Proposal on Hydrogen-Integrated Power and Heat Systems of Households Achieving Resilience

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***Abstract*—The energy system tries to be more resilient to severe disasters. The demand-side measures such as owing solar panels, batteries, and fuel cells mitigate the damage of such disasters. This paper proposes the residential system with hydrogen, including a water electrolyzer, a fuel cell, and hydrogen storage. The sufficient size of hydrogen storage is decided as $4\,\mathrm{Nm}^3$ from the simulation of the maximum supply shortages with a solar/battery residential system. The proposed system achieves $35.9\,\%$ supply shortages even in a severe 48-hour outage than the solar/battery system. However, the system is vulnerable to gas supply interruptions because the fuel cell cannot serve enough heat.**

***Index Terms*—Residential, Hydrogen system, Storage sizing, Heat demand, Resilience**

I. Introduction

The infrastructure in the energy system suffers from severe disasters. In Japan, typhoons and heavy rains sometimes damage the power transmission and distribution systems. The large earthquakes damage not only the power system but also the gas and water pipelines. These disasters causes extensive supply interruptions for a long time.

On the one side, energy suppliers take measures against disasters [1]–[3]. Damage mitigation [1], recovery [2], and prevention [3] are the main direction of these measures. On the other side, energy consumers also improve their resiliency. Consumers mainly mitigates supply interruptions by preparing generators and energy storages. The solar panels and batteries are considered a promising residential system [4]–[7]. Hydrogen and fuel cells also work as backup generators in apartments [8], buildings [9], and telecommunication bases [10]. The solar and battery system tends to be short in energy at night. The diesel generators [11] can support for such risks. However, they does not generate electricity in the normal state. Instead, the hydrogen and fuel cell system will actively work using low price electricity so that it can reduce the energy cost.

It is necessary for demand-side measures to construct the resilient energy system. This paper aims to propose the residential energy system including hydrogen for mitigating severe outages. The proposed system uses hydrogen as an energy storage in addition to the battery. This paper decides the hydrogen storage size focusing on the worst outage. In addition, this paper evaluates the system resiliency against electricity and gas supply interruption.

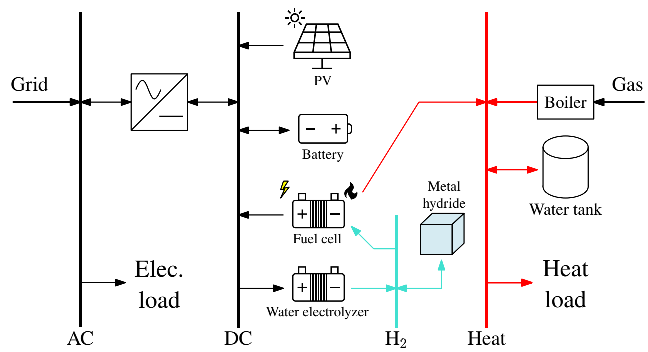

Fig. 1. Energy system model in a household. It omits DC/DC converters at solar panels, a battery, a fuel cell, and an electrolyzer.

II. Model

A. Household Model

This paper considers the electricity and heat demand. Fig. 1 shows the household model. The household connects the power grid and gas pipeline. The electricity prices connect to the wholesale market prices. In contrast, the gas has a constant unit price in a month. The boiler burns gas and supply hot water to fill heat demand. The heat is stored in the hot water tank.

The household has solar panels, a battery, a fuel cell, a water electrolyzer, and a hydrogen storage. Table I shows the properties of each element. The solar panels generate electricity, and the battery can absorb it. The fuel cell generates electricity and heat using pure hydrogen. This paper decides the size of solar panels, the battery, and fuel cell based on actual produces for a typical house in Japan. The efficiency of the fuel cell follows the target in 2030 ($55\,\%$) in terms of electricity and the actual product ($33\,\%$) in terms of heat. The electrolyzer produces hydrogen, which is stored by a metal hydride. This paper chooses a metal hydride as a hydrogen storage because it has a high volume density.

This paper uses the actual demand data in the case study. Fig. 2 shows the electricity demand and solar generation in the winter. The electricity demand rises from $1\,\mathrm{kW}$ to $2\,\mathrm{kW}$ in the evening and night. The solar generation with a $4\,\mathrm{kW}$ capacity rises around $2\,\mathrm{kW}$ in the daytime. Fig. 3 shows the

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TABLE I
MAIN PROPERTIES OF HOUSEHOLD'S EQUIPMENT.

Name	Value	Unit
Solar panel size	4	[kW]
Battery nominal output	5	[kW]
Battery nominal capacity	13.5	[kWh]
Battery efficiency	0.9	[-]
Fuel cell nominal input	1.27	[kW]
Fuel cell power nominal output	0.7	[kW]
Fuel cell heat nominal output	0.42	[kW]
Electrolyzer nominal input	2	[kW]
Hydrogen conversion efficiency	4.81	[kWh/Nm^3]
Hydrogen storage size	6	[Nm^3]
Boiler efficiency	80	[%]
Hot water tank size	100	[L]
Hot water tank heat dissipation	1.2	[%/h]

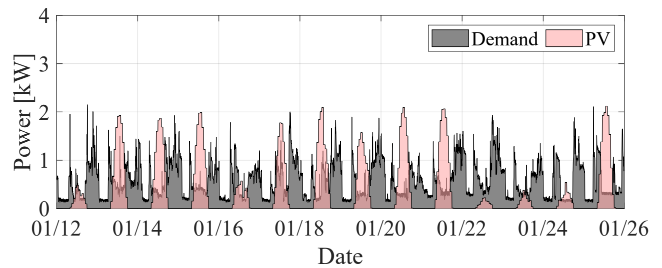

Fig. 2. Electricity demand and PV generation with 4 kW solar panels in the winter.

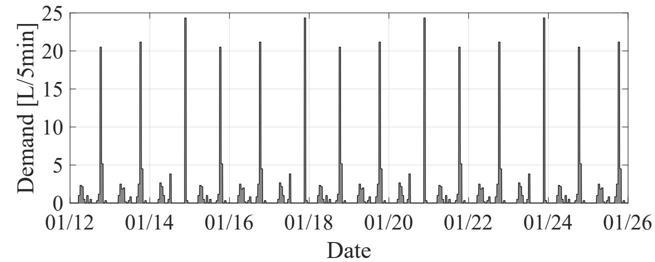

Fig. 3. Hot water demand per 5 minutes in the winter.

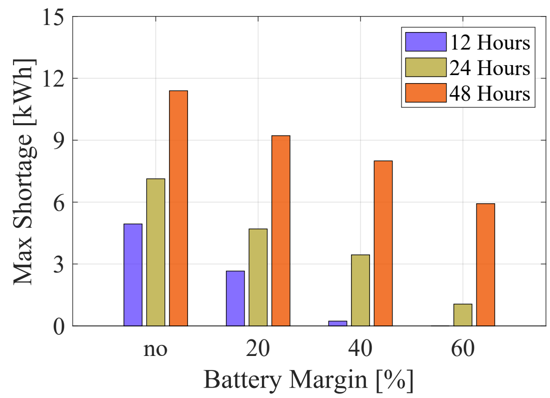

Fig. 4. Maximum shortage of necessary electricity demand during an unpredictable outage in the winter.

hot water demand in the winter. The household uses a large amount of hot water in the evening, describing a hot bath.

B. Hydrogen System Sizing

This paper introduces the hydrogen system to ensure electricity supply for necessary demand. It is important to decide the size of an electrolyzer and a storage that is enough for backup. The electrolyzer's maximum input is set 2 kW to meet a nominal input of the fuel cell.

The method to decide the storage size is based on the electricity supply shortage in various outage scenarios. The severity of shortages depends on the power outage timing and duration. Thus, this paper simulates different occurrence timings and durations using optimization. The method to simulate supply shortages is based on [12]. This paper considers 12-hour, 24-hour, and 48-hour outages with different occurrence timings. In all outage scenarios, the household cannot predict the outage occurrence. In the simulations, the household has 4 kW solar panels and a 5 kW/13.5 kWh battery but does not have the hydrogen system. The battery's operation is decided to minimize the total electricity and outage cost [12]. The simulations also considers margins of the battery's state-of-charge (SoC) [12]. It restricts discharging deeply to measure sudden outages.

The hydrogen system expects to measure the worst outage scenario. Fig. 4 shows the maximum shortage amount of necessary demand. The simulations considers a half of the electricity demand necessary during outages. 24-hour outages can cause a 3 kWh shortage with a 40 % SoC margin (equal to 4.86 kWh). The worst case in 48-hour outages causes a 6 kWh shortage even with a 60 % margin (equal to 7.29 kWh). The worst case happens with an outage happening at night and little solar generation in the next daytime. The hydrogen system supports supply in such less-generation situations. Considering the combustion heat of hydrogen (3.54 kWh/Nm^3) and the assumed efficiency of the fuel cell (55 %), the hydrogen system can eliminate the shortage of necessary demand with a 4 Nm^3 or larger storage. In addition, the electrolyzer can absorb the excess energy of solar generation caused by high SoC margins. Thus, the hydrogen storage has a 2 Nm^3 headroom.

III. OPTIMIZATION WITH SUPPLY INTERRUPTION

The optimization problem simulates the operation of the battery, fuel cell, and electrolyzer. The objective is to minimize the sum of electricity and supply shortage costs [12], as shown in Equation (1).

$$\begin{aligned} \text{min. } TC = \sum_t (&C_{\text{elec},t} \times E_{\text{grid},t} \\ &+ C_{\text{gas},t} \times E_{\text{gas},t} \\ &+ C_{\text{short,elec}} \times E_{\text{short,elec},t} \\ &+ C'_{\text{short,elec}} \times E'_{\text{short,elec},t} \\ &+ C_{\text{short,heat}} \times E_{\text{short,heat},t}). \end{aligned} \tag{1}$$

E_{grid} and E_{gas} denotes the energy from the grid and gas pipeline. $E_{\text{short,elec}}$ and $E'_{\text{short,elec}}$ denote the electricity supply shortage of necessary and other demand, respectively. $E_{\text{short,heat}}$ denotes the heat supply shortage. C_{elec} and C_{gas}

denotes the electricity and gas prices. $C_{\mathrm{short,elec}}$ and $C'_{\mathrm{short,elec}}$ denote the power outage unit costs, which correspond to the necessary and other demand, respectively. $C_{\mathrm{short,elec}}$ denotes the heat shortage unit costs. The unit cost of supply shortages is larger than the electricity and gas prices. This paper does not weight heat demand on its importance. t denotes the index of time slots.

The optimization problem describes the supply shortage in the constraints. Equations (2) and (3) show the balance of supply and demand, and the maximum power from the grid, respectively.

$$\begin{aligned} E_{\mathrm{grid},t} &+ E_{\mathrm{BTd},t} + E_{\mathrm{PV},t} \\ &+ E_{\mathrm{FC,elec},t} + E_{\mathrm{short,elec},t} + E'_{\mathrm{short,elec},t} \\ &= E_{\mathrm{dem,elec},t} + E_{\mathrm{BTc},t} + E_{\mathrm{EL},t}. \end{aligned} \tag{2}$$

$$E_{\mathrm{grid},t} \leq (1 - BIN_{\mathrm{outage},t}) \times E_{\mathrm{grid}}^{\max}. \tag{3}$$

On the electricity supply, E_{PV}, E_{BTd}, and $E_{\mathrm{FC,elec}}$ denote the solar generation, battery's discharge, and fuel cell generation, respectively. On the electricity demand, $E_{\mathrm{dem,elec}}$, E_{BTc}, and E_{EL} denote household's demand, battery's charge, and electrolyzer's input, respectively. BIN_{outage} denotes the power outage state. The supply shortage can happen during the power outage ($BIN_{\mathrm{outage}} = 1$).

The problem also includes the supply and demand balance of hot water and hydrogen. Equations (4) and (5) show each balance.

$$\begin{aligned} E_{\mathrm{gas},t} \times \eta_{\mathrm{b}} &+ E_{\mathrm{FC,heat},t} + E_{\mathrm{out,heat},t} + E_{\mathrm{short,heat},t} \\ &= E_{\mathrm{dem,heat},t} + E_{\mathrm{in,heat},t}. \end{aligned} \tag{4}$$

$$H_{\mathrm{EL},t} + H_{\mathrm{out},t} = H_{\mathrm{FC},t} + H_{\mathrm{in},t}. \tag{5}$$

On the heat supply, $E_{\mathrm{FC,heat}}$ and $E_{\mathrm{out,heat}}$ denote the fuel cell generation and discharge of the hot water tank. On the heat demand, $E_{\mathrm{dem,heat}}$ and $E_{\mathrm{in,heat}}$ denote household's demand and charge of the hot water tank. The household's demand is calculated by the hot water amount (Fig. 3), the specific heat of water ($1.16\,\mathrm{Wh/L/K}$), and the temperature difference between tap water ($10\,^{\circ}\mathrm{C}$) and heated water ($60\,^{\circ}\mathrm{C}$). The boiler has a conversion coefficient of η_{b}. It equals the combustion heat of gas ($12.5\,\mathrm{kWh/m^3}$) muliplied by the boiler efficiency ($80\,\%$). On the hydrogen supply, H_{EL} and H_{out} denote electrolyzer's production and discharge of the hydrogen storage. On the hydrogen demand, H_{FC} and H_{in} denote the fuel cell input and charge of the hydrogen storage.

The fuel cell generates electricity and heat simultaneously using hydrogen, as shown in Equations (6) and (7).

$$E_{\mathrm{FC,elec},t} = H_{\mathrm{FC},t} \times \eta_{\mathrm{FC,elec}} \tag{6}$$

$$E_{\mathrm{FC,heat},t} = H_{\mathrm{FC},t} \times \eta_{\mathrm{FC,heat}} \tag{7}$$

$\eta_{\mathrm{FC,elec}}$ and $\eta_{\mathrm{FC,heat}}$ denote the conversion coefficients of electricity and heat. They equal the combustion heat of hydrogen ($3.54\,\mathrm{kWh/Nm^3}$) multiplied by the fuel cell efficiencies.

Stored energy in storages changes by charging and discharging electricity, heat, or hydrogen. Equations (8), (9), and (10) show the change of stored energy in the battery, hot water tank, and hydrogen storage.

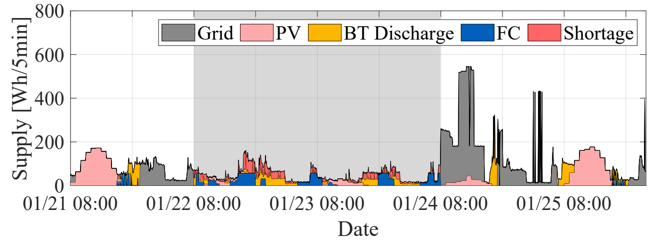

Fig. 5. Electricity supply around a 48-hour unpredictable supply interruption. Grey area shows a supply interruption.

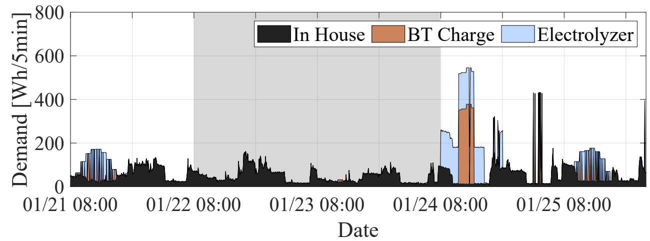

Fig. 6. Electricity demand around a 48-hour unpredictable supply interruption. Grey area shows a supply interruption.

$$E_{\mathrm{BT},t} = E_{\mathrm{BT},t-1} + E_{\mathrm{BTc},t} \times \eta_{\mathrm{BT}} - E_{\mathrm{BTd},t}/\eta_{\mathrm{BT}}. \tag{8}$$

$$\begin{aligned} E_{\mathrm{tank,heat},t} &= E_{\mathrm{tank,heat},t-1} \times (1 - \alpha) \\ &\quad + E_{\mathrm{in,heat}} - E_{\mathrm{out,heat}}. \end{aligned} \tag{9}$$

$$H_{\mathrm{tank},t} = H_{\mathrm{tank},t-1} + H_{\mathrm{in},t} - H_{\mathrm{out},t}. \tag{10}$$

E_{BT}, $E_{\mathrm{tank,heat}}$, and H_{tank} denote the stored electricity, heat, and hydrogen, respectively. η_{BT} denotes the efficiency of battery's charge and discharge. Such a efficiency of hot water and hydrogen is assumed $100\,\%$. The heat can be dissipated from the tank described as α. The battery tends to work with daily cycles according to excess solar generation. Thus, the simulation can ignore the self-discharging of the battery. In addition to stored energy changes, the storages have a margin to mitigate supply shortages. In the optimization, the battery has a $60\,\%$ SoC margin, the hot water tank has a $20\,\mathrm{L}$ margin, and the hydrogen storage has a $4\,\mathrm{Nm^3}$ margin.

IV. Case Study Result

This paper considers a 48-hour interruption of both electricity and gas supply. It starts at the morning with continuous

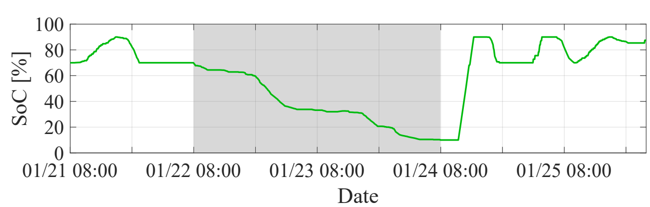

Fig. 7. State-of-charge (SoC) of the battery around a 48-hour unpredictable supply interruption. Grey area shows a supply interruption.

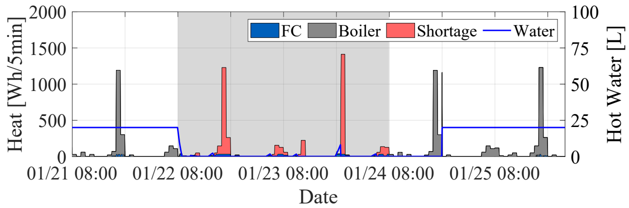

Fig. 8. Hot water supply and storage around a 48-hour unpredictable supply interruption. Grey area shows a supply interruption.

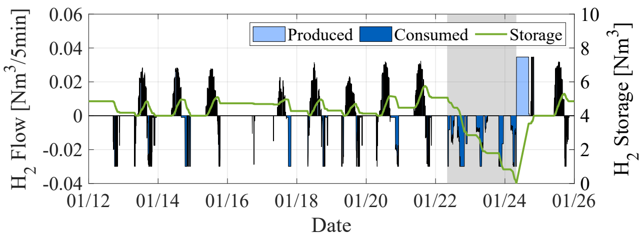

Fig. 9. Hydrogen inflow, outflow, and storage in the optimization. Grey area shows a supply interruption.

little generation of solar panels. Thus, it is considered one of the worst cases within a 48-hour interruption in the winter.

The hydrogen system can mitigate the severe supply interruption by suppling electricity. Figs. 5 and 6 show the electricity supply and demand around the supply interruption. Fig. 7 shows the battery SoC around the supply interruption. The supply shortage remains even with the hydrogen system. However, the battery and fuel cell supply most of the electricity demand. The total shortage is $8.14\,\mathrm{kWh}$, which is $35.9\,\%$ lower than that of the solar/battery system with a $60\,\%$ SoC margin.

In contrast, the interruption of the gas supply has a larger impact than the electricity supply. Fig. 8 shows the hot water supply and storage around the supply interruption. The total hot water shortage is $44.2\,\mathrm{kWh}$ or $760\,\mathrm{L}$. It equals $86.4\,\%$ of the hot water demand during the interruption. A large amount of shortages happens in the evening because the fuel cell cannot supply enough heat. The fuel cell can only generate $35\,\mathrm{Wh/5min}$, but the demand is 30 times larger. The household must suppress the hot water demand during the gas interruption.

The electrolyzer produces hydrogen when it can use excess solar generation. Fig. 9 shows the hydrogen flow and storage in the 2-week optimization. Hydrogen is produced only in the daytime and consumed in the evening. The battery cannot absorb all of the excess solar generation because of a high SoC margin. Thus, the electrolyzer absorbs it and produces hydrogen. In addition, the fuel cell consumes hydrogen in the evening because of the high electricity price.

V. Conclusion

This paper proposes the household energy system including hydrogen to mitigate supply interruptions. Solar panels and a battery have a limitation to supply electricity during power outages. The analysis of different power outage scenarios finds that a $7.29\,\mathrm{kWh}$ margin of the battery and $4\,\mathrm{Nm}^3$ hydrogen storage will fulfill the necessary demand. This paper also simulates a lengthy interruption of both electricity and gas supplies. The hydrogen system reduces the electricity supply shortage by $35.9\,\%$ with a severe 48-hour interruption. However, it does not supply enough heat because the fuel cell has a small heat output.

This paper shows the mitigation of supply interruptions by the hydrogen system. However, we confirm that the system does not work actively in the normal state when there is not enough excess solar generation. It causes the worse economic efficiency of the system. Evaluation of and improvement in the economic efficiency are our future work.

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