NUMERICAL SIMULATIONS ON OPTIMAL UTILIZATION OF RENEWABLE ENERGY AND COGENERATION FOR RESIDENTIAL ENERGY SYSTEM

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ABSTRACT

This paper describes field experiments and numerical simulations on hybrid utilization of renewable energy and polymer electrolyte fuel cells for a residential energy system. It presents the 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 on sunny days in Sapporo. The system achieved a 46.6% 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 shows that the optimum capacity of the polycrystalline silicon photovoltaic cell and polymer electrolyte fuel cell to minimize primary energy consumption in Sapporo was 27 m² (max. output: 2.8 kW) and 1.1 kW, respectively, under the condition where reverse power flow was not taken in account. The hybrid system of electric power and domestic hot water supply was analyzed for residential energy systems in Sapporo and Tokyo. It was also clarified that when heat from the hybrid system with a solar collector was used only for domestic hot water supply, the optimum capacity of the fuel cell was approximately 1 kW in Sapporo.

KEYWORDS

Simulation, Residential energy system, Polymer electrolyte fuel cell

INTRODUCTION

This paper describes hybrid utilization of renewable energy and fuel cells for a residential energy system. 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 cogeneration 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. Technical development for practical use has been promoted in Japan and overseas. Such development is especially active in Japan, involving the Ministry of Land, Infrastructure and Transport, the Ministry of Economy, Trade and Industry, the Japan Gas Association, the Fuel Cell Commercialization Conference of Japan (secretariat: New Energy Foundation) and other organizations. Although the New Energy Foundation and the Institute for Building Environment and Energy Conservation have carried out demonstration projects for performance evaluation of systems

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commercially available, data from these projects have not been published. No reports on such a system's potential have addressed detailed power generation and exhaust heat recovery under actual operation. 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 on a sunny day to determine the reduction rate in primary energy compared with the energy use of a conventional system. Next, hybrid systems were analyzed in Sapporo and Tokyo to clarify the relationship between regional characteristics and optimum capacity to minimize primary energy consumption of the fuel cell.

ANALYSIS OF A FUEL CELL/SOLAR HYBRID SYSTEM

Study subject and calculation conditions

The hybrid system was analyzed by using the heat efficiency and partial load performance measured in previous studies [1, 2]. Since conventional systems for the use of exhaust heat from fuel cells have tended to focus on providing heat for hot water supply, the subjects of this analysis were limited to hot water demand and electric power demand for lighting and other purposes; air conditioning was excluded. Fig. 1 diagrams the hybrid system. A photovoltaic (PV) system and a solar collector (SC) were used to maximize the contribution of natural 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 [3] of the Committee for Air Conditioning Systems of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. The load test model (L mode) of the Institute for Building Environment and Energy Conservation [4] 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 fuel cell (11 p.m. – 5 a.m.) 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 operation were considered, and operation was conducted at a load factor close to the power demand in the case of reverse power flow. Consideration was given to the case in which operation of the fuel cell was stopped when the power demand fell below the minimum load factor of 50% (small reverse power flow), the case in which operation was continued at a load factor of 50% even when the power demand fell below the minimum load factor (medium reverse power flow), and the case in which the load factor

![Fig. 1. Hybrid system of solar energy and fuel cell.](image-url)
A single-crystal silicon solar cell (area: 24 m²; nominal system power: 3.1 kW; nominal average conversion efficiency: 13%), a polycrystalline silicon solar cell (area: 14.4 m²; nominal system power: 1.5 kW; nominal average conversion efficiency: 11%) and a flat-plate solar collector (area: 8 m²; absorptivity of selective absorption film: 0.9) were presented in previous studies [5] as solar energy utilization systems. Each type of panel was placed facing due south at an incline of 31 degrees.

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 (¥142,000/m²), polycrystalline silicon (¥114,000/m²), solar collector (¥50,000/m²), hot water storage tank (¥1,500/L) and fuel cell (¥500,000/kW).

### Table 1 Calculation conditions

<table>
<thead>
<tr>
<th>Target house</th>
<th>Area/type of residence</th>
<th>Total floor area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapporo/detached house</td>
<td>128 m²</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy demand (MJ/m²/year)</th>
<th>Lighting etc.</th>
<th>Hot water supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>107.8</td>
<td>161.2</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel cell load factor</th>
<th>Higher heating value (HHV)</th>
<th>Exhaust heat recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>25.9%</td>
<td>0.6 L/min</td>
</tr>
<tr>
<td>75%</td>
<td>26.0%</td>
<td>0.5 L/min</td>
</tr>
<tr>
<td>50%</td>
<td>25.4%</td>
<td>0.3 L/min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conversion factor</th>
<th>Commercial power</th>
<th>City gas</th>
</tr>
</thead>
</table>

| Primary energy                | 9.887 MJ/kWh     | 46.05 MJ/m³     |
| Carbon dioxide                | 0.480 kg-CO₂/kWh | 2.361 kg-CO₂/m³ |

### Table 2 Calculation results

<table>
<thead>
<tr>
<th>RUN</th>
<th>Solar cell type</th>
<th>Reverse power utilization system</th>
<th>Power load following</th>
<th>Thermal load following</th>
<th>Annual reduction rate (%)</th>
<th>Fuel cell</th>
<th>Payback time (year)</th>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Solar collector (8 m²)</td>
<td>27.52</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
</tr>
<tr>
<td>2</td>
<td>Small</td>
<td>None</td>
<td>None</td>
<td>Solar collector (8 m²)</td>
<td>27.52</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>None</td>
<td>None</td>
<td>Solar collector (8 m²)</td>
<td>27.52</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
</tr>
<tr>
<td>4</td>
<td>Large</td>
<td>None</td>
<td>None</td>
<td>Solar collector (8 m²)</td>
<td>27.52</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
</tr>
<tr>
<td>5</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Small</td>
<td>61.99</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
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<tr>
<td>6</td>
<td>Small</td>
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<td>None</td>
<td>Small</td>
<td>64.30</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
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<tr>
<td>7</td>
<td>Medium</td>
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<td>None</td>
<td>Small</td>
<td>65.24</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
</tr>
<tr>
<td>8</td>
<td>Large</td>
<td>None</td>
<td>None</td>
<td>Small</td>
<td>65.49</td>
<td>1/2</td>
<td>31.60</td>
<td>28.64</td>
</tr>
</tbody>
</table>

Calculation results and discussion

In the case of fuel cell/solar hybrid utilization (RUNS – 12) under the power load following operation, the annual total percent reduction of primary energy and carbon dioxide during operating hours ranged from 43% to 66% and 35% to 57%, respectively (Table 2). The percent reduction of operating cost was also very high, ranging from 22% to 58%. Although the percent reduction in the case of using a single-crystal silicon solar cell with a high photovoltaic conversion rate (RUN 5 – 8) far exceeded the rate for the polycrystalline silicon solar cell (RUN 9 – 12), payback time was smaller for the latter because energy consumption, carbon dioxide emissions and cost at the installation stage exceeded...
that of the former. There was not much difference in performance between operation under the power
load following operation and that under the thermal load following operation of fuel cells (RUN 21 – 24).
In the case of fuel cell/solar collector hybrid utilization (RUN13 – 20), the percent reductions were 26% to 28%, 22% to 24% and 11% to 24%, respectively, for primary energy, carbon dioxide and cost. Partly because subsidies were not taken into account, the cost payback time of hybrid utilization with a solar
energy system was estimated to exceed 30 years under the calculation conditions of this study.

EXPERIMENT OF A FUEL CELL/SOLAR HYBRID SYSTEM

Summary of the experiment

A full-scale experiment was conducted under three conditions (none of which had reverse power flow),
using the analysis results of the percent reduction in primary energy under various operation conditions
as a reference. Fig. 2 diagrams the experiment facility. This experiment used a 14.4-m² polycrystalline
silicon solar cell (maximum output: 1.5 kW), a flat-plate solar energy collector (8 m²) and a polymer
electrolyte fuel cell (maximum AC output: 1 kW). Separate hot water storage tanks were installed for the
solar collector (300 L) and fuel cell (200 L). The system first used PV cells to supply the power demand,
and then operated the FC when the supply by PV cells was insufficient. Although the power-load
system used to simulate the power demand can change load within the range of 0.1 to 6 kW (0.1 kW at a
time) at minimum intervals of 15 minutes, we set the changes for intervals to 1 hour in this experiment.
The opening and closing of the solenoid valve to run hot water in the bathroom was controlled in
accordance with the test model of the hot water supply. When the temperature of running water
exceeded the preset value (42°C), the water volume converted to the equivalent heating value was
discharged. When water was discharged without auxiliary heating in the experiment where the preset
value was not reached, the amount of heat under the assumption that the water was reheated by a gas
water boiler was calculated from the required water volume and temperature. Temperature correction
was made for gas consumption. Experiment 1, which was conducted in April (average feed-water
temperature during the experiment: 16.3°C, maximum intensity of global solar radiation on the panel
surface: 1018 W/m², outside air temperature during the experiment: 2-17°C), was equivalent to RUN9
in the analysis results shown in Table 2, and the FC operating time was 6 hours. Experiments 2 and 3 in August (average feed-water temperature during the experiment: 23.0°C; maximum intensity of global solar radiation on the panel surface: 944 W/m²; outside air temperature during the experiment: 17-25°C) used a combination of PVs and a solar collector, and operation was planned based on hot water demand. Although all of the experiments were conducted on sunny days, the duration of PV power generation differed in Experiments 1 and 3 because these experiments were conducted on separate days.

**Experiment results and discussion**

In Experiment 1, the net electrical efficiency and exhaust heat recovery efficiency of FC power generation were approximately 23% and 41%, respectively, and they were stable regardless of load factor. Most of the daytime power demand was supplied by PV generation. The total amount of PV power generation in two days was 53.5 MJ, of which 32.6 MJ was reverse-power-flow energy. The capacity used in this experiment was about half that for a commonly used residential PV system in which the amount equivalent to the annual nighttime power demand is stored by reverse power flow during the daytime. Because the experiment was conducted on a sunny day, approximately 60% of PV power generation was reverse-power-flow energy. Power was supplied from FC after 5 p.m., and the power output was 33.8 MJ. The dependences on PV and FC excluding reverse power flow were 27.9% and 45.5%, respectively. The dependence including reverse power flow reached 71.7%. The FC was not operated during the daytime because the power demand was satisfied by PV, and auxiliary heating was required during many hours of hot water supply. Dependence on the FC for hot water supply was 35.5%. Fig. 3 breaks down the use by type of energy (secondary conversion value). PV accounted for 12.6% of total output, and FC accounted for 20.5% of electric power output and 19.4% of heat output. The primary energy reduction rate reached 64.4%. The net electrical efficiency and exhaust heat recovery efficiency in Experiment 2 were 23% and 41%, respectively. As in Experiment 1, they were stable regardless of load factor. Dependence on the solar collector was 28.0%, and dependence on the
FC was 8.3% for both power and heat. The primary energy reduction rate was 37.2%. Whereas the energy balance in Experiment 3 tended to be the same as those in Experiments 1 and 2, PV power generation in Experiment 3 was 66% of that in Experiment 1 due to differences in solar radiation conditions. The primary energy reduction rate in Experiment 3 was 64.2%.

**ANALYSIS OF THE OPTIMUM SCALE OF PV AND FC AND THE EFFECT OF INTRODUCTION OF THESE DEVICES ON ENERGY CONSUMPTION**

**Subjects of the study and calculation conditions**

A program was developed to analyze a fuel cell/solar hybrid system. Input data included the demand for power and hot water supply by hour, external weather data and tap water temperature. The subject of analysis was the demand for hot water and power for lighting and other purposes. Air conditioning was not taken into account. PV power generation was calculated based on external weather conditions, and thermal energy collection by the solar collector was found from the temperature of the heat medium to calculate the temperature of water in the hot water storage tank. It was considered possible to operate the FC to supplement the power demand that cannot be satisfied by PV (power load following operation) or to supplement the shortage of hot water supply by the solar collector (thermal load following operation). Calculations were made for the respective operation patterns to determine FC power generation, exhaust heat collection and gas consumption. The grid-connected system with commercial power supply was adopted for use of that power when the power demand was not satisfied by the combined power of PV and FC. An auxiliary heat source was used when the demand for hot water supply was not satisfied by the combination of solar heat collection and FC exhaust heat recovery. An annual simulation was performed by changing the respective scales of the PV, SC and FC for calculation of the optimum capacity to minimize primary energy consumption and the percent reduction in primary energy, carbon dioxide and cost from conventional power generation methods.

The subjects of calculation were detached houses (families of four) in Sapporo and Tokyo in which fuel cell/solar hybrid systems were installed. The analysis used the demand for power by a family of four, which was calculated using the prediction program [3] of the Committee for Air Conditioning Systems of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. The load test model (L mode) of the Institute for Building Environment and Energy Conservation [4] was adopted to represent hot water demand. The hot water demand per unit floor area is 132.7 MJ/m² year based on the tap water temperature in Tokyo. In this analysis, the performance of a next-generation system (LHV-based heat efficiency of power generation at the alternating current end: 34%; heat efficiency of exhaust heat collection: 47%; power load factor: 30% to 100% in continuous operation) was used in accordance with the manufacturer’s literature. Late-night FC operation (11 p.m. – 5 a.m.) was avoided because both power and hot water supply loads are low during those hours, and the operation method was the power load following or vice versa. Reverse power flow was not applied and operation was stopped when the power load fell below the minimum power load factor of the FC. Startup energy consumption of the FC and standby power consumption were not taken into account in this analysis because improvement of these factors was considered necessary for commercialization; thus, the effect of introduction of the FC would become higher than in practical application. Modeling of these factors must be addressed in the future. Since most of the standby power at present goes to measurement, standby power consumption may be reduced significantly in use of residential FC if the FC is installed indoors in cold regions and does not require anti-freezing measures. The polycrystalline silicon solar cell and a flat-plate solar collector were used as the solar energy utilization system.

**Calculation results and discussion**

Fig. 4 shows the relationship between primary energy consumption, including initial consumption for the system production and the installation, and the capacity of a solar energy utilization system installed in Sapporo, in the case in which excess PV power generation was not considered in energy-saving
Energy required for equipment maintenance was not taken into account here. The horizontal axes represent the area of PV cells and the rated output of FC, respectively. When the capacity of FC were 27 m² (maximum output: 2.8 kW) and 1.1 kW, the primary energy consumption tended to be the smallest, and the percent reduction was 34.8% for 42.5 GJ/year. In this case, PV accounted for 12.7% of total energy consumption; FC accounted for 23.2% of electric power and 34.7% of heat. Dependence on power generation reached 31.6% for PV and 57.7% for FC. Dependence on the FC for hot water supply was 58.0%. The percent reduction in primary energy, carbon dioxide and cost compared with the costs of conventional systems (commercial power supply and gas water boiler) were 39.1%, 34.6% and 47.2%, respectively, showing the potential for very high favorable effects of introduction.

Similar calculations were conducted in Tokyo, where primary energy consumption was smallest when the area of PV was 23 m² (maximum output: 2.4 kW) and FC capacity was 1.1 kW. PV generation accounts for 11.8% of the total energy consumption and is slightly lower than in Sapporo because the annual PV power output per unit panel area is approximately 3% greater in Sapporo. Since this led to an increase in FC operation rate, the percentages of electric power and heat were 27.5% and 38.9%, respectively, and were higher than in Sapporo. Dependence on the PV and FC for power generation was 26.3% and 61.2%, respectively, and that on the FC for hot water supply was 70.5%.

For analysis of hybrid utilization of the SC and FC, the type of FC operation was the thermal load following. Fig. 5 shows the relationship between primary energy consumption and the capacity of a solar energy utilization system installed in Sapporo. The horizontal axes represent the area of SC and the rated output of the FC. The primary energy consumption tended to be the smallest when the collector area was 19 m² and FC capacity was 1 kW, and the percent reduction of energy consumption was 33.1% for 43.6 GJ/year. In this case, FC power generation accounts for 9.8% of total energy consumption. For hot water supply, the SC and exhaust heat from the FC account for 54.7% of the total energy consumption. Dependence on the FC for electric power was 24.2%; the combined dependence

![Fig. 5. Relationship between primary energy consumption and installed capacity (FC and PV, Sapporo).](image-url)
on the SC and FC for hot water supply reached 91.9%. The percent reductions for primary energy, carbon dioxide and cost were 35.6%, 36.9% and 33.3% lower than those of the conventional system, respectively.

As a result of similar calculations in Tokyo, primary energy consumption was the smallest when the collector area was 15 m² and FC capacity was 1.0 kW. Because the solar heat collection conditions were more favorable than in Sapporo, the SC scale was approximately 20% smaller. FC power generation accounted for 8.7% of total energy consumption, which was lower than that in Sapporo. Since most of the hot water can be supplied by the SC, there was less dependence on the FC. SC and FC for hot water supply collectively accounted for 53.4% of total energy consumption. Dependence on the FC for electric power was 19.4%, and combined dependence on the SC and FC for hot water supply stood at 96.7%.

REFERENCES