ministry of the Environment, was used extensively. The survey targets 13,000 Japanese households (0.026 % of all Japanese households) and gathers information not only on energy consumption but also on the presence and patterns of use of appliances in the home. We had earlier developed a multinominal logistic regression model which predicts the appliance possession status from household appliances (Matoba et al. 2020).

Statistical data were also used to validate our simulation results. Figure 4 shows a comparison of the annual energy consumption per household estimated by our TREES simulation and the estimates reported in the 2015 Household CO_2 Statistics. The comparison shows that the simulation accurately reproduced the differences in energy consumption among regions and according to family size. The simulated gas and oil consumption estimates are both less than the corresponding statistic values especially in cold region or large family and the difference in the electricity consumption between the simulation results and statistics is small. Although there are some underestimates in heating and hot water fuel consumption, the simulation model was able to rather accurately represent the current residential energy consumption situation in Japan.

For non-residential buildings, there are no comprehensive government statistics available. However, the Japan Sustainable Building Consortium (2020) publishes its Database for the Energy Consumption of Commercial Buildings (DECC), which provides data on the energy consumption, building use, and building size for 44,000 buildings. Using this database, results of non-residential model were validated for each building use and scale (Yamaguchi et al. 2022).

USE OF SMART METER DATA

Smart meters measure and record the electricity consumption of individual houses/buildings at 30-minute intervals. With a sufficient amount of data, collected over several years, such data can play two important roles in the proposed energy and carbon management system:

- The data make it possible to analyse not only changes in total power consumption, but it will also be possible to determine which electrical appliances have experienced changes in energy use. Since the operation times and electricity consumption of each appliance are different, we should be able to estimate the cause of any secular change in the smart meter data by using the simulation to calculate the effect on the load curve when the efficiency of each appliance is improved.
- The data can also be used to validate and calibrate the simulation model. In fact, we have previously used smart meter data to correct the bedtime and waking hours of occupants used in the TREES simulation model (Kurokawa et al., 2021).

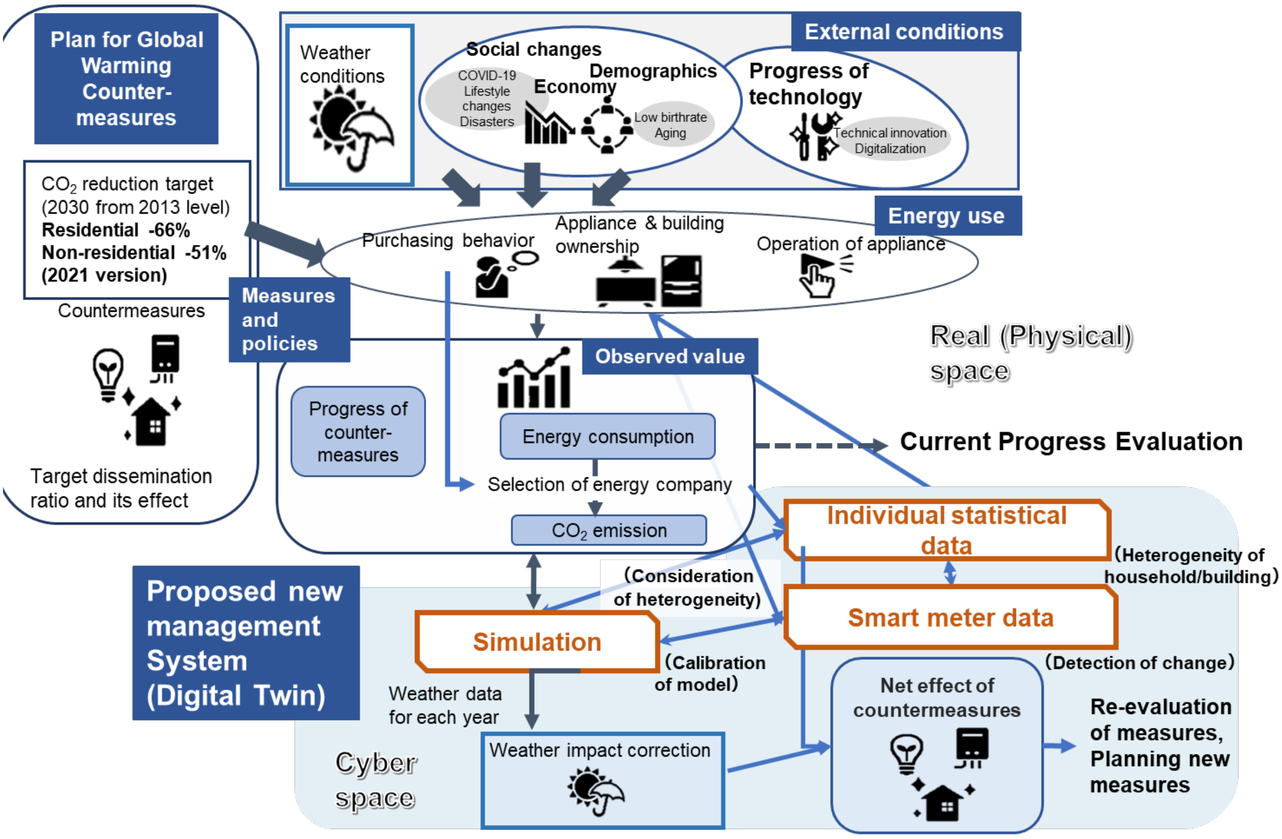

Figure 1. Overview of proposed energy and carbon management system.

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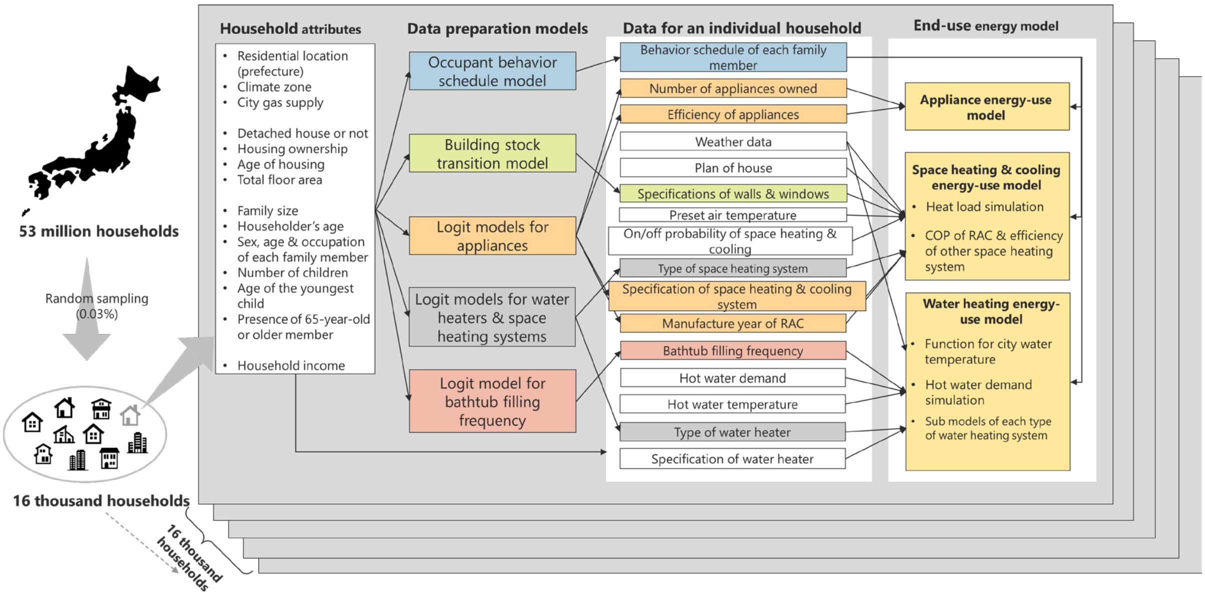
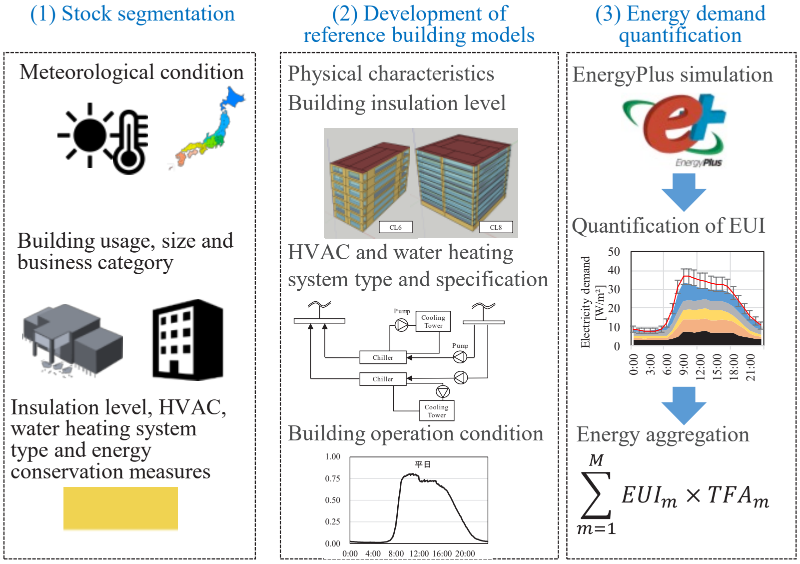


Figure 2. Procedure of the TREES simulation model.



$$\sum_{m=1}^{M} EUI_m \times TFA_m$$

Figure 3. Overview of the model for the Japanese commercial building stock.

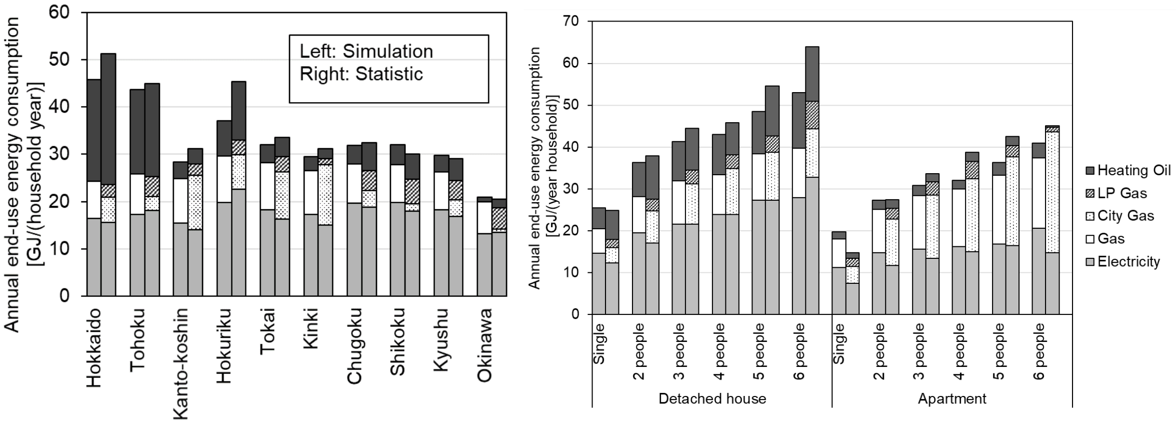


Figure 4. Comparison of annual energy consumption per household (left: by region; right: by family size).

Evaluation on progress of Plan for Global Warming Countermeasure

In this section, the results of our evaluation of the progress of the PGWC for the Japanese residential and non-residential sectors using the end-use energy simulation model are presented. While CO_2 emissions and energy consumption in the residential and non-residential sectors steadily decreased over the period from 2013 to 2019, it is speculated that the annual changes include the effects of weather conditions. Therefore, the weather conditions for each year were input into the end-use demand model, and the progress of the major energy efficiency measures, together with their effects, was quantitatively evaluated.

RESIDENTIAL SECTOR

Table 4 shows the progress of the energy efficiency measures considered in the simulation for the residential sector. In this simulation, the energy efficiency of the various appliances was calculated from our stock transition model, which estimates the average energy efficiency each year from the estimated shipment rate for that year. (Shimoda et al. 2010, Shimoda et al. 2021) The change in the energy consumption of refrigerators is shown in Figure 5 as an example of the input condition. Since test procedure for energy efficiency of refrigerator was revised in 2006 and 2015, energy efficiency before revision is modified to connect seamlessly with the revised data. The difference in energy consumption depending on capacity is small in recent refrigerators.

Figure 6 shows the simulated annual end-use energy consumption of the Japanese residential sector from 2013 to 2019. As suggested in the figure, the simulation values are 17–20 % lower than the national statistics; however, the trends in year-to-year fluctuations are in good agreement. It is considered that the difference between simulated value and statistics include not only the error of the simulation but also the error of the statistical value. Therefore, in the following, comparison is made based on the deviation from the 2013 value. Figure 7 shows the simulated reductions in energy consumption for the various energy efficiency measures and the differences in weather

Table 4. Progress of the energy efficiency measures considered in the simulation of the residential sector.

		2013	2019	Source
Manufacture year (Ratio of appliance manufactured after 2011)	TV	31%	48%	Household CO_2 Statistics
	Refrigerator	26%	47%	
High efficiency lighting devices (LED) [unit]		0	330 million	Government estimate (submitted to the council)
High efficiency water heaters [unit]	Heat Pump	4,220,000	6,920,000	
	Condensing water heater	4,480,000	10,510,000	
	Fuel cell	72,000	310,000	
Ratio of houses that meet the latest energy efficiency standard to the total housing stock		7%	13%	Estimation by the authors

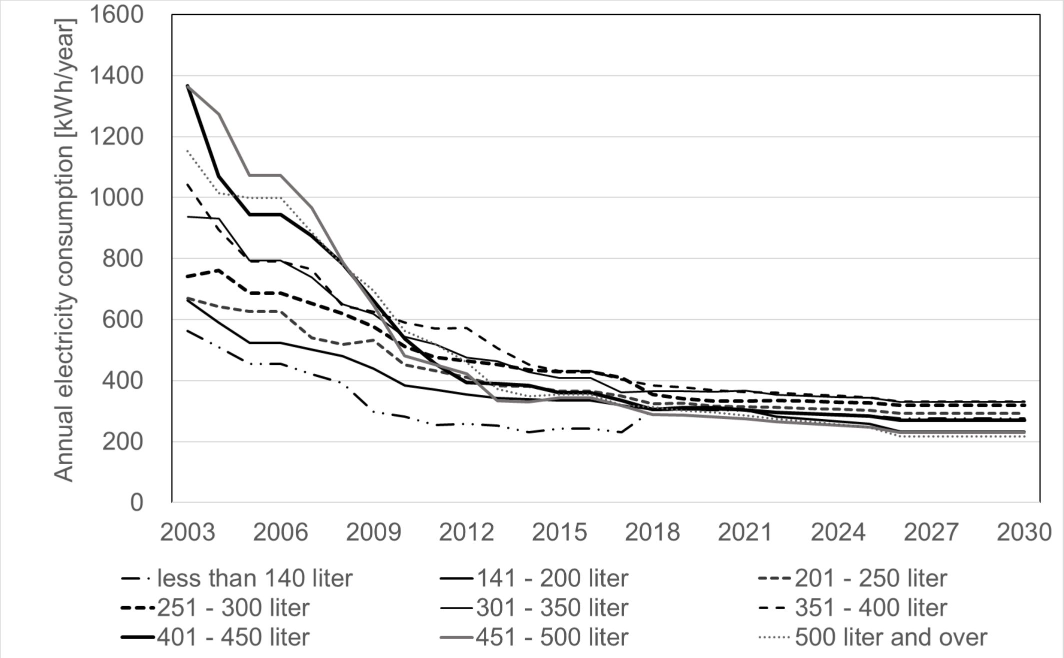


Figure 5. Change in energy consumption of Japanese refrigerators.

conditions from 2013. The effects of the yearly differences in weather conditions were evaluated as follows:

In the TREES model, the weather data were given for each of the 47 prefectures. The effect on energy consumption in year *i* due to the difference in weather from 2013 is calculated according to the equation

$$\Delta_i = X_{i,i} - X_{i,2013}$$

where $X_{i,i}$ is the simulated energy consumption under the energy efficiency and weather conditions in year *i,* and $X_{i,2013}$ is the simulation result calculated from the progression of the energy efficiency measures in year *i* and the weather data in 2013.

Somewhat surprisingly, in terms of reductions, the simulation results and the statistics are in good agreement for most years, demonstrating the considerable accuracy of the simulation model (Figure 7). However, the difference is quite large in 2017, a year in which the winter was unusually cold. Taking this together with the results shown in Figure 4, it would appear that the simulation model for heating energy use needs to be improved. A breakdown of the reduction amounts suggests that the influence of weather condition is substantial, reaching 50 % in 2018 and 37 % in 2019. Looking at the factors behind the changes in 2019, heating energy use decreased by 100 PJ and hot water energy use decreased by 14 PJ, primarily due to the warm winter. On the other hand, cooling energy use increased by 36 PJ due to the extreme heat. Regarding the effect of the government's energy efficiency measures, which means the sum of "Hot water", "Heating and cooling", "Lighting", "TV" and "Refrigerator" in Figure 7, our results show 129.8 PJ, which is less than the government estimate of 136.4 PJ. The major reason for this difference is that the TREES simulation considers the usage time of home appliances in greater detail (Taniguchi-Matsuoka et al, 2020). In the simulation, the energy efficiency of appliances other than TVs and refrigerators, HEMS, and the efforts by citizens, among the government energy efficiency measures shown in Table 1, are not considered, as it is considered that there would be no significant impact. The estimated effect of the government's efficiency measures is well below its 2019 target of 172 PJ, and it is clear that the government PGWC is not progressing as planned.

NON-RESIDENTIAL SECTOR

The results of similar simulations for the non-residential sector are shown in Figure 8. Since the "commercial industry" sector of Japanese energy statistics contains non-building energy use such as water supply, sewage treatment and waste treatment, and our simulation model does not consider some kinds of building such as restaurant, datacentre and communication facilities at present, we compare simulation results with the "government estimation" which calculated as product of the amount of dissemination and the effect per unit.

Figure 8 gives the end-use energy reduction achieved by the various measures, including

- Replacement of lighting devices by LEDs,
- Improvement in appliance energy efficiency,
- Improvement in building energy efficiency by adoption of envelope insulation, energy conservation measures, change in the selection of HVAC systems and improvement in heat source efficiency,
- Improvement in building operation indicated by "BEMS" (building energy management system), and
- Dissemination of advanced water heating systems.

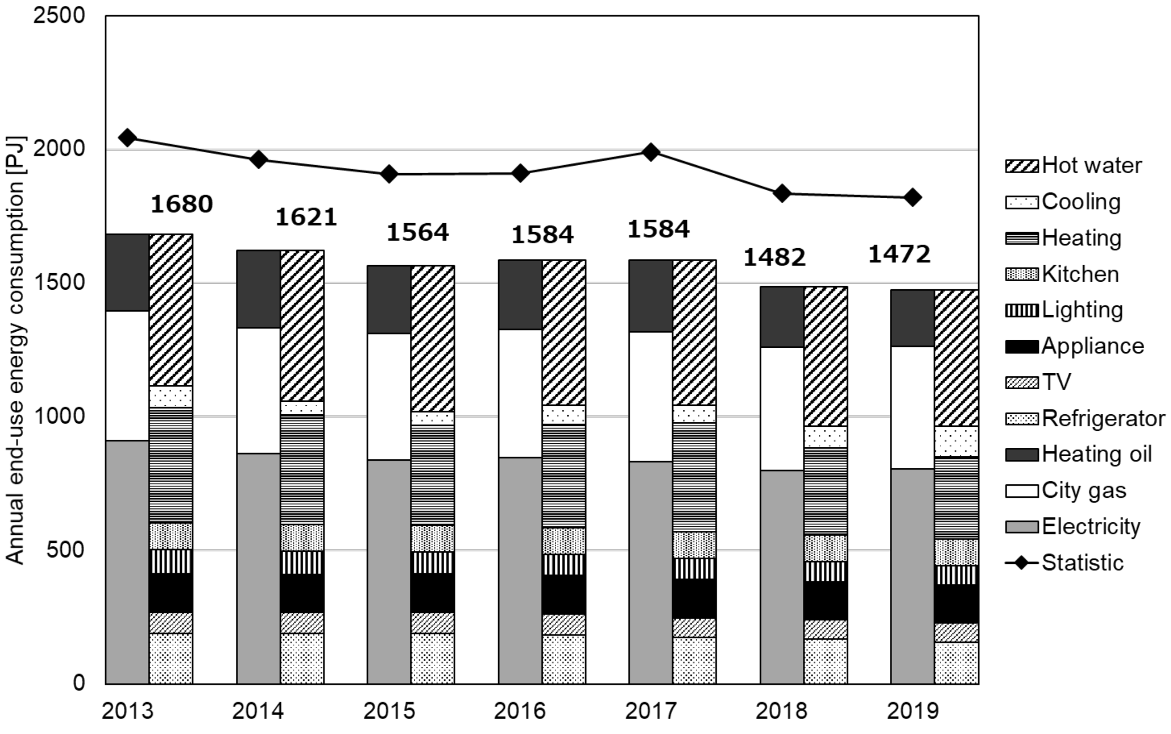


Figure 6. Simulated annual end-use energy consumption of the Japanese residential sector from 2013 to 2019.

The model estimates here do not include estimates for water heating. The model estimates do include the difference in energy consumption due to differences in weather conditions from the year 2013, shown as "Weather condition." The government's reduction in 2019 for building efficiency is not included since it is not quantified in the government report. "Others" in the simulation indicates the increase due to the increase in the total floor area of non-residential building stock.

Since heating is dominant in the residential sector, the effect of weather differences is large, whereas in the non-residential sector, where cooling is dominant, the effect of weather differences ("Weather condition") is relatively small. One of the reasons that the influence of high-efficiency lighting ("LED") is small in the simulation is that the increase in heating energy due to the decrease in internal heat gain is taken into consideration in the simulation. Similar to the residential sector, the results of the progress assessment by the simulation show that the government assessment is overstated. In 2018, influence of weather difference is 20 %, and the simulation results of reductions for LED, appliance and buildings is 22 % smaller than the

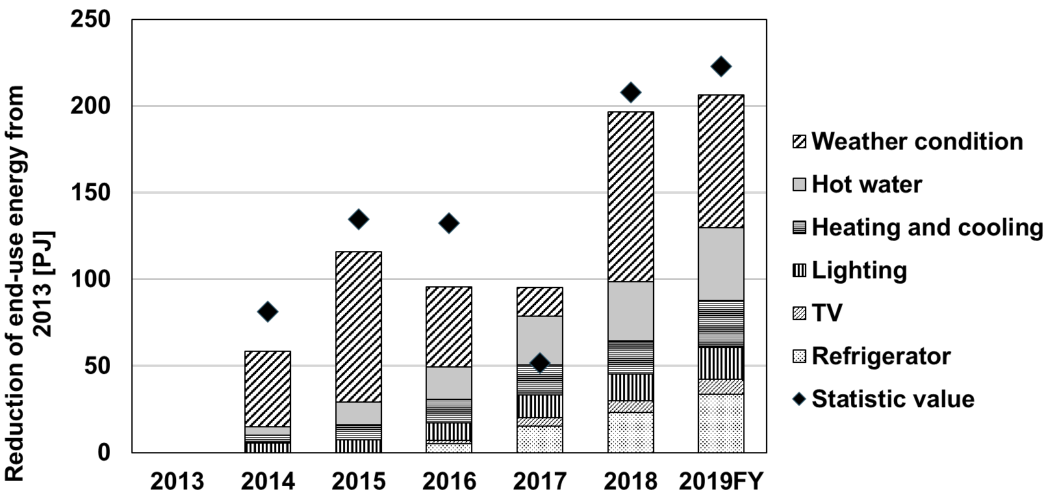


Figure 7. Simulated reduction of energy consumption by energy efficiency measures and differences in weather conditions from 2013.

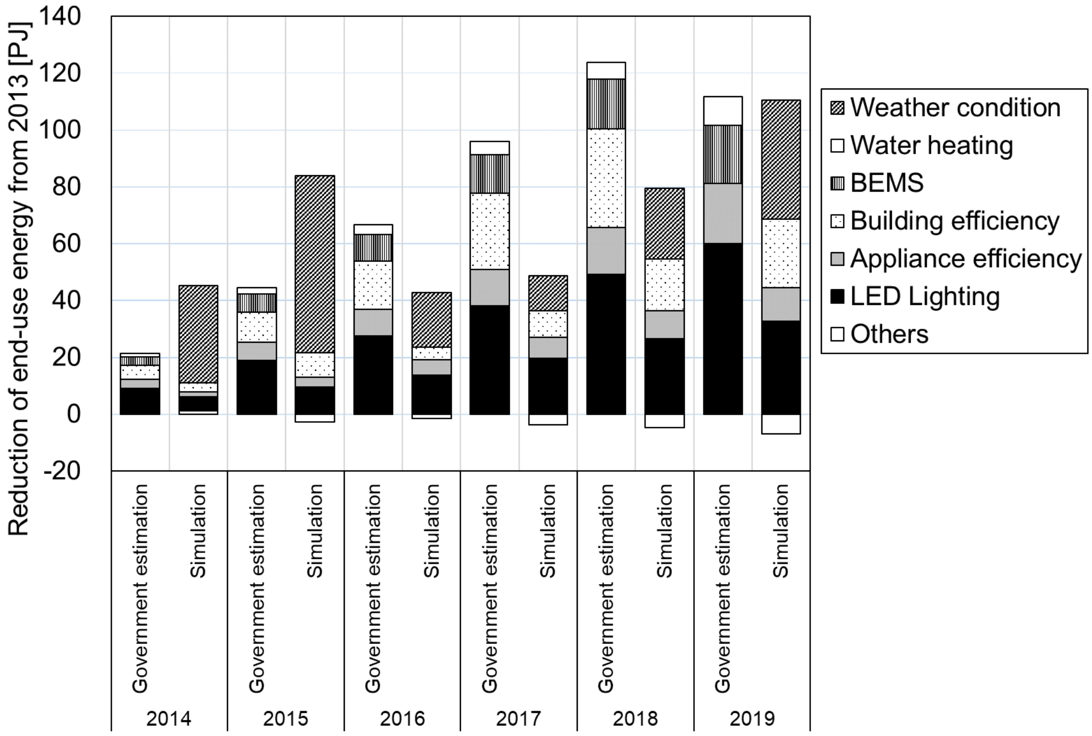


Figure 8. Composition of reduction made by the considered measures and that due to the difference in weather conditions. "Government estimation" indicates the reduction given in the government's report (product of the amount of dissemination and the effect per unit); "Simulation" indicates the model estimates.

government estimates. However, this lower reduction effect of the technical measures is attributed to that the model only covers the building stocks of office, hotel, medical, retail and school, that stock emitted 62 % of CO_2 emission of the non-residential building sector in the year 2013 (238 $MtCO_2$/year). Considering the cover ratio, the reductions in lighting and appliances are comparable between the government estimation and the simulation result. Note that we assumed that the energy efficiency of all plug-load appliances has been improved, whereas the government estimation only covers those regulated in the Japanese energy efficiency code for appliances. The sum of the reductions for building efficiency and BEMS quantifies the reduction obtained by the improvement in building energy efficiency. The government estimation is much larger than the simulation result, though the simulation did not consider the efficiency improvement due to BEMS explicitly. This may be due to an overestimate in the government estimation. In the government estimation, the reduction in building efficiency is estimated by the product between unit reduction per floor area of newly constructed and renovated buildings. The unit reduction may double-count the reduction obtained by installing LED. The reduction of BEMS is estimated by the product between the unit reduction per installation and the number of installations. The uncertainty in these numbers is high. Thus, the progress should be critically reviewed.

Conclusions

In this paper, a new energy and carbon management system for municipal and national building sectors is proposed. This system is a so-called "digital twin model," which reproduces in cyberspace the actual energy consumption occurring in the real world. The model consists of 1) a bottom-up, end-use energy simulation model that replicates the energy demand mechanism for a city or a country, 2) individual statistical data that explain the relationships between household/building characteristics and the energy consumption, appliance ownership status and energy-saving behavior of building occupants in order to consider the heterogeneity of households/buildings, and 3) smart meter data that can be used to analyse the energy efficiency progress of households and buildings. These three components, either individually or in combination, can provide valuable information for assessing the present situation of energy consumption and CO_2 emissions and for evaluating the progress of various energy efficiency measures.

As an illustrative example, the progress of the Japanese PGWC and LESDO for Japan's residential and non-residential sectors is assessed using the proposed end-use energy simulation models. The results are as follows:

- In the residential sector, the impact of differences in weather conditions is substantial, reaching 50 % in one case. Most of this is due to changes in heating energy use. In contrast to the residential sector, the effect of weather differences in the non-residential sector is relatively small.
- The effect of the government's energy efficiency measures as estimated by the simulation is smaller than the effect estimated by the government in both the residential and non-residential sectors, and it is much smaller than the government's 2019 target.

As mentioned above, we succeed to evaluate the progress of Japanese energy efficiency measures with high accuracy by considering heterogeneity of households/buildings and change of weather condition. However, further improvement in accuracy is required; for example, fuel consumption in residential sector.

In this paper, we focused the evaluation of national energy efficiency policy. To apply similar management system to cities, difficulty of municipalities to obtain accurate statistics on energy consumption of city is one of the major barriers. It is required to conduct intensive questionnaire surveys such as Household CO_2 statistics and to develop simulation model which reflect the characteristics of the city.

In the next phase of our study, we will continue to collect individual statistical data and available smart meter data, explore further possibilities for the proposed management system, and use our work as a tool for developing new energy efficiency measures.

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