Evaluation of the feasibility of distributed energy supply system for existing multi-family housing in Nagoya City

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ABSTRACT

The Japanese government is promoting a distributed energy system to realize not only energy-saving but also an energy supply and demand structure renovation by the demand side in the basic energy plan. In terms of the distributed energy system, there are many district heating and cooling (DHC) system combining heat and power generation (CHP) and renewable energy sources for communities and large-scale buildings.

In this paper, the possibility of introducing distributed energy system consisting of CHP for existing multi-family housing is discussed in order to make an academic ground for calling for the spread of distributed energy systems in existing multi-family houses.

Case study was conducted to evaluate energy-saving effect of the distributed energy supply system and obtain the findings concerning on its feasibility. The case study was focusing on all municipal multi-family housing in Nagoya city, Japan, and it was evaluated based on primary energy consumption reduction, CO_2 emission reduction, simple pay-back period, and recurring expenses merit by introducing the system.

Annual energy consumption was estimated for nine typical municipal multi-family houses with different average occupied floor area and number of dwelling for each individual building. Based on the results of the case study, it was found that the effect of the distributed system varies depending on the average occupied floor area and the number of residences, and the generator capacity of CHP.

In addition, when assuming adapting a distributed energy supply system into a type of housing has occupied floor area of $30m^2$-$50m^2$ per a dwelling that accounts for 83.5% of the total municipal housing in Nagoya, at least the overall reduction of 16.7% CO_2 emission reduction rate could be expected.

KEYWORDS

CHP, Distributed Energy System, Heat pump, Multi-family house, Feasibility

INTRODUCTION

Multi-family houses owned by Nagoya City (2017) were built during the 1950s and 1960s, and 17% of the buildings were over 40 years old by 2010. In addition, Nagoya City (2011) launched the "Low Carbon Nagoya City Strategy Implementation Plan" in December 2011, which sets the goal of reducing greenhouse gas emissions by 25%

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from 1990 levels and by 15% from 2008 levels by 2020. The final reduction goal is 80% from 1990 levels by 2050.

As environmental efforts like this continue to grow, the buildings continue to get older. Thus, the motivations for refurbishing such buildings for longer service life is also growing, in terms of the financial situation.

After the Great Eastern Japan Earthquake of 2011, Japan's electric power supply and demand structure faced a major turning point. Before the earthquake disaster, the energy supply chain was dominated by the electric power companies, which met most of the electric power demand, but the disaster revealed the vulnerability of this supply chain.

Over the past few years, consumers on the demand side, who previously were only purchasers of energy, have joined the energy supply chain, so that they can supply energy for themselves through the use of distributed energy systems (METI 2014).

Therefore, in this paper, a distributed energy supply system using a combined heat and power system (CHP) is discussed. Regarding the target building for a CHP system, we focused on existing multi-family houses, especially the municipal housing in Nagoya City, because of the relatively high energy density and ease of infrastructure repair. To grasp the current state of all municipal housing in Nagoya City upon introduction of the system, 1,361 municipal housing units were investigated, as described in Refs. (Nagoya City 2017) and (Nagoya City) and were considered as subjects of this research.

As shown in Table 1, we classified housing units A to I into nine categories based on the number of households and the average occupied floor area of each household. Fig. 1 shows the breakdown of the number of housing units in each category. Of the 1,361 municipal housing units, the buildings classified as categories D, E, and F comprise about 83.5% of the total, which shows that most buildings have 50–80 m^2 of average occupied floor area per household.

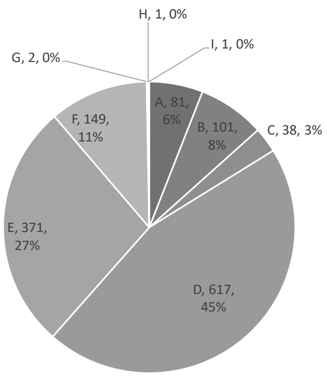


Figure 1. *Number of housing units in each category*

Table 1. *Number of households and average occupied floor area in each category*

Floor area per household / Number of households	Under 50m^2 (small)	50-80m^2 (middle)	80-120m^2 (large)
1-38 (little)	A	D	G
39-75 (middle)	B	E	H
76 even or more (many)	C	F	I

Table 2. *Outline of representative housing units*

Floor area per household / Number of households	Under 50m^2 (small)	50-80m^2 (middle)	80-120m^2 (large)
1-38 (little)	A unit 35 houses, 42.9 m^2	D unit 35 houses, 57.3 m^2	G unit 25 houses, 81.5 m^2
39-75 (middle)	B unit 63 houses, 41.2 m^2	E unit 63 houses, 67.0 m^2	H unit 63 houses, 82.2 m^2
76 even or more (many)	C unit 117houses, 45.0 m^2	F unit 117houses, 59.5 m^2	I unit 76 houses, 81.8 m^2

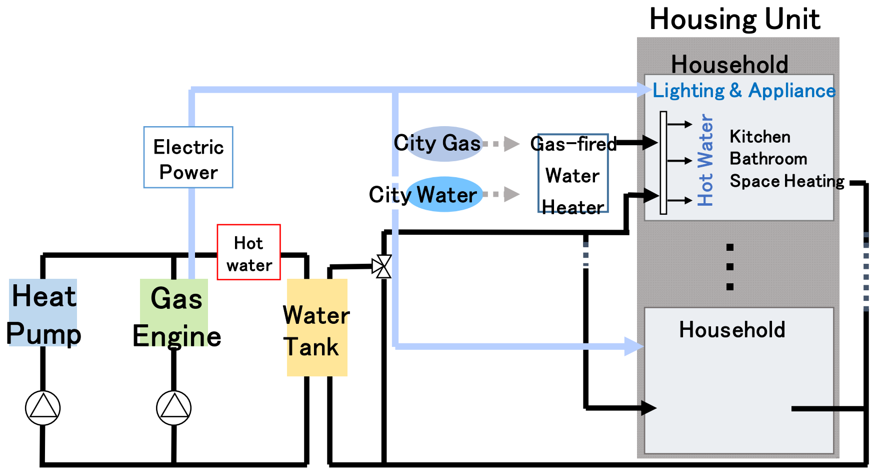


Figure 2. *Diagram of proposed system*

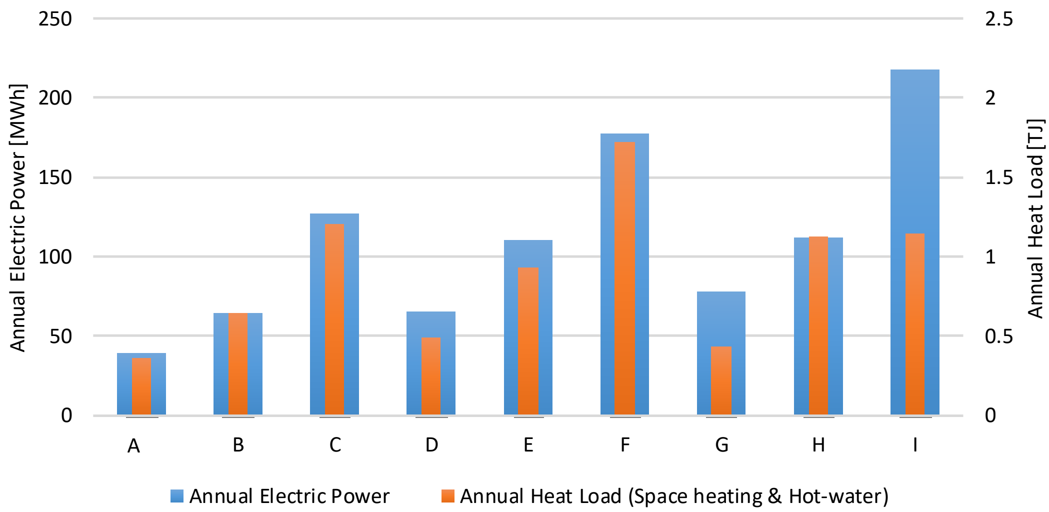


Figure 3. *Annual thermal and electric power loads of each representative building*

A representative building was extracted from each of the nine categories and examined. We clarified the effect of introduction of a distributed energy supply system through economic and environmental evaluation and considered a method for quantitatively estimating the effect.

RESEARCH OUTLINE

Distributed Energy Supply System Overview

Fig. 2 shows a diagram of the distributed energy supply system that is discussed in this paper. The distributed energy supply system consists of an electric generator using city gas as fuel (a micro gas engine was adopted in this study), an air-source heat pump, steam boiler and a hot-water storage tank. The heat pump, steam boiler and water tank are installed as a backup heat source and to stabilize equipment operation. The system provides electric power to each household and common space lighting and provides every household thermal energy for heating and hot water.

The electric power for common equipment, such as elevators and water and sewage pumps, is supplied from the commercial power grid. In addition, each household possesses a gas-fired water heater and fan heater and can be self-sufficient with regard to hot water and space heating.

The system is designed to be installed on the rooftop of the housing unit or on the ground near the parking lot or bicycle parking when there is not enough space for rooftop installation.

For this study, representative housing units were extracted from each category and used for case studies. Table 2 shows the nine representative housing units in this case study. First, we estimated electricity demand, heating load, and hot-water supply load for nine representative housing units. Fig. 3 shows annual electric power demand and thermal demand for each representative housing unit. The power demand and heat demand of each housing unit were created using hourly data for every month (JIE 2008).

The floor area of each housing unit was divided into residences and common space, and the primary energy consumption of the residential portion was determined from reference (MRI 2013). The annual primary energy consumption indexes were set by 20.5 GJ per household has floor area under 50m^2, set by 29.4 GJ and 35.6 GJ respectively for household has floor area of 50-80m^2 and 80-120m^2. Regarding the common space, the primary energy consumption for each season was created using the raw data from housing unit K and reference (Yuasa et al 2009).

Case Study Overview

Simulations were conducted using the power and heat demand of the representative housing units described above. CASCADE III was used to evaluate energy savings, CO_2 emissions reduction, and cost performance.

Five different capacities of micro-gas engine were used, corresponding to generator outputs of 5 kW, 9.9 kW, 25 kW, 30 kW, and 35 kW in accordance with the manufacturer’s product lineup (YANMA 2018). The generator operation tracked the thermal heat load of the housing unit to utilize all exhaust (waste) heat from the generator. The waste heat was used first for water heating and then for space heating.

Table 3. *Operational efficiency of reference systems*

Equipment	Rated COP (-)
Gas-fired fan heater	0.8
Gas-fired water heater	0.8

Table 4. *Volume of hot-water tank based on gas engine capacity*

Capacity of gas engine (kW)	Volume of hot-water tank (m^3)
5	1.5
9.9	2.5
25	5.0
30	6.5
35	7.5

Table 5. *Increase in initial cost for housing unit A*

Unit A	Capacity of gas engine(kW)				
	5	9.9	25	30	35
Cost of Gas engine (10^4yen)	244	390	815	1030	1030
Cost of hot-water tank(10^4yen)	125	165	270	380	450
Cost of heat pump (10^4yen)	17.8	13.6	-	-	-
Cost of Pipe work (10^4yen)	234	234	234	234	234
Total cost (10^4yen)	621	803	1319	1644	1714
(10^4yen per kW)	124.2	81.1	52.8	54.8	49.0

Table 6. *Increase in initial cost for all categories*

Unit	Capacity of gas engine(kW)				
	5	9.9	25	30	35
A	124.2	81.1	52.8	54.8	49.0
B	165.4	102.2	61.1	61.3	54.5
C	258.0	149.1	79.2	75.9	67.0
D	136.6	87.4	55.2	56.9	50.7
E	211.6	123.0	69.5	68.3	60.4
F	279.2	159.8	83.4	80.3	70.3
G	139.4	88.7	55.8	57.3	51.1
H	208.0	123.8	69.1	68.0	60.3
I	268.6	154.4	81.3	78.5	69.1

As mentioned above, the backup heat source is a gas-driven air source heat pump and steam boiler. The rated coefficients of performance (COPs) of these heating units are 2.98 and 0.8, respectively.

Table 3 shows the rated COP of the reference system, which is a conventional system in which every household in a housing unit has a gas-fired fan heater for space heating and gas-fired water heater for hot water. Table 4 shows the volume of the hot-water tank corresponding to the capacity of the gas engine generators. The number of hot-water storage tanks (SEKISUI Co. 2018) was set to 1, and the volume was determined by assuming that an effective hot-water storage amount is 0.7 (SHASE.J 2010).

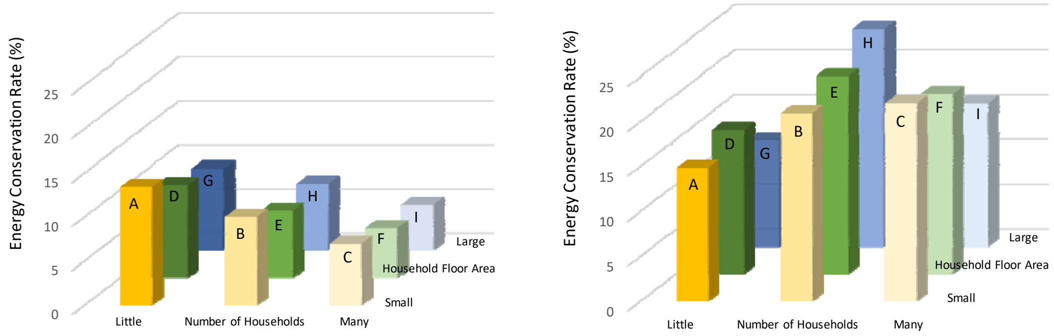
Table 5 shows the increase in facility cost for housing unit A. The cost consists of the initial cost of the micro gas engine, hot-water tank, and heat pump and the construction cost of the plumbing to connect them (Zen-nichi 2016).

Table 6 shows the total cost increase for each of the nine representative housing units.

RESULTS AND DISCUSSION

Fig. 4 shows the energy conservation rate achieved by introducing gas engines of different capacities from 5 kW to 35 kW in the nine representative housing units. It was found that the energy conservation rate is influenced by the capacity of the gas engine; the housing unit expected the largest energy conservation rate is changed according to gas engine capacity.

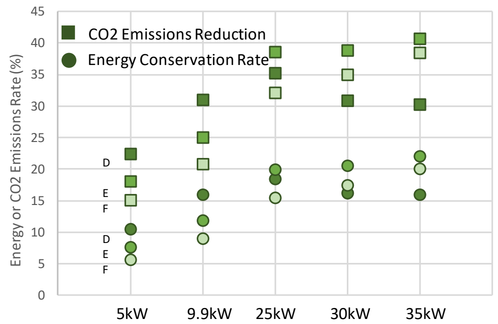
Also, focusing on housing unit H, the energy conservation rate in case of a 5-kW generator becomes smaller than the other cases because of the small capacity of the gas-fueled generator, but in the case of a 35-kW generator, the rate increased because the larger generator could offer its housing unit much more waste heat than could the 5-kW generator.



(a) Case with gas engine capacity of 5 kW (Left hand)

(b) Case with gas engine capacity of 35 kW (Right hand)

Figure 4. *Comparison of energy conservation rate in nine representative buildings*



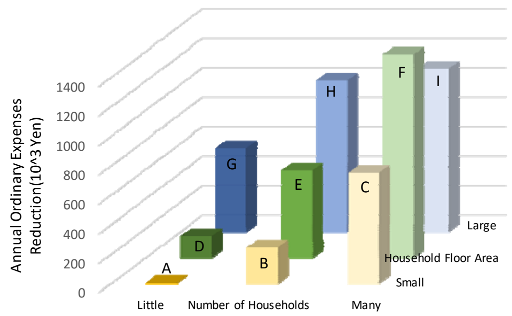


Figure 5. *Energy conservation rate and CO_2 emissions reduction for housing units D, E, and F (Left hand)*

Figure 6. *Reduction of ordinary expenses for 5-kW gas engine capacity (Right hand)*

In the case shown in Fig. 4(a), the number of households per housing unit is small, and the energy conservation rate is larger in the region where the average household occupied floor area is small.

This is thought to be due to the fact that the energy conservation rate increases when the gas engine capacity is as small as 5 kW but the heat demand is also small.

In contrast, in the case shown in Fig. 4(b), housing unit H has the largest energy conservation rate, and it shows a tendency different from the case with a gas engine capacity of 5 kW. This is considered to be due to the balance of waste heat from gas engine against the thermal demand. Consequently, the operation time of the introduced system could be relatively long, then it could reduce the operation time of auxiliary heat system.

Fig. 5 shows the energy conservation rate and the CO_2 emissions reduction rate according to the different gas engine capacities for housing units D, E, and F. Here, it was found that a CO_2 emissions reduction of 16.7% can be expected in Nagoya City as a whole if the proposed system with 5-kW generators is introduced in the 1,137 buildings belonging to categories D, E, and F. These account for about 83.5% of the total number of housing units in Nagoya City. Fig. 6 shows the reduction of ordinary expenses of the nine representative housing units for the introduction of the system with a gas engine capacity of 5 kW. For the same average occupied household floor

area, the expense reduction is greater for a larger number of households per housing unit. This tendency was the same even if the generator capacity is changed.
In addition, compared with Fig. 4(a) focusing on a housing unit A, it is considered that the energy conservation rate is high, but the ordinary expense reduction is small because the gas engine capacity is larger than the thermal demand of the housing unit.

Fig. 7 shows the reduction of ordinary expenses by introducing gas engines with different capacities in housing units D, E, and F. It can be seen that the smaller the gas engine capacity is, the larger the ordinary expense reduction is. It also can be seen that the ordinary expense reduction can be a negative value when the annual thermal demand of a housing unit is relatively small against the introduced gas engine capacity.

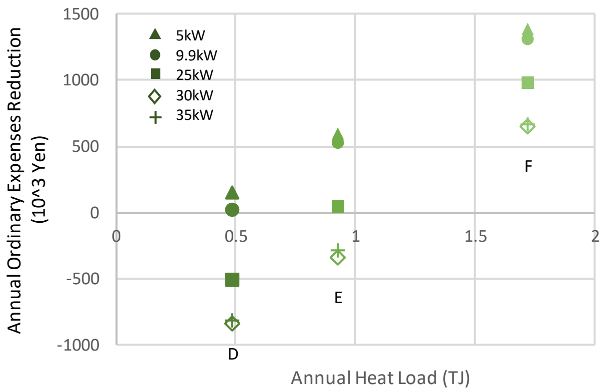


Figure 7. *Reduction of ordinary expenses according to annual thermal load*

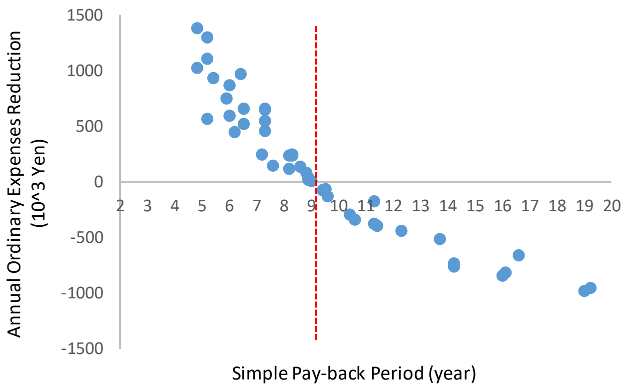


Figure 8. *Reduction of ordinary expenses according to simple pay-back period*

Figure 8 shows the simple pay-back period according to the reduction of ordinary expenses. In most cases, the ordinary expense reduction turns negative after a 9-year pay-back period. However, the simple pay-back period is 9 years less for the case of a small gas engine capacity (5 kW and 9.9 kW) for housing units E through I.
Table 7 shows the predicted expressions created by multiple regression analysis for the four evaluation indexes of system introduction effect used in this study. Regarding the coefficient of determination, the prediction formula for the simple pay-back period and the ordinary expenses reduction is relatively reliable, and it can be said that the estimated effects of introducing the proposed system are reliable.

Table 7. Estimation formula using multiple regression analysis

Purpose variable	Estimation formula	Coeff. of determination
Simple pay-back period (yr)	$Y=-0.13X_1-0.70X_2+0.19X_3+18.37$	0.89
Ordinary expenses (10^3yen/yr)	$Y=20.05X_1+13.0X_2-32.62X_3-1275.21$	0.98
CO2 emissions reduction rate (%)	$Y=-0.15X_1-0.009X_2+0.5X_3+29.73$	0.53
Energy conservation rate (%)	$Y=-0.07X_1-0.01X_2+0.32X_3+13.79$	0.59

CONCLUSION

Surveys and examination for all the municipal housing units in Nagoya City showed that 83.5% of the total occupancy comprises residences with an average occupied floor area of 50–80 m^2 in each building. It was found that a total CO_2 emission reduction rate of at least 16.7% could be expected if a distributed energy supply system was introduced into these housing units.

It was also clear that ordinary expenses would increase for housing units with a large number of households and a large average occupied floor area. The ordinary expenses would be negative for the cases under 9 years.

Finally, a prediction formula for estimating the effect of energy system introduction was presented for the ordinary expenses reduction and simple pay-back period.

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