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Hybrid utilization of renewable energy and fuel cells for residential energy systems

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ABSTRACT

This paper describes field experiments and numerical simulations on hybrid utilization of renewable energy and fuel cells for a residential energy system. It presents results of empirical testing and evaluation of hybrid utilization involving solar energy. First, field experiments were conducted on an electric power and domestic hot water supply system that uses both solar energy and fuel cells. The system achieved a large amount of reduction in primary energy consumption compared with conventional systems. Secondly, a simulation was performed on the optimum scale and effect of introduction of the system. The simulation results proposed the optimum capacities of the solar energy utilization and fuel cells to minimize primary energy consumption of the system.

1. Introduction

Previous studies [1,2] evaluated the performance of a polymer electrolyte fuel cell (PEFC) test system to be used for empirical testing and clarified the following: the system's partial load performance, the influence of inlet temperature of water from exhaust heat recovery on performance, start-up and follow-up performance, and environmental protection performance in terms of exhaust emissions. In the case where actual electric power and hot water supply loads were applied, the primary energy reduction effect was also clarified experimentally, and the optimum capacity of a fuel cell combined heat and power system was analyzed using numerical analysis.

The PEFC makes it possible to reduce fuel cell material costs because the cell works in the low-temperature range from room temperature to approximately 80 °C. Furthermore, the PEFC can relatively ease the control of starting and stopping, ensure high total efficiency, and is environmentally friendly and quiet. Regarding the hybrid utilization of renewable energy and the PEFC for the residential use, a stand-alone system [3], a hydrogen system using an electrolyser [4,5] and so forth are worthy of special mention. Although studies [6–9] have addressed the grid-connected utilization of renewable energy and fuel cells in residential energy systems, the optimization using the measured performance of the PEFC and equipments for the renewable energy utilization should become considerably important.

This study tested and evaluated hybrid utilization of fuel cells and solar energy. First, an experiment involving a power generation and hot water supply system was conducted by hybrid utilization of solar energy and fuel cells to determine the percent reduction in primary energy compared with the energy use of a conventional system. Next, hybrid systems were analyzed in Sapporo and Tokyo to clarify the optimum capacity to minimize primary energy consumption of the fuel cell.

2. Analysis of a fuel cell/solar hybrid system

2.1. Study subject and calculation conditions

The hybrid system was analyzed by using the efficiency and partial load performance measured in previous studies [1,2]. Fig. 1 diagrams the hybrid system. A photovoltaic (PV) system and a solar collector (SC) were used to maximize the contribution of renewable energy, with fuel cells (FC) as an auxiliary system. Table 1 lists the calculation conditions. The analysis used the demand for power by a family of four, which was calculated using the prediction program [10] of the Committee for Air Conditioning Systems of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. The load test model of the Institute for Building Environment and Energy Conservation [11] was adopted to model the demand for hot water supply. Here, a commercial power source and a gas water boiler were used as conventional systems. Late-night operation of the FC was avoided because both power and hot water supply loads are small during those hours, and the 24 patterns of operation shown in Table 2 were studied. The cases of the power load following operation and the thermal load following

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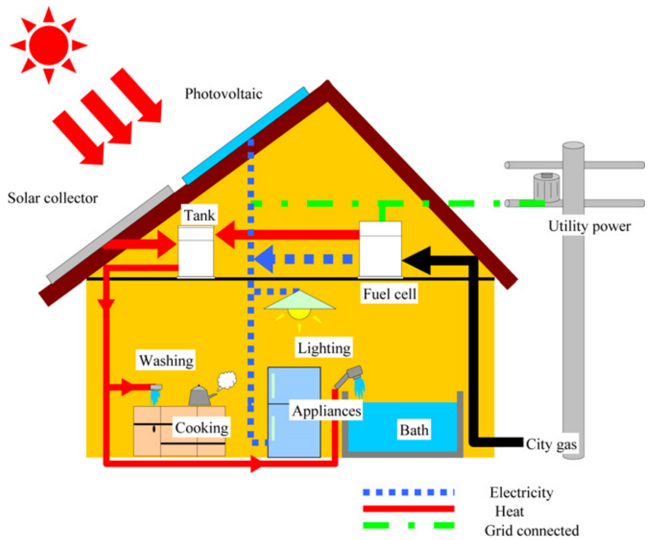

Fig. 1. Hybrid system of solar energy and fuel cell.

Table 1
Calculation conditions.

Target house	Area/type of residence	Total floor area
	Sapporo/detached house	128 m^2
Energy demand (MJ/m^2 year)	Lighting etc. 107.8	Hot water supply 161.2
Fuel cell load factor	AC electrical efficiency	Volumetric flow rate of exhaust heat recovery
100%	25.9%	0.6 L/min
75%	26.0%	0.5 L/min
50%	25.4%	0.3 L/min
Conventional system	Commercial power	City gas

operation were considered, and operation was conducted at a load factor close to the power demand in the case of reverse power flow. The reverse power flow is the electricity that an electric power company buys. Consideration was given to the case in which operation of the FC was stopped when the power demand fell below the minimum load factor (small reverse power), the case in which operation was continued at the minimum load factor even when the power demand fell below the value (medium reverse power), and the case in which the load factor was set to exceed the power demand constantly (large reverse power). A single-crystal silicon PV (area: 24 m^2; nominal system power: 3.1 kW; nominal average conversion efficiency: 13%), a polycrystalline silicon PV (area: 14.4 m^2; nominal system power: 1.5 kW; nominal average conversion efficiency: 11%) and a flat-plate SC (area: 8 m^2; absorptivity of selective absorption film: 0.9) were presented in previous studies [12] as solar energy utilization systems. Each type of panel was placed facing due south at an incline of 31°. As the main basic units for payback-time calculation based on the above-mentioned conventional systems (commercial power source and gas water boiler), the following values were used: single-crystal silicon (energy consumption 7200 MJ/m^2; carbon dioxide emission: 420.6 kg-CO_2/m^2; cost: US$1420/m^2), polycrystalline silicon (energy consumption: 1800 MJ/m^2; carbon dioxide: emission 111.1 kg-CO_2/m^2; cost: US$1140/m^2), solar collector (energy consumption: 1110 MJ/m^2; carbon dioxide emission: 84.0 kg-CO_2/m^2; cost: US$500/m^2), hot water storage tank (energy consumption: 11.6 MJ/L; carbon dioxide emission: 1.0 kg-CO_2/L, cost: US$15/L) and fuel cell (energy consumption: 4000 MJ/kW; carbon dioxide emission: 250 kg-CO_2/kW). The sources of the above basic units related to solar energy utilization systems have been detailed in previous studies [12]. The basic units of energy consumption and carbon-dioxide emission of the fuel cell are estimated from interviews with manufacturers. The future price of fuel cells for domestic use was estimated to be US$5000/kW. The costs of city gas and commercial power supply were assumed to be US$0.97/m^3 and US$0.24/kWh, respectively.

2.2. Calculation results and discussion

In the case of FC/PV hybrid utilization (RUN 5–12) under the power load following operation, the annual total percent reduction of primary energy and CO_2 during operating hours ranged from 43% to 66% and 35% to 57%, respectively (Table 2). The percent

Table 2
Calculation results.

RUN	Fuel cell		Solar energy utilization system	Annual reduction rate (%)			Payback time (year)		
	Operation	Reverse power		Primary energy	CO_2	Cost	Primary energy	CO_2	Cost
1		None		22.18	15.88	17.49	0.50	0.97	28.64
2		Small		23.39	16.66	10.65	0.48	0.92	47.03
3		Medium	None	22.82	15.24	-0.56	0.49	0.97	–
4		Large		22.60	14.69	-3.29	0.49	1.04	–
5		None		61.99	53.03	57.73	4.39	5.82	39.80
6		Small	Single-crystalline silicon photovoltaic (24 m^2)	64.30	55.61	54.36	4.23	5.55	42.27
7		Medium		65.24	56.30	47.04	4.17	5.48	48.85
8	Power load following	Large		65.49	56.27	42.74	4.16	5.48	53.75
9		None		43.51	35.88	41.46	1.16	1.72	32.96
10		Small	Poly-crystalline silicon photovoltaic (14.4 m^2)	45.74	38.27	37.33	1.10	1.62	36.60
11		Medium		46.50	38.40	25.78	1.08	1.61	53.01
12		Large		46.43	37.96	21.47	1.08	1.63	63.64
13		None		27.25	23.43	22.13	1.09	1.86	42.88
14		Small		27.73	23.78	19.48	1.07	1.83	48.71
15		Medium	Solar collector (8 m^2)	27.55	23.27	13.51	1.08	1.87	70.27
16		Large		27.29	22.76	11.50	1.09	1.91	82.53
17		None		27.25	23.61	23.67	1.09	1.85	40.09
18		Small		27.58	23.98	23.32	1.08	1.82	40.70
19		Medium	Solar collector (8 m^2)	26.83	22.80	16.96	1.11	1.91	55.95
20	Thermal load following	Large		26.67	22.49	15.64	1.12	1.94	60.68
21		None		44.37	37.05	41.74	1.13	1.67	32.73
22		Small	Poly-crystalline silicon photovoltaic (14.4 m^2)	46.59	39.43	37.68	1.08	1.57	36.26
23		Medium		47.23	39.87	32.12	1.07	1.55	42.55
24		Large		47.31	39.60	27.51	1.06	1.56	49.66