Effect of a 1 kW Polymer Electrode Fuel Cell system for residential usage on Reduction of CO_2 emission

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***Abstract*— In the present paper, the reduction of carbon dioxide by using a Polymer Electrode membrane Fuel Cell (PEFC) power generation system for residential usage was verified. The consumption of electric and heat energy of a family introduced PEFC system in Okayama prefecture was recorded for more than one month, then the data were analyzed in comparison with the cases where only commercial electricity is used and electricity and kerosene are used in combination. Furthermore, the effect of the capacity of hot water tank and the usage of nighttime electric power was estimated. As a result, it was found that the PEFC contributed to reduce CO_2 emission more than 22%, 27%and 42% for the family compared with the electricity-kerosene combined usage and the all-electric usages with and without nighttime electric power respectively. Further it has been suggested that further reduction of CO_2 emission is possible by optimizing the demand balance of hot water and electricity.**

Keyword-CO_2, emission, Fuel Cell, Residential usage, Electricity, Heat recovery.

I. Introduction

The reduction target of the total amount of greenhouse gas emissions in 2010, which Japan has promised to the world in December 1997 in the "Kyoto Protocol to the United Nations Framework Convention on Climate Change", is the reduction by 6% to the fiscal 1990[(1)]. With regard to environmental and new energy research in Japan, "Cool Earth - Innovative Energy Technology Program" 1) was settled on by ministry of economy trade and technology in Japan (MITI) in 2008. In the program , 21 technologies that may potentially contribute greatly to substantial CO_2 emissions reduction was selected as technologies with which our country can lead the world in the fields such as power generation/transmission, transport, industry, and in the commercial/residential sectors and so forth, in order to accelerate innovative technological development in the energy field.

Polymer Electrode membrane Fuel Cell (PEFC) power generation system for residential usage is one of the 21 technologies since high total efficiency can be obtained by utilizing exhaust heat produced as hot water during power generation. Therefore practical applications have been accelerated[2)] on the basis of the researches on related technologies[3), 4)] and large scale verification projects.

PEFC system was sold in September 2009 in Japan, 5,000 sets were sold in the first year, then sales have been enhanced to 7,000 sets in 2010 and to 13,000 sets in 2011, so far it is expected that the total number of systems will be exceed 40,000 sets in the end of FY 2012[5)]. Especially, coping with the electricity shortage originated from the Great East Japan Earthquake, advanced systems having a specification for emergency power supply has developed, further homebuilders has accelerated to employ PEFC systems to smart house to correspond the requirement of the saving, storage and generation of energy from customers. The total efficiency of PEFC, however, depends heavily on the operation the operation conditions like electricity and heat demand. In the present paper, the energy consumption of a family introduced a PEFC system in Okayama was analysed, then the reduction effect of carbon dioxide was verified.

II. Methods of Measurement and Analysis

A. *Measurement of the operation condition*

The amount of CO_2 emission was estimated from the consumption of the energy, that is, the generated electricity by the PEFC system, the purchased electricity from commercial grid and hot water. The hot water tank has a capacity of 200 litters. The consumption was read from electricity indicator of the system, shown in Fig.1. The purchased electric and total electric consumption were measured by cramp meters and data logger.

Fig.1 Appearance of a 1 kW PEFC system

B. Analysis of CO_2 emission

The energy balance of PEFC for residential usage can be expressed in the following equation,

$$Q_T = Q_p + (Q_g + Q_r + Q_l) \qquad (1)$$

where, Q_T :total energy [GJ/month], Q_p: purchased electric energy [GJ/month], Q_g: generated electric energy by the PEFC [GJ/month], Q_r: recovered heat energy of the system [GJ/month], Q_l: energy loss of the system [GJ/month]. Q_p and Q_g can be estimated from measured electricity [kWhr] and Q_r is estimated by the amount of hot water supplied.

Next, the amount of CO_2 emission can be reduced by the following equation,

$$_pK_T = K_p + K_g \qquad (2)$$

where, $_pK_T$: total CO_2 emission during PEFC operation, [kg・CO_2/month], K_p: CO_2 emission originated from the purchased electricity [kg・CO_2/month], K_g: CO_2 emission originated from the power generation by the PEFC system [kg・CO_2/month], here CO_2 emission for hot water is included in K_g, since the energy of the hot water is by-products of the power generation. It should be noted that additional energy for reheating may be required when the demand of hot water is greater than the capacity of the recovered heat energy of the system.

In the case of All-electric house, the hot water should be heated by purchased electricity, thus the CO_2 emission originated from supplying hot water (K_r) needs to be added. In this case, it is assumed that the amount of the energy for hot water exceed to the maximum capacity (0.2 m^3) of the hot water storage tank contributes to the CO_2 emission, when the hot water is accumulated by using night-time electricity, since the electricity generated by atomic power station where CO_2 emission is almost zero. As a reference, a condition in which night-time electricity is not utilized and a conventional condition where all of the hot water is heated up with kerosene were also calculated for comparison. The basic formulas are shown as follows:

$$K_p = (Q_p/\eta_p)a_p \qquad (3)$$

$$K_g = (Q_g/\eta_g)a_g \qquad (4)$$

where, η_p: the efficiency of electric generation at power station (0.3688), η_g: the efficiency of power generation by the PEFC system, a_p: the constant of CO_2 emission (transmission end, 0.069[kg・CO_2/MJ]), a_g: the constant of CO_2 (Propane, 0.0628[kg・CO_2/MJ]).

$$K_r = (\rho c V \triangle T)\, a_p/\eta_p/\eta_b \qquad (5)$$

K_r: CO_2 emission due to hot water [kg・CO_2/month], V: capacity of hot water tank [m^3], η_b : thermal efficiency for hot water (0.825)

$$K_{ad} = (Q_w - Q_r)\, a_g/\eta_b \qquad (Q_w > Q_r) \qquad (6)$$

K_{ad}: additional CO_2 emission when hot water demand exceeds the amount of recovered heat [kg・CO_2/month], Q_w: required energy for hot water demand [GJ/month]

$$K_{ad}' = (Q_w - Q_d)\, a_g/\eta_p \qquad (Q_w > Q_d) \qquad (7)$$

K_{ad}': additional CO_2 emission when hot water demand exceeds the capacity of hot water storage tank [kg・CO_2/month], Q_d: accumulated heat energy in hot water [GJ/month]

$$K_{ad}'' = Q_w\, a_k/\eta_b \qquad (8)$$

K_{ad}'': CO_2 emission when all hot water are heated up with kerosene [kg・CO_2/month], a_k: the constant of CO_2 emission (kerosene, 0.0682[kg・CO_2/MJ])

C. Pattern of energy demand and case of consumption

Figure 2 shows the distribution of the demand of electric and heat energy for the Japanese families, the distribution of model case where verification test have been conducted in a study by New Energy Foundation (NEF). In Fig.3, six selected conditions for discussing CO_2 emission in this study are shown as point A, B, C, D, E and F. As mentioned later, case A represents the demand condition of the family measured in the present study.

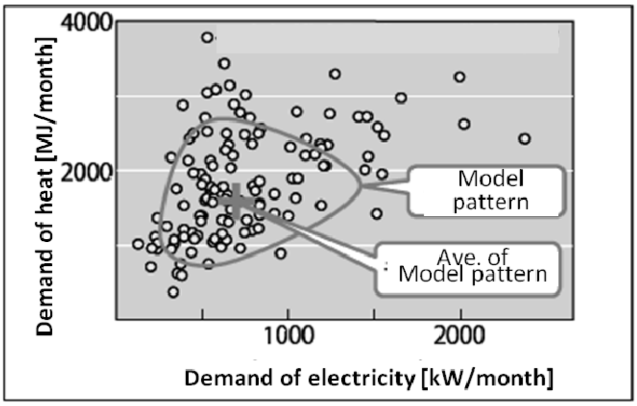

Fig.2 Energy demand pattern where verification test was conducted by NEF

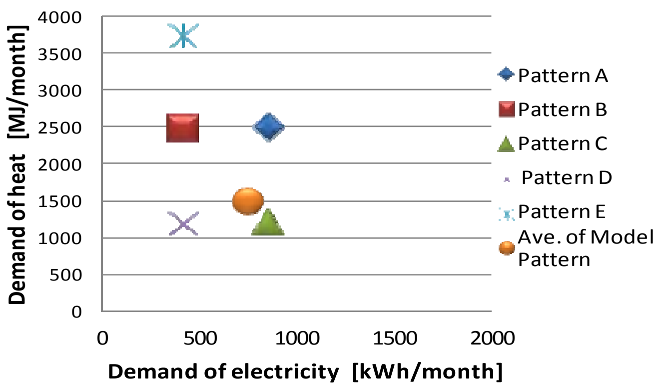

Fig.3 Patterns of energy demand studied

III. Result and Discussion

A. CO_2 emission of pattern A

The measured data of electric and heat energy for the PEFC operation condition shown as A in Fig.3 were analysed, and the amount of CO_2 emission was estimated shown as case 1 in Table 1. Case 2 to case 4 were also calculated in the condition for day-time electricity only (case 2), electricity only included night-time electricity (case 3) and combination of electricity and kerosene (case 4) respectively by using above equations. The results are shown in Table 1. The ratios to the case 4 for case 1, case 2 and case 3 are shown in the bottom row of the table. As a result, it was found that the PEFC contributed to reduce CO_2 emission more than 22%, 27%, 42% for the family compared with the electricity-kerosene combined usage(Case4) and the all-electric usages with (Case2) and without (Case3) night-time electricity respectively. It has been also suggested that the present pattern A is a preferable condition for PEFC system, since the heat demand 850 [kWhr/month] is relatively greater than the electricity demand 2500[MJ/month] due to the family constituted by three generations, although pattern A is within the condition where the research of NEF has been conducted.

Table 1 CO_2 emission of energy demand pattern A

	Consumption	CO_2 emission [$kgCO_2$/month]			
		PEFC (Empirical)	Electric only		Electric & Kerosene
			-	Night	
		Case1	Case2	Case3	Case4
Electric(Purchased) [kWh/month]	444	299	←	←	←
Electric(Generated) [kWh/month]	414	267	253	←	←
Hot water [m^3/month]	13	28	468	257	207
Total	-	594	1020	809	759
Ratio	-	0.78	1.3	1.1	1.0

B. 3.2 CO_2 emission of pattern B

Pattern B is the condition where the demand of electricity is lower than pattern A keeping the demand of hot water in the same level. Regarding the pattern B, the CO_2 emission is 40% less than that of electricity-kerosene combination (case 4), and in comparison to all-electric with (case 2) and without (case 3) night-time electricity, the reduction of CO_2 emission is decreased by 59% and 42 % respectively. From this result, it is suggested that this pattern B is the best for the house introduced PEFC system. The reason why the pattern B is the best is that all electricity required can be generated by the PEFC system without purchasing commercial electricity and most of the hot water required can be supplied by the PEFC system.

Table2 CO_2 emission of energy demand pattern B

	Consumption	CO_2 emission [$kgCO_2$/month]			
		PEFC (Empirical)	Electric only		Electric & Kerosene
			-	Night	
		Case1	Case2	Case3	Case4
Electric (Generated) [kWh/month]	414	267	253	253	253
Hot water [m^3/month]	13	28	468	257	207
Total	-	295	721	510	460
Ratio	-	0.6	1.6	1.1	1.0

C. CO_2 emission of pattern C

Pattern C is a case where the demand of hot water is less and the demand of electricity is greater than those of pattern A. In the pattern C, the CO_2 emission is 10% less than that of kerosene combination (case 4), and the CO_2 reduction of 27%and 0.4% are obtained in the case of with (case 2) and without (case 3) night-time electricity respectively. This is the worst pattern among these patterns resulting from the small demand of heat energy.

Table3 CO_2 emission of energy demand pattern C

	Consumption	CO_2 emission [$kgCO_2$/month]			
		PEFC (Empirical)	Electric only		Electric & Kerosene
			-	Night	
		Case1	Case2	Case3	Case4
Electric(Purchased) [kWh/month]	444	299	299	299	299
Electric (Generated) [kWh/month]	414	267	253	253	253
Hot water [m^3/month]	6.5	0	229	18	101
Total	-	566	781	570	653
Ratio	-	0.9	1.2	0.9	1

D. CO_2 emission of pattern D

Pattern D is a case where the demand of both electricity and hot water are less, and the demand of electricity by the PEFC satisfies the demand of electricity. The CO_2 emission in pattern D shows a reduction of

20% to kerosene combination (case 4), 45%, 1.4% to with (case2) and without (case 3) night-time electricity. The case of pattern D is a little better than that of pattern C.

Table4 CO_2 emission of energy demand pattern D

	Consumption	CO_2 emission [$kgCO_2$/month]			
		PEFC (Empirical)	Electric only		Electric & Kerosene
			-	Night	
		Case1	Case2	Case3	Case4
Electric (Generated) [kWh/month]	414	267	253	253	253
Hot water [m^3/month]	6.5	0	229	18	101
Total	-	267	482	271	354
Ratio	-	0.8	1.4	0.8	1.0

E. CO_2 emission of pattern E

Pattern E is a case where the demand of hot water is greater, and the demand of electricity is less. In the operation condition of pattern E, the reduction of CO_2 emission is 30%, 59% and 48% less than that of kerosene combination (case 4), with (case 2) and without (case 3) night-time electricity respectively. In this pattern, the demand of heat energy is so great that additional heating up by gas, electricity or kerosene is required, that is the most disadvantageous case for all-electric house.

Table5 CO_2 emission of energy demand pattern E

	Consumption	CO_2 emission [$kgCO_2$/month]			
		PEFC (Empirical)	Electric only		Electric & Kerosene
			-	Night	
		Case1	Case2	Case3	Case4
Electric(Generated) [kWh/month]	414	267	253	253	253
Hot water [m^3/month]	20	124	704	493	311
Total	-	391	957	746	564
Ratio	-	0.7	1.7	1.3	1.0

F. Influence of the capacity of hot water tank

The influence of the capacity of hot water storage tank on the CO_2 emission was investigated as shown in Fig. 4, since large storage tank is expected to be advantageous for the case of all-electric usage resulting from the use of nuclear power generation which emits little CO_2. The results of pattern B for case 1 and case 3 are shown in Fig.4. It is found that with increasing the capacity of the hot water storage tank the CO_2 emission decreases due to the increase of utilization of heat energy produced by electric power generation. Then, the value of CO_2 emission saturated at a constant value around 300 [kg/month], meaning the demand of hot water has already satisfied. The difference of CO_2 emission between PEFC and all-electric in the range of the tank capacity more than 400 litters come from the difference of the efficiency of electric generation, that is, in this study, efficiencies of the electric generation for PEFC and commercial power station are assumed 38% and 38.5% respectively.

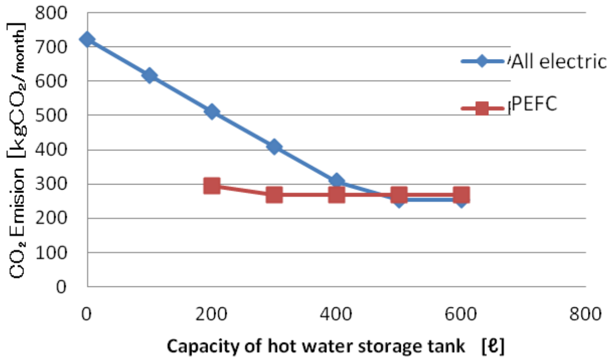

Fig.4 Influence of the capacity of hot water tank on theCO_2 emission for case 1and case 3.

IV. Conclusion

The energy consumption of a family introduced a 1 kW PEFC system for residential usage was analysed, and following results were obtained.

(1)It was found that the PEFC contributed to reduce CO_2 emission more than 22%, 27% and 42% compared with the electricity-kerosene combined usage, the all-electric usages with and without night-time electricity respectively from the empirical data for a month.

(2)The above effect was endorsed by an analysis of a one day demand of electricity and hot water showing the greater demand of both energies in day time

(3)Although the best operation condition is an electric to heat energy demand ratio of 2190/2500, this family's demand ratio was 6459/2500. Namely the family purchased electricity from commercial grid to satisfy the electric demand. Further reduction of CO_2 emission is possible if the demand ratio is optimized.

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