ANALYSIS OF ENERGY SYSTEMS SUPPLYING HOT WATER AND ELECTRICITY FOR RESIDENTIAL USE

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Abstract: The optimal operation planning of energy supply systems to meet domestic hot water and electricity demands is analyzed, including CO_2 heat pump systems, gas engine co-generation systems, and polymer electrolyte membrane fuel cell (PEFC) co-generation systems. Projected demands were taken from data measured in the Kansai area in Japan, over one year, with a sampling period of 30 minutes. The objective function of the optimization is the minimization of primary energy consumption. The optimal operation of the PEFC and gas engine based co-generation systems, and that of the CO_2 heat pump system are compared with that of a reference system consisting of a condensing gas boiler and grid electricity. The primary energy consumption ratios and CO_2 emission ratios between the systems and the reference system are compared. The results show that the CO_2 heat pump system is superior to the other co-generation systems in minimizing both primary energy consumption and CO_2 emissions.

Key words: Energy Supply System, Residential Energy, Energy Saving, CO_2 Emission, Optimal Operation

1 INTRODUCTION

The paper presents a comparative analysis on primary energy consumption (P^{ene}) and CO_2 emission ($CO2$) from residential energy supply systems in order to assist rational selection for users. In Japan, domestic hot water demand accounts for 35 % of the total energy demand for residential use (Jyukankyo Research Institute Inc. 2009). Reducing the energy used for heating domestic hot water is an effective means to reduce domestic energy consumption. In 2010, there are several kinds of energy supply systems commercially available in Japan. For example, CO_2 heat pump systems (HP-S), gas-engine co-generation systems (GE-CGS), and polymer-electrolyte-membrane fuel-cell co-generation systems (PEFC-CGS) are available.

Some studies have presented simulation models for micro-cogeneration (Vidal et al., 2006; Beausoleil-Morrison et al., 2007; Nieto-Morte et al., 2010; Alanne et al., 2010). A HP-S has been considered under daily changes with standardized demand (Yokoyama et al., 2008). It has been reported that the primary energy consumption of the HP-S on representative days is almost equal to that of the PEFC-CGS (Hashimoto et al., 2001). Based on these trends, domestic hot water heating systems have been released in Japan, but it is important that a direct comparison be based on actual demand patterns.

In this study, based on demand patterns measured in the Kansai area in Japan over a one-year period, the optimal operation of each system is calculated, with the maximum potentials and the ideal control strategy to meet demands. Then, using a conventional condensing-gas

boiler system as a baseline, the relative superiority of a HP-S, a PEFC-CGS, and a GE-CGS are compared to determine the most rational selection for residential use in Japan.

2 SYSTEM SPECIFICATIONS

Figures 1 to 5 show schematic diagrams with the specifications of the HP-S, GE-CGS, PEFC-CGS, and C-S energy supply systems.

2.1 CO_2 Heat Pump System (HP-S)

Electricity is supplied from the grid. Domestic hot water is supplied from the HP-S only. The capacity of the hot-water storage tank is 370 liters, and the rated heat output from the HP unit is 4.5 kW. The Coefficient of Performance (COP) of the HP unit is dependent on the hot water outlet temperature and the ambient air temperature (Yokoyama et al., 2008). The lowest thermal storage hot capacity is set to 10 %, as for the other systems.

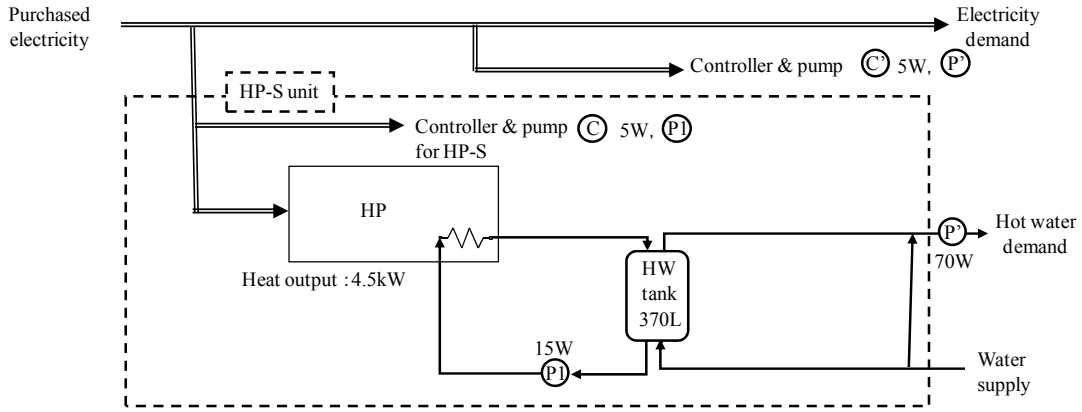


Figure 1: CO_2 heat pump system (HP-S)

2.2 Gas Engine Co-generation System (GE-CGS)

Electricity is supplied from the grid and also from the GE-CGS. Domestic hot water is supplied from the CGS only. Since reverse flow of electricity from a CGS to the grid is not allowed in Japan, a margin of 30 W is set. Surplus electricity produced by the CGS is supplied to the electric heater to prevent reverse flow to the grid. The auxiliary boiler efficiency in the GE-CGS is 80 % (based on LHV, except Table 1). As shown in Fig. 2, the GE-CGS rated electrical power output is 1000W, the electrical power conversion efficiency is 22.5 %, and the heat recovery efficiency is 63 %. The GE-CGS is allowed only the rated output; in other words, partial-load operation is not possible. However, in the calculations below, virtual below-rated output, i.e., partial-load operation, can be allowed during start and stop procedures per term. Energy consumption during the start-up procedure is excluded.

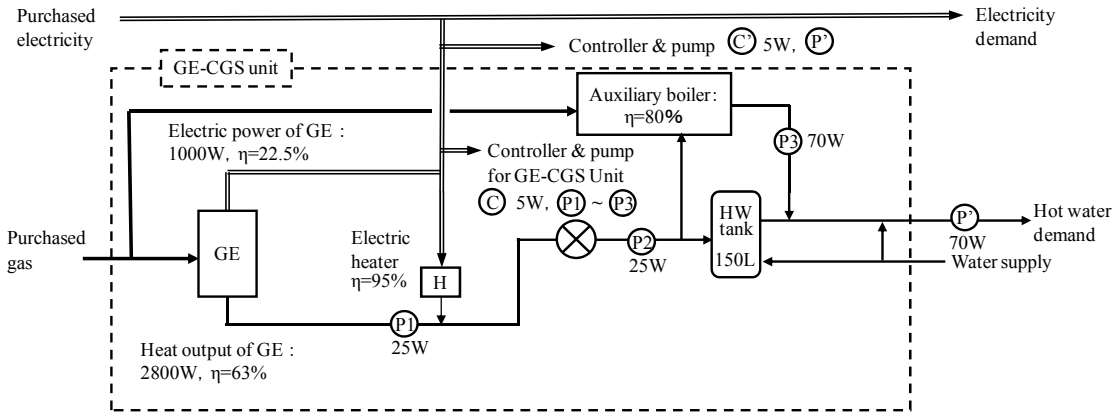


Figure 2: Gas engine co-generation system (GE-CGS)

2.3 Polymer Electrolyte Membrane Fuel Cells Co-generation System (PEFC-CGS)

Electricity is supplied from the grid and also from the PEFC-CGS. Hot water is supplied from the CGS only. As shown in Fig. 3, the rated electrical power output of the PEFC-CGS is 700 W, and the output ranges from 250 W (35.7 %) to 700 W (100 %) in partial-load operation. The load-following capability ranges from 15 to -60 W / min. The rated electrical power conversion efficiency is 35 % (LHV), and the rated heat recovery efficiency is 55 % (LHV). The auxiliary boiler efficiency in the PEFC-CGS is 80 % (LHV). In the partial-load operation shown in Fig. 4, the lowest electrical power conversion efficiency (at 35.7 % load) is 30 % (LHV), and the lowest heat recovery efficiency is 30 % (LHV).

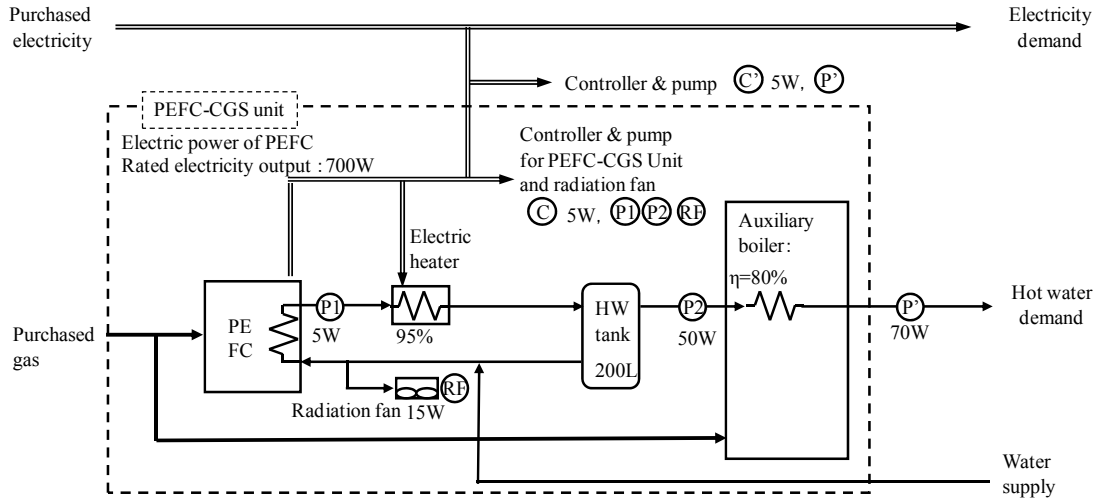


Figure 3: Polymer-electrolyte-membrane fuel-cell co-generation system (PEFC-CGS)

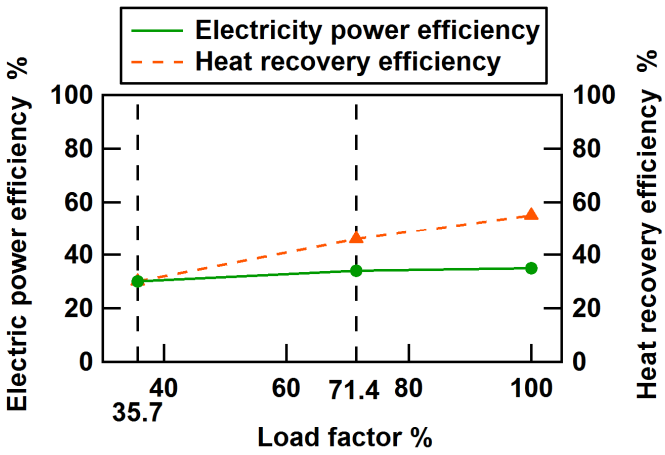


Figure 4: Partial load characteristics of PEFC

2.4 Conventional System (C-S)

As shown in Fig 5, electricity is supplied from the grid, and hot water is supplied from the condensing gas boiler which has an efficiency of 92 %.

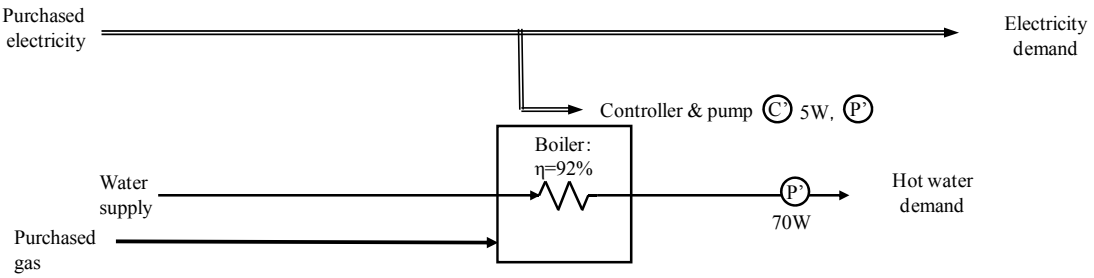
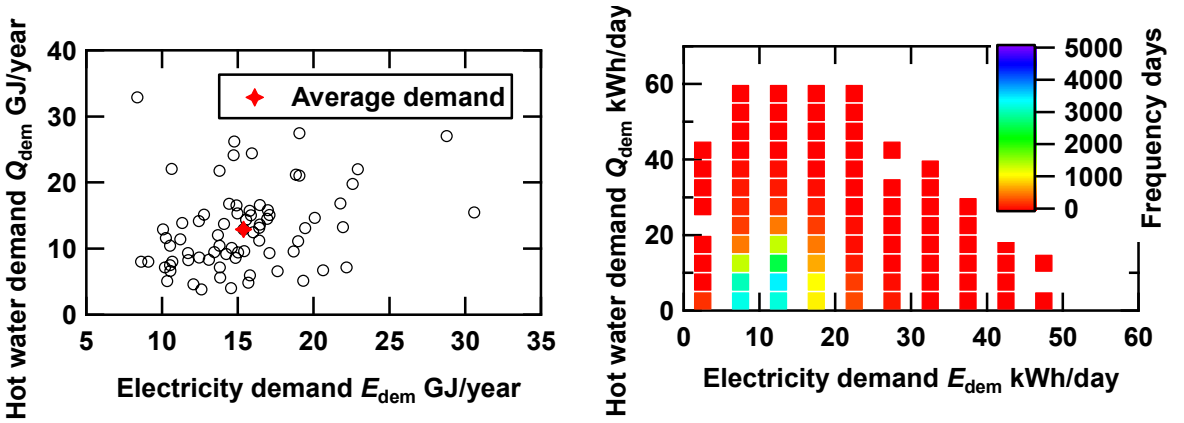


Figure 5: Conventional system (C-S)

3 LOAD

Figure 6 shows an annual demand map measured in households including 40 detached houses and 32 apartments with 3 ~ 5 occupants each. In Fig. 6 (a), the bottom axis is the annual electrical demand, and the left axis is the annual hot water demand for each household. In Fig. 6 (b), the bottom axis is the daily electrical demand and the left axis is the daily hot water demand for each household. The color scale represents frequency, that is, the number of days occurring divided by the total number of days (≈ (72 households) x (365 days)).

Electrical demands for space heating and cooling are excluded. The average heat-to-power ratio based on annual demand for all households is $Q_{dem}^{hw}/E_{dem} = 12.90/15.37 = 0.84$. Fig. 6 (b) shows that the daily energy demand is distributed with high density around the points of an electrical demand of 10 kWh / day and a hot water demand of 5 kWh / day.



(a) Annual hot water and electrical demand (b) Daily frequency distribution of demand
Figure 6: Annual demand in all households

4 OPTIMISATION OPERATION

4.1 Conditions for Calculation

The objective of the optimization is to minimize the daily primary energy consumption of each household over the entire year. The domestic hot water storage tank is set to be equal at the start and end of each day. In order to reflect actual usage, the HP-S model has an operation priority at night. In other words, it is assumed to be mostly operated at night. The optimization problem is formulated as a mixed integer linear programming problem. The model is coded with AMPL - Version 12.1, and the solver is CPLEX - Version 12.1. The primary energy conversion factors of purchased gas and electricity are shown in Table 1. Energy demand is set based on actual annual data with a sampling time interval of every 30 minutes.

Table 1: Conversion factors

Conversion factors			Value (HHV)	
Primary energy conversion factor of purchased gas	CF_g^{ene}	MJ/Nm^3	45.0	(a)
Primary energy conversion factor of purchased electricity	CF_e^{ene}	MJ/kWh	Day time 9.97 Night time 9.28	(*b) (*b)
CO_2 emission factor of purchased gas	CF_g^{co2}	kg-CO_2/Nm^3	2.29	(a)
CO_2 emission factor of purchased electricity	CF_g^{co2}	kg-CO_2/kWh	0.282 (All sources)	(c)

(*) Day: 8:00 ~ 22:00, Night: 22:00 ~ 8:00
(a) Osaka Gas, http://www.osakagas.co.jp
(b) Law Concerning the Rational Use of Energy in Japan, http://law.e-gov.go.jp/htmldata/S54/S54F03801000074.html
(c) Kansai Electric Power Co., Inc. (average from 2008 to 2009), http://www.kepco.co.jp

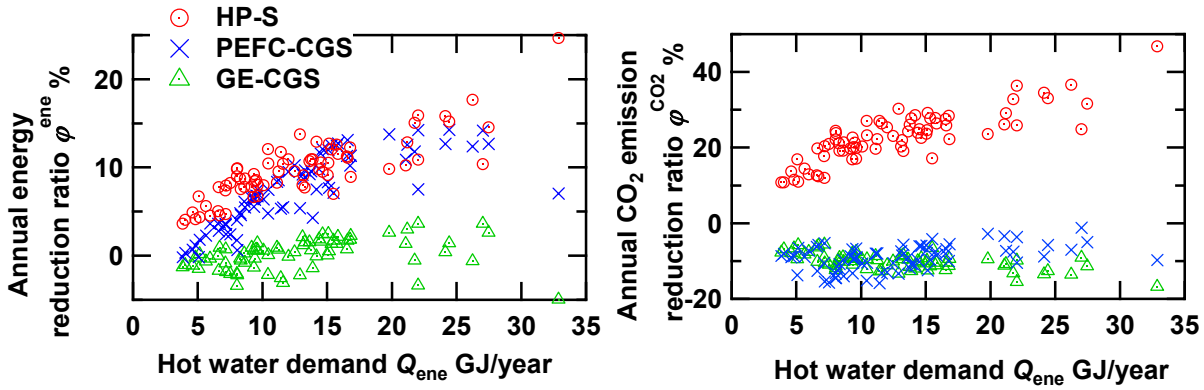
4.2 Results and Discussion

The result of the optimization gives the ideal performance of each system, X, relative to that of the reference system, C-S. Two kinds of evaluation index are defined in Equations (1) and (2): the primary energy reduction ratio φ_X^{ene} % with Eq. (1) and the CO_2 reduction ratio φ_X^{co2} % with Eq. (2).

$$\varphi_X^{ene} = (P_{CS}^{ene} - P_X^{ene}) / P_{CS}^{ene} \times 100 \quad (1)$$

$$\varphi_X^{co2} = (CO2_{cs} - CO2_X) / CO2_{cs} \times 100 \quad (2)$$

Figure 7 (a) shows the annual primary energy reduction ratio φ_X^{ene} which is equivalent to the ideal maximum annual primary energy reduction ratio with an ideal control strategy. Figure 7 (b) shows the annual CO_2 emission reduction ratio φ_X^{co2} for all households. The results for HP-S, indicated by the red circles in Fig. 7 (a), show a higher primary energy reduction ratio than those of other systems in almost all households. The GE-CGS results, indicated by the green triangles, showed little energy reduction. The energy reduction ratio of the HP-S and the PEFC-CGS increase with an increase in the hot water demand. The annual primary energy reduction ratio, in the lower range of the heating demand for hot water, shows a negative primary energy reduction ratio. The annual average primary energy reduction ratio of the HP-S is 9.69 %, that of the GE-CGS is 0.17 % and that of the PEFC-CGS is 7.38 %. The annual average CO_2 emission reduction ratio of the HP-S is 22.96 %, that of the GE-CGS is -10.16 %, and that of the PEFC-CGS is -9.13 %.



(a) Annual energy reduction ratio (b) Annual CO_2 reduction ratio

Figure 7: Energy saving ratio versus hot water demand

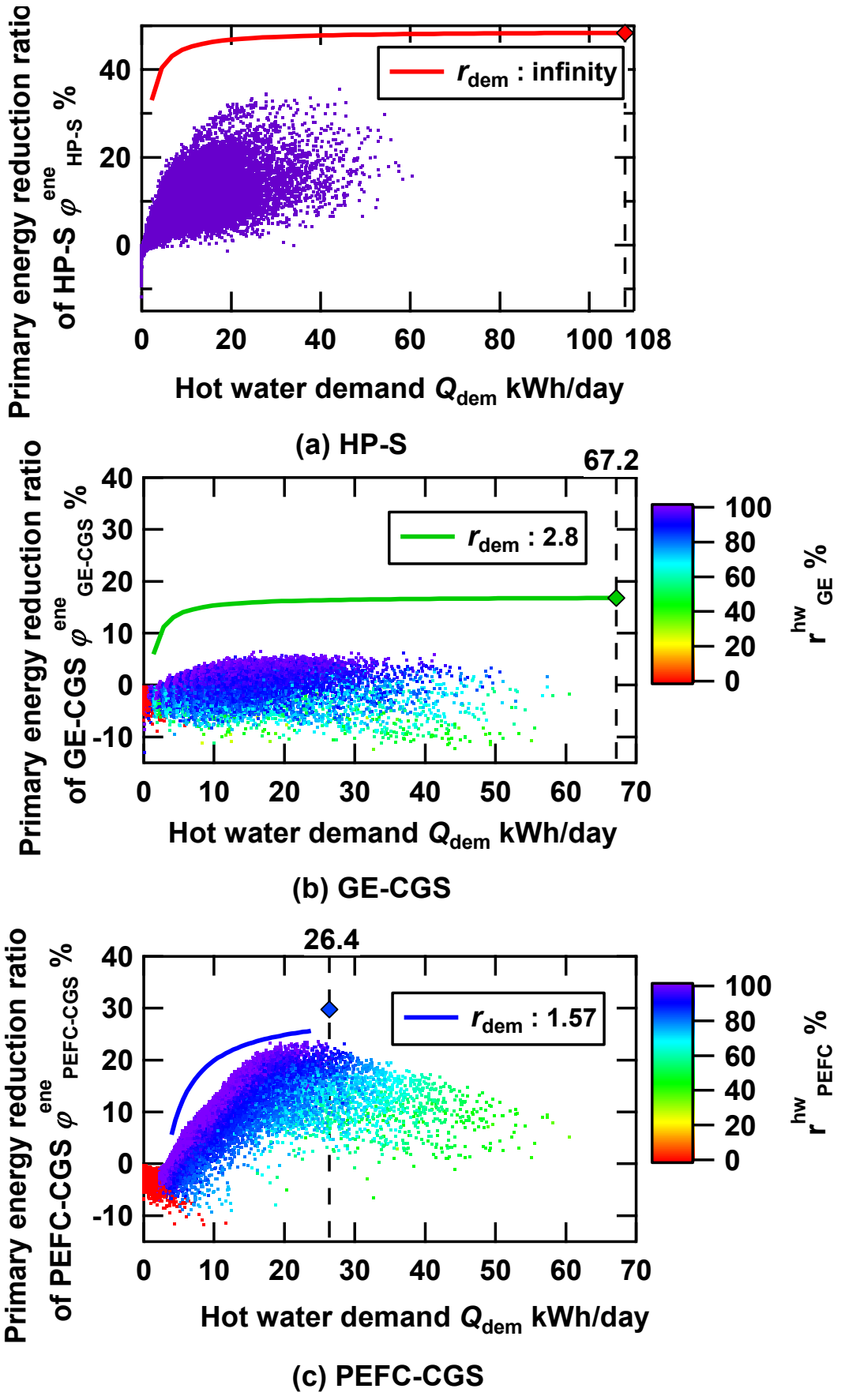


Figure 8: Daily primary energy reduction ratio versus hot water demand

Figure 8 shows the daily primary energy reduction ratio and contribution ratio of the system output to the domestic hot water demand. In the legend of Fig. 8 (a), r_{dem} represents the heat-to-power ratio of the demand. The heat-to-power ratio r_{dem} (3) is defined as the amount of domestic hot water used Q_{dem}^{hw} kWh divided by the electricity used E_{dem} kWh.

$$r_{dem} = Q_{dem}^{hw}/E_{dem} \quad (3)$$

The diamonds in Fig. 8 (a) show the analyzed energy reduction ratios of the HP-S for the following three conditions: (1) the COP of the HP is 4.72, (2) the E_{dem} is 0 kWh / day, and (3) the Q_{dem}^{hw} is 108 kWh / day (operating at rated capacity for 24 hours). The red line in Fig. 8 (a) shows the analyzed energy reduction ratio of the HP-S for the following three conditions: (1) the COP of the HP is 4.72, (2) E_{dem} is 0 kWh / day, (3) gradually shifting hot water demand (2.25 ~ 108 kWh / day).

The diamonds in Fig. 8 (b) show the analyzed energy reduction ratio of the GE-CGS for the following two conditions: (1) Q_{dem}^{hw} is 67.2 kWh / day (operating at rated capacity for 24 hours), and (2) the heat-to-power ratio is 2.8 (rated value). The green line in Fig. 8 (b) shows the analyzed energy reduction ratio of the GE-CGS for the following two conditions: (1) Gradually shifting hot water demand (1.4 ~ 67.2 kWh / day), and (2) the heat-to-power ratio is 2.8 (rated value). The diamonds in Fig. 8 (c) show the analyzed energy reduction ratio of the PEFC-CGS for the following two conditions: (1) Q_{dem}^{hw} is 26.4 kWh / day (operating at rated capacity for 24 hours), and (2) the heat-to-power ratio is 1.57 (rated value). The blue line in Fig. 8 (c) shows the analyzed energy reduction ratio of the PEFC-CGS for the following two conditions: (1) Gradually shifting hot water demand (the range of possible hot water output), and (2) the heat-to-power ratio is 1.57 (rated value).

In Figs. 8 (b) and (c), the color scale represents the contribution ratio. The contribution ratio, r^{hw}, (4) of the system output for hot water demand is defined by the heat supplied by the HP or the CGS excluding both the heat supplied from the auxiliary boiler Q_{BX}^{hw} and that from the electric heater, divided by the total heat supplied.

$$r^{hw} = Q_X / (Q_X + Q_{BX}^{hw} + Q_{HEAT,X}) \times 100 \quad (4)$$

Since the efficiency of the auxiliary boiler is poor, the closer the color is to purple, the higher the system efficiency. In Figs. 8 (b) and (c), the red dotted points for lower hot water demand represent that the total heat demand for hot water was supplied almost exclusively by the auxiliary boiler.

In Fig. 8 (b), the purple dotted points indicate a high contribution ratio and a high primary energy reduction ratio. The purple points also appear for the hot water demand of every 1.4 kWh / day. Because the rated electricity output of the GE-CGS is 2.8 kW, and the sampling time interval is every 30 minutes, the virtual lowest output in electricity is 1.4 kW from the GE.

In Figs. 8 (b) and (c), the red dots represent the situation where the primary mover (GE and PEFC units) did not operate. In this case, the primary energy reduction ratio is negative because of the poor efficiency of the auxiliary boiler.

In Figs. 8 (b) and (c), purple dots appear around the upper edge of the distribution. This shows that the higher the contribution ratio, the higher the primary energy reduction ratio. In particular, the primary energy reduction ratio of the PEFC is not much less than that of the HP-S. However, the annual average ratio of the HP-S is superior to that of PEFC-CGS.

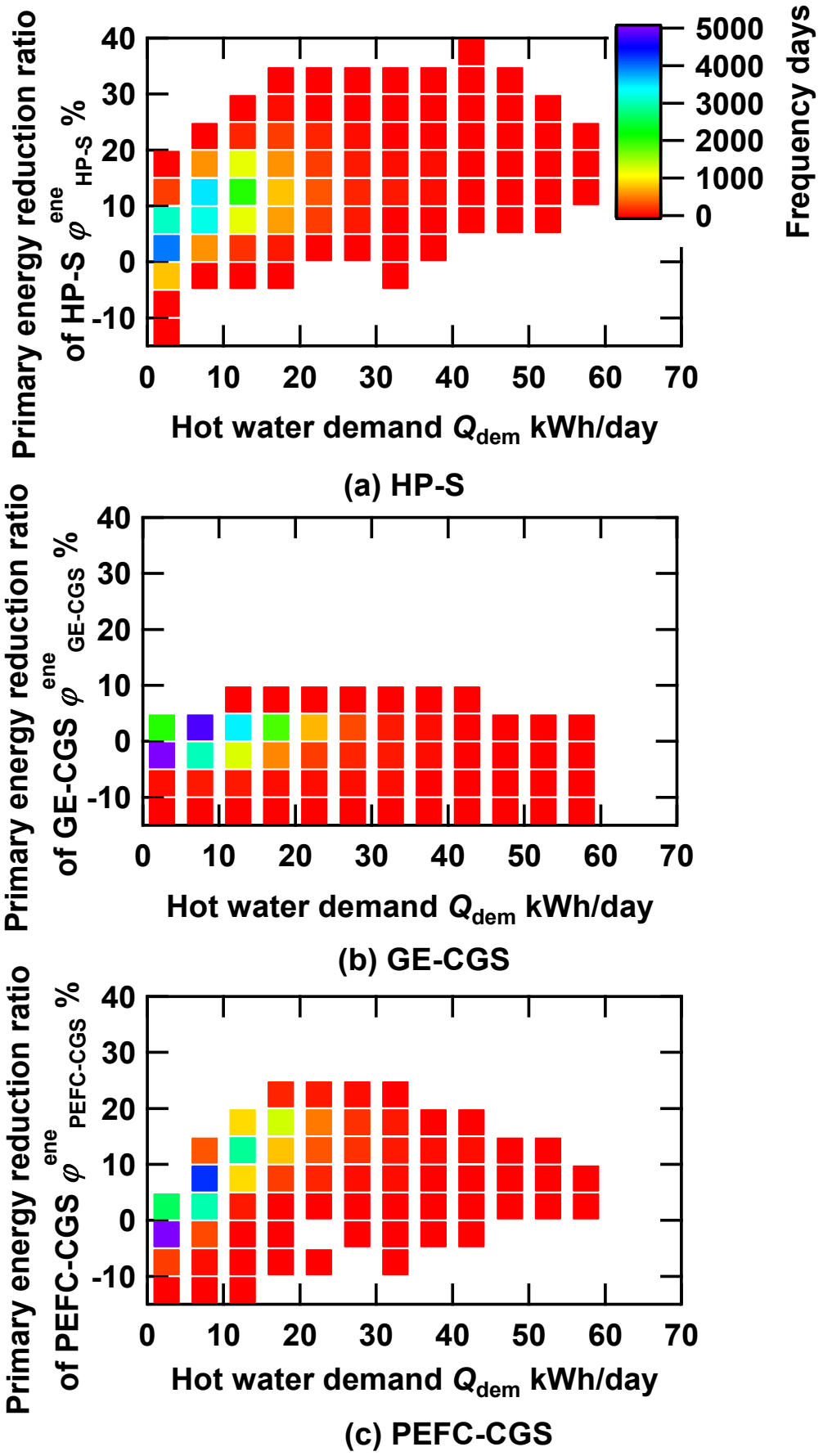


Figure 9: Frequency of daily primary energy reduction ratio

To investigate the reason why the annual performance of the PEFC-CGS is lower than that of the HP-S, the frequency of the daily primary energy reduction is shown in Fig. 9.

As shown in Fig. 6 (b), the daily demand frequency has a peak around 5 kWh / day for Q_{dem}^{hw}, and 10 kWh / day for E_{dem}.

This shows that the daily demand is densely distributed around the level of hot water demand of 5 kWh / day, and the popular hot water demand level is too small for CGSs. From Fig. 8, even at the low hot water demand level, the HP-S shows better performance than the CGSs.

Fig. 9 (a) shows that the blue to purple color, which corresponds to high frequency days, marks a reduction ratio from 0 to 22 %. The annual energy reduction ratio of the HP-S is 9.69 %. On the central portion of Fig. 9 (b), high frequency days mark an energy reduction ratio of almost 0. The annual energy reduction ratio of the GE-CGS is 0.17 %. In Fig. 9 (c), the high frequency days range from -10 to 20 %. Consequently, the annual energy reduction ratio of the PEFC-CGS is 7.38 %.

Therefore, the potential energy reduction ratio of the PEFC-CGS is not much less than that of HP-S. For low hot water demand, the energy reduction ratio of the PEFC-CGS is not higher than that of the HP-S.

5 CONCLUSIONS

Using the domestic electricity demand and hot water demand data from 72 households in the Kansai area in Japan, three kinds of energy systems are compared in terms of optimal operation throughout a year, which shows the energy and CO_2 reduction potentials for each system. The comparisons are carried out relative to a conventional gas boiler based system, C-S. Conclusions are summarized as follows:

A) Relative to the C-S, the annual energy reduction ratio of the HP-S was 9.69 %, that of the GE-CGS was 0.17 %, and that of the PEFC-CGS was 7.38 %.
B) Relative to the C-S, the annual CO_2 reduction ratio of the HP-S was 22.96 %, that of the GE-CGS was -10.16 %, and that of the PEFC-CGS was -9.13 %.
C) To reduce the energy consumption for domestic hot water demand, it is necessary to select the equipment to fit the level of hot water demand per household. In a broad range of the demand patterns of households, HP-S shows superiority in both of primary energy reduction and CO_2 emission reduction.

6 ACKNOWLEDGEMENT

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