Journal of Power Sources 195 (2010) 3779–3784

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

A study on energy saving in residential PEFC cogeneration systems

Kazushige Maeda [a,*], Kouji Masumoto [a], Akihito Hayano [b]

[a] Osaka Gas. Co. Ltd., Fuel Cell Development Department, 1-3-4 Hokkou Shiratsu, Konohanaku, Osaka 554-0041, Japan
[b] Osaka Gas. Co. Ltd., Gas Utilization Technology Department, 1-3-4 Hokkou Shiratsu, Konohanaku, Osaka 554-0041, Japan

ARTICLE INFO

Article history:
Received 28 September 2008
Received in revised form
10 December 2008
Accepted 17 December 2008
Available online 28 December 2009

Keywords:
Cogeneration
Distributed generation
Polymer electrolyte fuel cell
Residential

ABSTRACT

We have been developing technologies for energy saving in the residential sector. Recently, we have been concentrating our resources specifically into the development of polymer electrolyte fuel cell (PEFC) cogeneration systems. The system has excellent energy saving characteristics. However, the total amount of energy saved depends on how the system is operated. The characteristics of residential energy consumption are more complicated than in industrial use and depend on individual living patterns. It is therefore not easy to develop a control method for a system that can be generally applied across a wide variety of residential use.

In this paper, we propose a system configuration and operation planning method developed for a residential PEFC cogeneration system. Using an operation planning method we developed, we demonstrate that our system provides higher energy savings than the conventional method. The energy saving rates are 15.9% under a large heat demand, 18.4% under a relatively high electrical demand and low heat demand, 1.3% under relative low electrical and heat demands.

1. Introduction

Osaka Gas started developing 1 kW-class PEFC systems in 1999, including the development of an original natural gas fuel processing system (FPS), an exhaust heat recovery unit (EHU), the evaluation of a single cell membrane electrode assembly (MEA), and the development of an integrated PEFC cogeneration system with manufacturers [1–3].

During this development, we noticed the importance of the operation planning method in energy saving. In fact, in comparison with the conventional system consisting of a gas boiler and a thermal power plant, we can achieve effective energy saving with PEFC cogeneration, without the need for any special invention. However, the total amount saved is not high enough. It is important to achieve an energy saving rate high enough to exemplify the capabilities of PEFC, and thus we have been developing the technology for energy saving, mainly focusing on the PEFC cogeneration system configuration and operation planning methods. The PEFC cogeneration system has the disadvantage that it makes use of generated electricity only. It should also make effective use of the heat energy, because the electric power generation efficiency of PEFC is not significantly higher than the power generation efficiency of a thermal power plant. The operation planning method we have developed focuses on the supply and demand of heat, whereas conventional methods of operation planning focus on the supply and demand of electricity. Our control concept is based on the "eco-will" gas engine residential cogeneration system [4]. The important points in this operation planning method are effective use of excess power consumption by the heater and radiator, and our development technologies are able to achieve near maximum energy saving levels for the target system.

Section 2 describes the system configuration of the PEFC cogeneration system, Section 3 describes the operation planning method of the PEFC cogeneration system and its effect, and Section 4 states our conclusions.

2. Approach and methodology

2.1. Special features of the developed PEFC system

The configuration of the PEFC cogeneration system is shown in Fig. 1. The system consists of two sub-systems, a PEFC and an EHU. The PEFC consists of an FPS, cell stack, grid connected inverter and so on. The EHU consists of an auxiliary boiler and storage tank. Basic operation of the system is as follows. The FPS reforms city gas (natural gas) or liquefied petroleum gas into hydrogen (specifically, reformed gas). Hydrogen reacts with oxygen in the MEA to generate electricity and heat. The electricity generated is converted into AC power by a grid connected inverter, and the converted electricity is supplied to the electrical load. The heat energy generated by the FPS and cell stack is collected and stored in a storage tank as hot water to supply the demand of heat. The PEFC cogeneration

* Corresponding author. Tel.: +81 6 6460 7342; fax: +81 6 6464 2102.
E-mail address: kazushige-maeda@osakagas.co.jp (K. Maeda).

0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2009.12.075

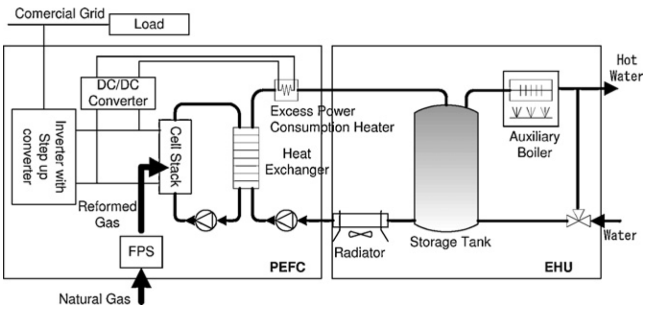

Fig. 1. Configuration of PEFC cogeneration system.

systems developed by Osaka Gas with manufacturers has some special features.

First, the system has a heater to absorb the excess electric power generated. The heater is needed because generally, the Japanese electric power corporations do not purchase excess power generated by residential cogeneration systems, and consequently, the reverse power cannot be fed back into the grid. As a result, an excess electric power management is necessary to prevent reverse power flow into the grid. A heater is also installed in the residential gas engine cogeneration system sold under the name "eco-will." The eco-will system only operates at nominal output because the efficiency of the gas engine with a partial load is much lower than with a nominal load, and so the system needs excess electric power management. Other than this, PEFC cogeneration systems can be controlled to follow the electric power demand. Many PEFC cogeneration systems did not have excess electric power management in the beginning [5]. Basically, reverse power flow is not included in the estimation of energy saving for this system [6]. However, our system has excess electric power management because the estimated amount of reverse power was large.

Energy can be saved by including excess electric power management in the operation planning method. The operation planning method for a system that incorporates a heater can control the heat–power ratio and improve the energy savings. Since use of a heater should give greater energy savings than using an auxiliary boiler, we use a heater to generate heat instead of an auxiliary boiler. With electric load-following operation for low electrical demand, the PEFC shows low efficiency. However, if there is large demand for heat which cannot be covered just by the exhaust heat generated from the PEFC, the system will generate much more power than the electrical demand, and this excess power can be converted into heat to meet the heat demand. This improves the total efficiency of the PEFC in comparison with the conventional operation planning method.

Next, the system has a radiator. The radiator prevents the coolant temperature from exceeding its top limits. This makes continuous operation possible even when the storage tank is full of hot water. Continuous operation prevents the negative effects of repetitive stop–start operation [7]. A reduction in the number of start-ups with non-continuous operation is necessary to improve durability. If the actual heat demand arrives later than predicted and the storage tank is full of hot water, there is no way to shut down the system without a radiator. In this case, the excess heat caused by the difference in the timing of the heat demand will be absorbed by the radiator. Use of the radiator increases energy savings overall, because continuous operation reduces start-up losses in the PEFC.

These technologies work effectively by predicting the demand for electricity and heat. A large amount of hot water is used to take a bath in Japan, and it is therefore important to predict the timing and the amount of heat needed to take a bath.

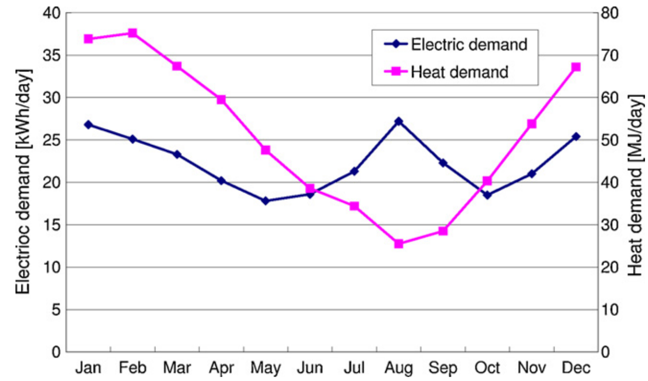

Fig. 2. Annual energy demand trends.

2.2. Operation planning method that saves energy

The operation planning logic is constructed to meet the predicted heat demand, mainly because a PEFC has a lower efficiency in generating electricity than a power plant. It is important to predict the demand for electricity and heat. We developed the prediction method of the energy demand, but we do not mention it in this paper.

Fig. 2 shows the annual energy demand trends at a test site for a large-scale stationary fuel cell demonstration project by the New Energy Foundation [6]. The heat demand through the year shows large fluctuations compared with the electrical demand. Therefore, an operation planning method is needed that can adapt effectively to variations in the heat demand throughout the year. The operating plan for the system needs to match the predicted energy demand. The general flow chart of the operation planning logic is shown in Fig. 3. This logic shows four PEFC operating modes. There are two main operation planning methods: continuous operation and non-continuous operation. Continuous operation can be subdivided into three operating modes according to the balance in the supply and demand for heat. These calculations are carried out the basis of the predicted electricity and heat consumption, the electric and heat

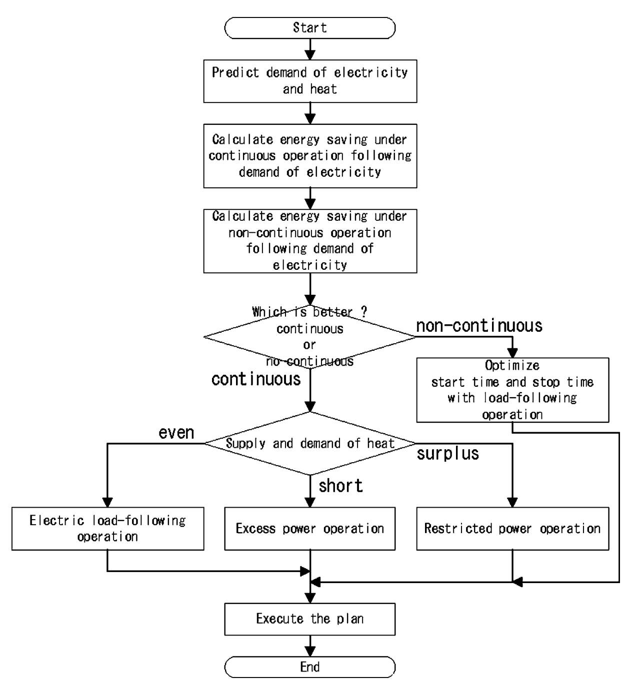

Fig. 3. General flow chart of operation planning logic.

efficiency of the PEFC, start-up losses in the PEFC, the efficiency of the auxiliary boiler, the capacity of the storage tank, and the thermal radiation rate for the storage tank and so on. The control logic is able to adapt to a range of systems configurations, including one that does not have an excess power consumption heater and/or a radiator [8–11].

For example, when a large demand for heat is predicted in the winter, the control system estimates the optimum energy saving mode between continuous operation or excess power operation using the heater. If the control system selects excess power operation, the control system plans the timing of the excess power operation and generating power through the heater. At times other than excess power operation, the PEFC system operates according to the demand for electricity.

If a surplus of heat is predicted in the summer, the control system searches for a combination of starting time and stopping time for the PEFC to achieve the optimum energy saving in non-continuous operation mode. At the same time, control system compares energy saving of electrical demand following operation using radiator with restricted power operation that it is planed the time of restrict power operation and generating power in the time as best continuous operation. Then the control system chooses the best non-continuous operation plan and best continuous operation plan and automatically selects the best operation plan in according to the heat demand throughout the year. The planning scheme is formulated once a day and updated to match the stored heat every 30 min.

The values used in this paper are given by the following equations and constants. To meet an electrical energy demands of $D_e(t)$ [kW] and a heat demand of $D_h(t)$ [MJ], the required primary energy in a conventional system is given by:

$$P_c = \sum_t \left(k_1 \frac{D_e(t)}{\eta_{pp}} + \frac{D_h(t)}{\eta_{gb}} \right), \tag{1}$$

where $k_1 = 3.6\,\text{MJ}\,\text{kWh}^{-1}$ is the constant for adjustment of unit, $\eta_{pp} = 0.366$ is the electrical efficiency of the power plant, and $\eta_{gb} = 0.7$ is the heat efficiency of the gas boiler. For the PEFC system, the required primary energy is given by:

$$P_f = \sum_t \left(k_1 \left(\frac{G_e^i(t)}{\eta_{fe}} + \frac{B_p(t)}{\eta_{pp}} \right) + \frac{A_b(t)}{\eta_{gb}} \right), \tag{2}$$

where $G_e^i(t)$ [kW] is the power generated by the PEFC, the index "i" indicates the control methods: $i = 1$ is the conventional method, $i = 2$ is the developed method. η_{fe} and η_{fh} are shown in Fig. 4 represent the electrical and heat efficiencies of the PEFC system. $B_p(t)$ [kW] is the power supplied from the grid and given by:

$$B_p(t) \begin{cases} = D_e(t) - G_e^i(t), & \text{if } D_e(t) - G_e^i(t) > 0 \\ = 0, & \text{if } D_e(t) - G_e^i(t) \le 0. \end{cases} \tag{3}$$

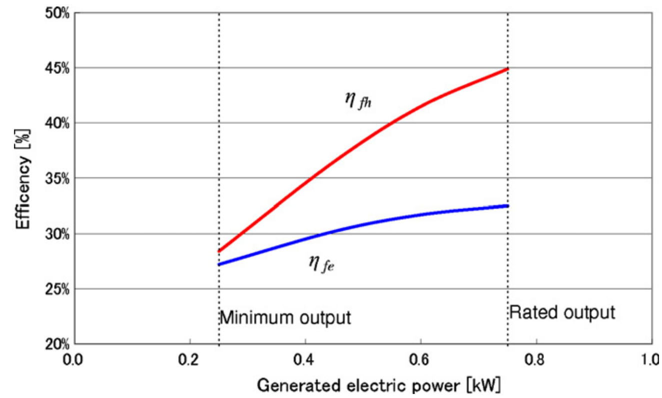

Fig. 4. Characteristic curves of PEFC efficiency.

and $A_b(t)$ [MJ] is the output of the auxiliary boiler given by:

$$A_b(t) \begin{cases} = D_h(t) - S_h(t), & \text{if } D_h(t) - S_h(t) > 0 \\ = 0, & \text{if } D_h(t) - S_h(t) \le 0. \end{cases} \tag{4}$$

In Eq. (4), $S_h(t)$ [MJ] is the heat energy stored in the storage tank and is given by:

$$0 \le S_h = \sum_t \left(k_1 \frac{G_e^i(t)}{\eta_{fe}} \eta_{fh} - r_p + k_1 H_p(t) \right) (1 - r_{tnk})^{stor} \le S_{hmax}, \tag{5}$$

where $H_p(t)$ [kW] is the power of the excess power consumption of the heater represented by:

$$H_p(t) \begin{cases} = (G_e^i(t) - D_e(t))\eta_h, & \text{if } G_e^i(t) - D_e(t) > 0 \\ = 0, & \text{if } G_e^i(t) - D_e(t) \le 0, \end{cases} \tag{6}$$

where $r_p = 0.209$ MJ is the radiation from the pipes, r_{tnk} is the thermal radiation from the hot water in the storage tank, s_{tor} is the storage time in the storage tank, and $\eta_h = 0.9$ is the efficiency of the excess power consumption heater. The value of $S_h(t)$ should not exceed S_{hmax} [MJ], which is the maximum heat energy that can be stored in the storage tank within the limits of temperature and volume. The rate of energy savings of the PEFC system over the conventional system is represented by:

$$R_{es} = \frac{P_c - P_f}{P_c} \times 100. \tag{7}$$

It should be noted that the efficiencies of the equipment are based on HHV (Higher Heating Value).

3. Results and discussion

The evaluations in this chapter are done by a computer simulation because it is difficult to comparison the real PEFC system with operation planning method developed and the imaginary system

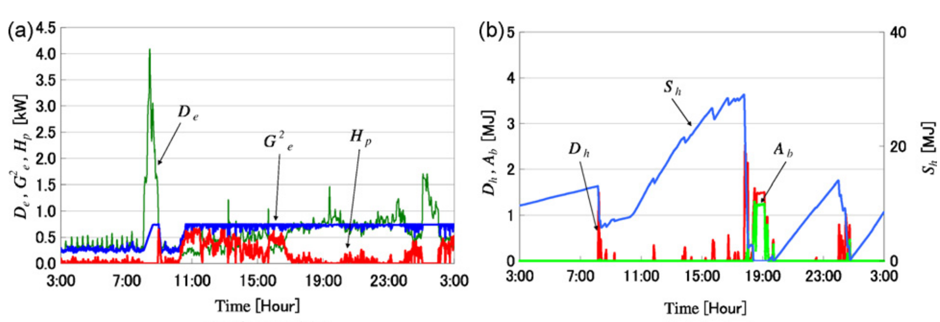

Fig. 5. Operation using a heater for excess power consumption: (a) plots for electricity and (b) plots for heat.

Table 1
Developed method operation versus load-following operation.

Operation method	Required primary energy [MJ/day]	Rate of energy saving [%]
PEFC		
Developed operation method (excess power operation)	281.9	15.9
Conventional operation method (load-following operation)	297.0	11.4
Conventional system	335.3	–

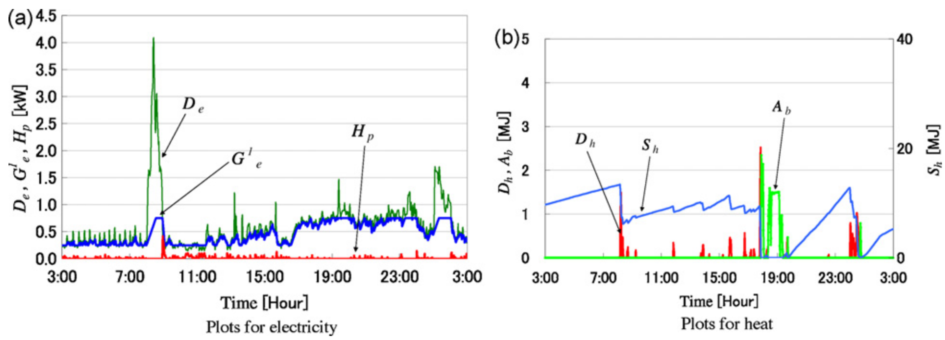

Fig. 6. Operation using the conventional method: (a) plots for electricity and (b) plots for heat.

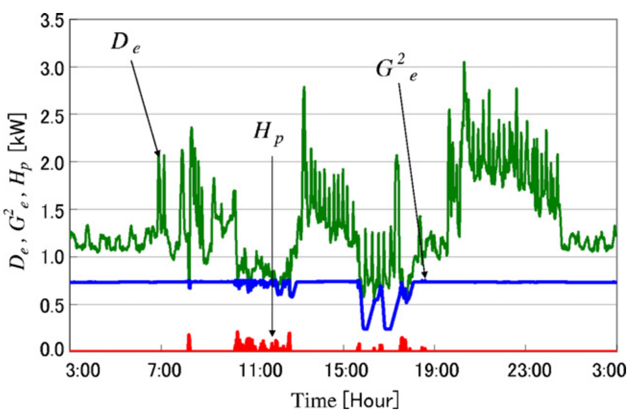

Fig. 7. Operation using a radiator for surplus heat: (a) plots for electricity and (b) plots for heat

with conventional operation method in the same condition. We use the efficiency of the system measured in laboratory and other data recorded in the actual residence.

3.1. Operation when a large heat demand is predicted

Actual system operation in Osaka Gas's own Field Tests is shown in Fig. 5. This figure shows the result of the operating method developed with a heater and radiator. In this example, the auxiliary boiler turns on at 19:00 and 0:30 as shown in Fig. 5(b). Since a large heat demand had been predicted (occurring at 18:00), the PEFC system with the developed method generates much more power than the electrical demand after 10:30, and this excess power is converted into heat as indicated by H_p and stored as S_h. As a result, the heat generated by the auxiliary boiler can be reduced compared to load-following operation. Primary energy for this method of operation versus the primary energy required for conventional load-following operations are shown in Table 1. Fig. 6 shows the same plots as in Fig. 5 for electric load-following operations; i.e., for the conventional method. As this figure shows, the auxiliary boiler output increases at about 18:00. In detail, the boiler input using the PEFC system under the developed operation decreases by 95.4 MJ day^{-1} compared with the conventional system. In addition, the thermal power plant input also decrease by 112.1 MJ day^{-1} with the developed operating method compared with the conventional system using PEFC. However, the PEFC system under the developed operating method requires an input of 154.1 MJ day^{-1}. As a result, we reduced the primary energy by 53.4 MJ day^{-1}. In the same way, we can reduce the energy input by 5.0 MJ day^{-1} for the thermal power plant and by 33.3 MJ day^{-1} for the boiler, but this is an increase of 23.2 MJ day^{-1} for the PEFC under the developed operation compared with the conventional operation. As a result, we can reduce the primary energy by 15.1 MJ day^{-1}.

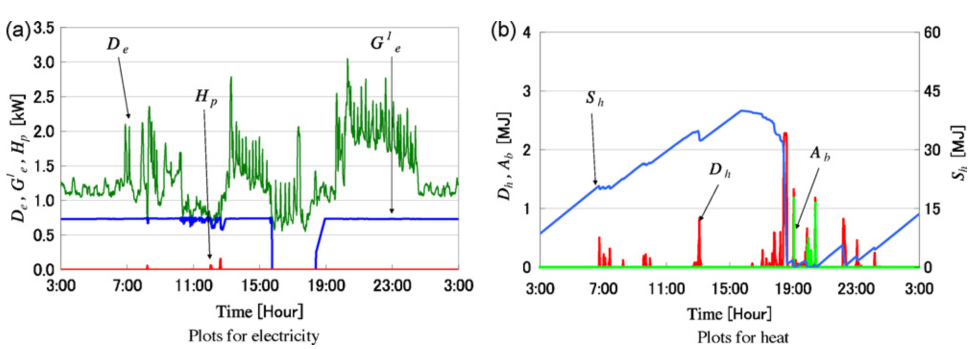

Fig. 8. Operation without a radiator for surplus heat: (a) plots for electricity and (b) plots for heat.

Table 2
Developed method operation versus non-continuous operation.

Operation method	Required primary energy [MJ/day]	Rate of energy saving [%]
PEFC		
Developed operation method (using radiator operation)	332.2	18.4
Conventional operation method (non-radiator operation)	351.3	13.7
Conventional system	406.9	–

Table 3
Developed method operation versus load-following operation.

Operation method	Required primary energy [MJ/day]	Rate of energy saving [%]
PEFC		
Developed operation method (Non-continuous operation)	100.5	1.3
Conventional operation method (Load-following operation)	113.3	-11.3
Conventional system	101.8	–

3.2. Operation when a small heat demand is predicted

Another actual operating example is shown in Fig. 7. In this example, the radiator works from 16:00 to 17:00 intermittently. The PEFC follows the electric load under restrained control intermittently 16:00 and 17:00 to restrain the surplus heat. The reason for the continuous operation is that the dumped heat is smaller than the energy required to starting the PEFC system. For reference, non-radiator operation is shown in Fig. 8. The storage tank is filled with hot water at 15:45, a PEFC system without a radiator would have to stop. Sufficient storage space in the tank is necessary to restart the PEFC, and several MJ of energy are needed to start up the PEFC system. Comparisons with the operation planning method with non-continuous operation developed by simulation are shown in Table 2. Fig. 8 shows the case of non-continuous operation without a radiator; i.e., the conventional method. In detail, the boiler input decreases by 95.8 MJ day^{-1} using the developed PEFC system operation compared to the conventional system. And the thermal power plant input also decrease by 166.3 MJ day^{-1} using the developed PEFC system operation compared with the conventional system. But the developed PEFC system operation requires 187.4 MJ day^{-1} input to the PEFC system. In the same way, we can reduce the energy input by 9.9 MJ day^{-1} for the boiler, by 22.3 MJ day^{-1} for the thermal power plant, but we need an increase of 13.1 MJ day^{-1} for the developed PEFC operation compared with non-radiator operation. As a result, the conventional system requires 406.9 MJ day^{-1} for primary energy. The PEFC system can reduce the primary energy by 55.6 MJ day^{-1} under non-radiator operation. The developed operation planning method gives a decrease in primary energy of 19.1 MJ day^{-1} compared to non-radiator operation. This verifies that the developed system has a larger energy-saving effect than the non-radiator system or the conventional system.

Another example of operation is shown in Fig. 9. The PEFC starts at 14:10 and stops at 22:10. Heat demand is very small. The heat dumped into the radiator under continuous operation is bigger than the energy needed to start the PEFC system. As a result, the PEFC works when there is a large electric load or large demand for heat. With this operation method, there are no starting con-

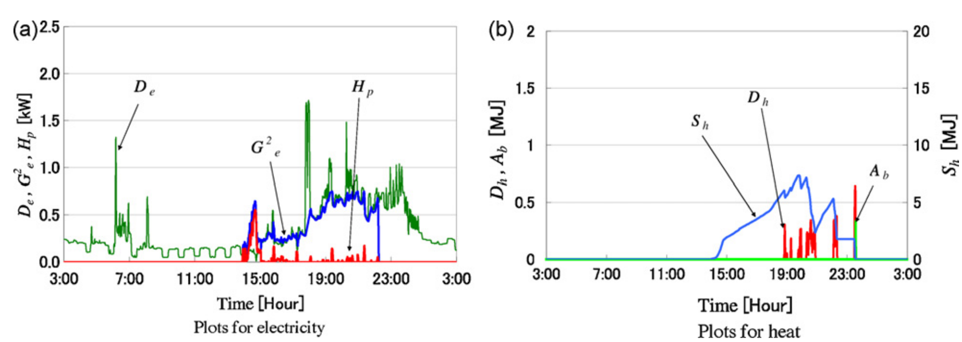

Fig. 9. Non-continuous operation for surplus heat: (a) plots for electricity and (b) plots for heat.

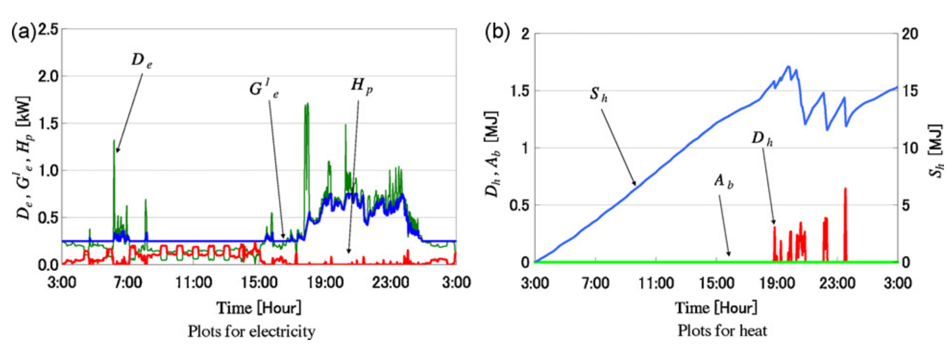

Fig. 10. Continuous operation for surplus heat: (a) plots for electricity and (b) plots for heat.

ditions for the PEFC system in a day; specifically, the PEFC does not work when there is enough hot water in the storage tank compared with the predicted heat demand. Therefore, the system sometimes stores heat for two or three days' demand in a day; for example, prediction of the heat demand is extraordinarily small for two or three days. Fig. 10 shows the case of electric load-following operations; i.e., the conventional method. A comparison of the developed operation method and load-following operation is shown in Table 3. In detail, the boiler input decreases by 22.0 MJ day^{-1} using the developed PEFC system operation compared with the conventional system. The thermal power plant input also decrease by 19.4 MJ day^{-1} using the developed PEFC system operation compared with the conventional system. But the developed PEFC system operation requires 40.1 MJ day^{-1} input for the PEFC system. In the same way, we can reduce the energy input by 63.1 MJ day^{-1} for PEFC operation but it increases by 1.5 MJ day^{-1} for the boiler, and by 48.8 MJ day^{-1} for the thermal power plant under the developed operation compared to non-radiator operation. As a result, the conventional system requires 101.8 MJ day^{-1} of primary energy. However, the PEFC system increases the primary energy by 11.5 MJ day^{-1} under load-following operation. Under the developed operation method, the system reduces the energy by more than 1.3 MJ day^{-1} compared with the conventional system. The total amount of primary energy required for the developed system is nearly equal to the conventional system because the system works for a short time only. However, we can see that the developed method is superior for load-following operations.

4. Conclusions

The residential PEFC cogeneration system we developed achieved energy savings. Of course, we can get a small saving in energy simply by installing and operating a PEFC cogeneration system. Our operation planning method was able to achieve maximum energy savings for the target system. Our studies revealed that the performance of the PEFC itself is important, but the operation planning method is also important. In the actual examples shown in this paper, the developed operation planning method achieved a higher reduction in primary energy than the conventional system. The developed operation planning method selects the operation mode according to the predicted heat demand. Non-continuous operation and power restricted operation are selected automatically for a small heat demand mainly in the summer. Under excess power operation, the plan selects the excess power heater for a large heat demand mainly in the winter season. Furthermore, when generating excess power, the total efficiency is bigger than with electrical demand-following operation. The values of energy saving rate is 15.9% under a large heat demand, 18.4% under a relative large electrical demand and a small heat demand, 1.3% under a relatively small electrical and heat demand. The energy saved was 53.4 MJ day^{-1} for a large heat demand, 74.7 MJ day^{-1} for a relative large electrical demand and small heat demand, and 1.3 MJ day^{-1} for a relative small electrical and heat demand.

Acknowledgements

We took advice to Prof. Y. Yasaka and Dr. H. Yonemori from Kobe University Graduate School for their guidance in the writing of this paper.

References

[1] M. Tanaka, Proc. 23rd World Gas Conf., 5.3EF.04, 2006.
[2] M. Echigo, The 8th FCDIC Fuel Cell Symposium Proceedings, 2001, p. 319.
[3] H. Aki, Proc. IEEE Power Engineering Society General Meeting, 2007.
[4] K. Takimoto, M. Yoshimura, T. Yoshida, Proc. Cogeneration Symposium, November, 2002, pp. 89–96.
[5] N. Fuziwara, K. Kobayashi, T. Sato, K. Ito, H. Yamada, Y. Nishizaka, H. Kitazawa, M. Otsuka, K. Maeda, Proc. 2006 Fuel Cell seminar, November, 2006.
[6] New Energy Foundation, Result of Large Scale Stationary Fuel Cell Demonstration Project (in Japanese), Report of Large Scale Stationary Fuel Cell Demonstration Project in 2007, March 2008, pp. 17–40.
[7] H. Kuriki, H. Fukumoto, S. Yoshioka, S. Matsumoto, Proc. 2006 Fuel Cell seminar, November, 2006.
[8] K. Maeda, A. Hayano, K. Takimoto, K. Masumoto, Proc. Cogeneration Symposium, November, 2005, pp. 91–98.
[9] A. Hayano, K. Takimoto, Proc. Cogeneration Symposium, November, 2004, pp. 139–145.
[10] K. Masumoto, K. Maeda, A. Hayano, K. Takimoto, Proc. The 23rd Annual Meeting of Japan Society of Energy and Resources, June, 2004, pp. 9–12.
[11] K. Maeda, M. Suzuki, H. Aki, Proc. IEEE PES 2008 General Meeting 08GM0215, July, 2008.