Enhancing Urban Sustainability Through Optimized PV/fuel cell/battery hybrid energy system Operations in Smart Communities

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ABSTRACT

In urban planning for low-carbon and disaster-resilient communities, smart communities with decentralised energy systems have gained continuous attention. These systems integrate photovoltaic (PV) generation with batteries and fuel cells to mitigate the intermittency of PV. PV battery systems focus on optimal household-level operation and consider peer-to-peer energy trading for community optimisation. Another promising approach involves a PV/fuel cell/battery hybrid energy system (three-battery hybrid system). However, there is limited understanding of the complexity of controlling multiple energy sources (generation, storage, and thermal systems). Consequently, the control during actual operation tends to become rigid and uniform. This study proposes a comprehensive and adaptive control scheme for a three-battery hybrid system. Moreover, it explores system optimisation at both household and community scales. We developed a model to simulate the behaviour of a three-battery hybrid system based on inputs of electricity and hot water demand, and PV generation. Validation with data from Osaka, Japan, confirmed our model's reproducibility, with a primary energy balance error of 2.7%. We expanded the conventional control schemes by proposing 6 control cases for household energy management and 13 control cases to promote community-level electricity purchases. Genetic algorithms were employed to minimise CO_2 emissions by identifying the optimal combination of control cases for each household at every time step. Future scenarios involving the decarbonisation of grid electricity were also evaluated. Household optimisation resulted in a 3.1% reduction in CO_2 emissions, whereas community optimisation achieved a 5.2% reduction. This observation showcases the enhanced decarbonisation effect of energy sharing within the community. Future projections exhibited potential CO_2 reductions of 8.9% and 16% for household and community optimisation, respectively. This highlights the growing benefits of optimal control and power sharing. The study explores the advantages of integrating three-battery hybrid systems with power sharing, thereby contributing to the development of sustainable smart communities.

Keywords: smart community; solid oxide fuel cell; energy management system; PV/fuel cell/battery hybrid energy system; genetic algorithm.

INTRODUCTION

Initiatives in Smart Communities

In the wake of the Paris Agreement and the Great East Japan Earthquake, there is a growing interest in developing smart communities that address diverse requirements of Japan, including low carbon emissions and disaster resilience. Smart communities introduce decentralized energy systems for household electricity generation. This energy system can reduce greenhouse gas emissions and achieve energy self-sufficiency during disasters. Although photovoltaic (PV) generation is widely adopted, it varies significantly with the weather and time of day. Therefore, combining PV with stabilising technologies, such as fuel cells and battery energy storage systems, is expected to provide a stable energy

supply. These resources are managed through home energy management systems (HEMS). Some smart communities also manage energy at the community level, such as peer-to-peer (P2P) energy trading, to achieve net-zero energy for the entire district. For this study, we conducted fieldwork in the "Senri Maruyama Hill Smart Community" in Osaka, Japan. Based on the acquired data, we propose appropriate energy management practices for smart communities. This community follows the concept of sustainable urban development. These homes are equipped with a PV/fuel cell/battery hybrid energy system (three-battery hybrid system). The system employs the residential fuel cell cogeneration technology, commonly referred to as Ene-Farm. Ene-Farm incorporates a solid oxide fuel cell (SOFC) that generates electricity, while also utilizing exhaust heat as a supplementary thermal source for floor heating and hot water supply.

Research on Decentralised Energy Systems

Research on PV battery systems include the optimisation of cost and PV self-consumption using dynamic programming algorithms (Li et al., 2022). In addition, combining PV battery systems significantly reduces community operational costs (Gomes et al., 2023). Multistage optimisation for smart homes, integrating HEMS with PV battery systems and P2P trading, has demonstrated greater cost and load reduction benefits than household-only optimisation (Hussain et al., 2023). Further flexibility in the power management can be achieved by integrating other power sources. Babatunde et al. (2019) examined the optimal integration of energy systems for low-income households. They analysed the optimal combination of PV, wind power, gasoline generator, and battery using a multi-criteria decision analysis based on technical, economic, environmental, and social criteria. Consequently, the PV/gasoline generator/battery hybrid was the most optimal. Wu et al. (2022) advocated SOFC as a low-carbon, clean power source suitable for decentralised energy systems. However, the control of three-battery hybrid systems is challenging owing to the numerous combinations of energy generation, storage, and thermal devices. This results in limited research and uniform control practices. Kitagawa et al. (2019) quantified the environmental performance and disaster resilience of three-battery hybrid systems in smart communities. Nakao et al. (2021) optimised the operation planning of three-battery hybrid systems using Mixed Integer Linear Programming (MILP), focusing on minimizing CO_2 emissions, maximizing power self-sufficiency, and minimizing costs.

This study extends system control to include battery charging sources and aims to clarify the optimal operation of the three-battery hybrid system at both the household and community scales. Optimization was conducted using Genetic Algorithms (GA), exploring the optimal combination of extended control cases. The input data for the simulations encompassed diverse electricity and hot water demands, with PV generation measured in the actual district covered by the fieldwork.

METHOD

Study Target

This study targeted a smart community in Osaka, Japan. The measurement data were obtained from 11 houses in the district. The measured data included 56 items, such as electricity, hot water demand, and power generation, measured at the distribution board level. The measured values were accumulated at a time step of 30 min. The data acquisition period was 28 days, i.e., from 1 February to 28 February 2023, considering the influence of hot water demand. Table 1 shows household information. The lifestyles of the residents and the capacity of PV systems are significantly diverse. In this district, houses are highly insulated with a UA value of 0.6 W/(m²·K) or higher, and three-battery hybrid systems are installed in subsidized houses. The control flow of the three-battery hybrid system is shown in Figure 1. The three-battery hybrid system discharges electricity in the following order: SOFC, battery, and PV. This SOFC generates electricity by extracting H_2 from natural gas through an internal fuel reforming system. The surplus electricity from the SOFC was used as the charging source for the battery, and that generated from the PV was sold to the grid.

Table 1: Household Residence Information.

House	A	B	C	D	E	F
PV capacity [kW]	3.43	3.40	3.92	3.92	3.92	3.92
House	G	H	I	J	K	
PV capacity [kW]	3.50	2.69	3.50	3.50	3.00	

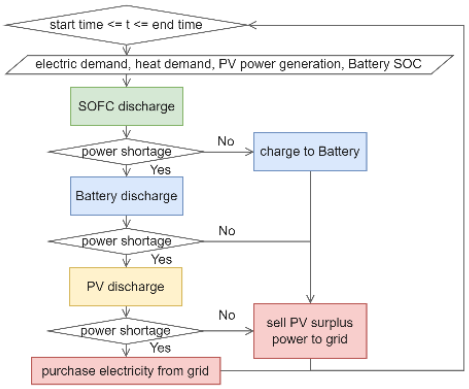

Figure 1: Control flow of a three-battery hybrid system.

Three-battery Hybrid Model

The inputs for the three-battery hybrid model were the electricity demand, hot-water demand, PV generation, and battery charge level for each time step. The model determines the SOFC generation, battery charge/discharge, and power sales/purchases for each time step, reproducing the energy supply and demand with a three-battery hybrid system. The SOFC generation efficiency was determined based on the generation. Additionally, the behaviour of the backup thermal source for hot-water demand was estimated through detailed heat load calculations, which reproduced the backup thermal source behaviour. In this study, the control of the power supply methods in the three-battery hybrid model was expanded to include both PV and SOFC as battery-charging sources. Each charging source had three discharge-priority settings to prevent arbitrary battery discharges (Table 2). The abbreviations for SOFC, battery, and purchase (purchasing power from the grid) in the table are FC, BT, and pur, respectively. In these control cases, the houses operated independently of the grid, prioritising low-power purchases. Case 0 represents the actual control of the three-battery hybrid system in the target community and serves as the business-as-usual (BAU) case. Evaluations of the operational characteristics of these control cases revealed that utilising the SOFC for continuous power generation, as in the "BT charger FC" case, enhanced the efficiency of SOFC operation. Moreover, charging from the fuel cell was appropriate for the small-capacity batteries adopted in target district. The impact of the discharge order was minimal; however, the "1st supply PV" contributed to the main goals of the smart community, such as economic benefits and CO_2 reduction. Thus, control case 2, combining "BT charger FC" and "1st supply PV", achieved the best evaluation indicators. However, it is noteworthy that the suitable control varies depending on social background and prioritised indicators. Comparing the BAU case of this model with the HEMS measurements, the error in the primary energy balance was 2.7% (Figure 2). Moreover, the model closely reproduced the time-series data observed in the HEMS measurements with minor discrepancies (Figure 3). The sources of these discrepancies include equipment loss, internal battery resistance, and periodic maintenance modes. Although the model represents an idealised state of a three-battery hybrid system without these occurrences, it has sufficient reproducibility to validate the control methods.

Table 2: Control case settings.

case	0 (BAU)	1	2	3	4	5
1st supply	FC	FC	PV	PV	PV	FC
2nd supply	BT	PV	FC	BT	FC	PV
3rd supply	PV	BT	BT	FC	BT	BT
4th supply	pur	pur	pur	pur	pur	pur
BT charger	FC	FC	FC	PV	PV	PV

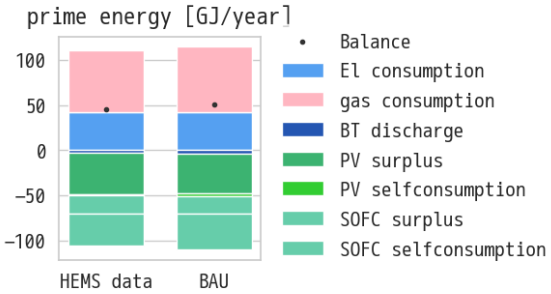

Figure 2: Cumulative validation of the three-battery hybrid model.

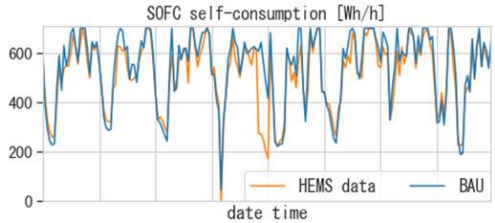

Figure 3: Comparison of time series validation data between the three-battery hybrid model and HEMS measurements.

Household Scale Optimisation

The actual control case for the three-battery hybrid system in the target district was fixed as Case 0 by the operator for economic reasons. However, if the case can be adaptively adjusted based on circumstances, the optimal control case for each timeslot, considering the household and weather conditions, can be determined. GA was used to optimise the control case for each household. Table 3 lists the GA settings used in this study. The objective function is defined by Equation (2), which minimises the CO_2 emissions for each household. Two optimisations were performed using f18 and f30. Here, f18 represents the actual value as of 2018 at 0.352 [kg-CO_2/kWh] in Japan, and f30 represents the target value for 2030 at 0.250 [kg-CO_2/kWh], assessing the future impact (Kansai Electric Power, 2020).

Table 3: GA settings for household–scale optimisation.

Offsprings	1200
Variables	control cases [0-5]
Length	336 time step (2023/2/1-7, 48 step/day)
Sampling	integer random sampling
Crossover	uniform crossover

Community Scale Optimisation

While household-scale optimisation individually optimised the three-battery hybrid system control case for each household (Table 4), optimising all households collectively allowed the consideration of interactions in overall energy use. For community-wide energy balance optimisation, the objective function was defined by Equation (4). The loss rate during power distribution was set to 7.8% according to Kansai Electric Power's consignment supply terms for low voltages (Kansai Electric Power, 2020). Additionally, control cases were included to induce grid power purchases in this simulation. Combination optimisation was performed for 13 cases, as listed in Tables 2 and 5. In individual optimisation, houses operate independently of the grid for the three-battery hybrid system management, prioritising power purchase low. However, community optimisation requires control, which increases the priority of power purchases to facilitate power sharing among houses. When purchasing power, it is assumed that all the deficit power is covered by power purchase without considering the subsequent discharge from the three-battery hybrid system. Similarly, it is assumed that no excess power is generated during the power purchase; therefore, battery charging does not occur simultaneously.

Table 4: GA settings for community-scale optimisation.

Offsprings	1200
Variables	control cases [0-12]
Length	3696 (11house * 336 time step)
Sampling	integer random sampling
Crossover	uniform crossover

$$\mathrm{CO_2}emission_{i,t} = (EL_{pur,i,t} - EL_{sur,i,t}) \times f_{el} + Gas_{purchase,i,t} \times f_{gas} \quad (1)$$

$$\min \sum_t (\mathrm{CO_2}\ emission_{i,t}) \quad (2)$$

$$\mathrm{CO_2}emission_t = \sum_i [(EL_{pur,i,t} - EL_{sur,i,t} \times f_{p2p}) \times f_{el} + Gas_{pur,i,t} \times f_{gas}] \quad (3)$$

$$\min \sum_t (\mathrm{CO_2}\ emission_t) \quad (4)$$

where i, t, $EL_{pur,t}$, $EL_{sur,t}$, $Gas_{pur,t}$, f_{p2p}, and f_{el} / f_{gas} are house number, time step, purchased electricity (kWh), power reverse flow (kWh), purchased gas (kWh), power distribution loss, and average CO_2 emission factor of electricity/gas (kg-CO_2/kWh), respectively.

Table 5: Control Case Settings for community scale

case	6	7	8	9	10	11	12
1st supply	FC	FC	PV	PV	FC	PV	pur
2nd supply	BT	PV	BT	FC	pur	pur	
3rd supply	pur	pur	pur	pur			
BT charger							

RESULTS AND DISCUSSION

This section summarizes the evaluation results for current/future estimation in Tables 6 and 7, with detailed results shown in Figures 4-11. Figures 4 and 5 present CO2 emissions, Figures 6 and 7 show energy breakdowns, Figures 8 and 9 depict the grid load curve, and Figures 10 and 11 illustrate the operational status of batteries and SOFCs for both current/future estimation.

Current Estimation

The behaviour of the three-battery hybrid system was estimated using a three-battery hybrid model based on electricity demand, hot-water demand, and PV generation data obtained from the HEMS. Table 6 shows the simulation results of the BAU scenario, which mimics the actual operation, alongside the optimised estimates

at both the household and community levels. Carbon dioxide emissions were reduced by 3.1% and 5.2% in household- and community-level optimisation, respectively, compared to the BAU scenario. This observation indicates that power-sharing within the community suppressed CO_2 emissions more efficiently (Figure 4). Both optimisations demonstrated reductions in CO_2 emissions in the individual residential assessments. A breakdown of the primary energy supply and demand is shown in Figure 6. This illustrates that PV self-consumption increased across all residences. An energy source that emits no CO_2 was selected. The minimisation of CO_2 emissions also reduced the load on the power distribution system (Figure 8). Household optimisation promotes the self-consumption of generated power, whereas community optimisation contributes to load reduction through power sharing. Consequently, the net energy cost, which subtracts the revenue from electricity sales from the purchase price of electricity and gas, demonstrated a slight reduction in cost for household optimisation and a slight increase in cost for community optimisation.

Subsequently, the charge–discharge cycles of the battery were analysed. In the BAU case, battery utilisation difference across residences was observed, with Residence D repeatedly charging and discharging and Residence B barely using the battery (Figure 10). This discrepancy is attributed to varying base and peak load power usage patterns among the residences. Moreover, the uniform control of the three-battery hybrid system did not align with individual demands. Under household optimisation, battery usage decreased in Residences D and K but increased in the other residences, resulting in a usage range of 7–12 kWh/day, except for Residence B. Figure 10 also shows that charging primarily occurred during the day, while discharging happened from evening to night. Planned control of the battery according to the time of day contributes to CO_2 reduction. In community optimisation, the battery operation was minimal. Charging and discharging the battery results in an approximate loss of 10%, where only ~81% of the electricity used for charging is available for discharging. However, P2P distribution incurred only a 7.8% loss, allowing 92.2% of the generated power to be utilised. Therefore, when power sharing is implemented, the control avoids charging and discharging the battery using it supplementarily.

As shown in Figure 10, In the BAU case, SOFCs operated continuously in all residences, with particularly low efficiency observed in Residences C and J. As a result, the average number of required SOFC units across all residences was 9.03 out of the total 11 units available. Household optimisation increased the time for which SOFCs operated at the rated efficiency, thus improving the generation efficiency. Temporally, PV generation was utilised domestically during the day, reducing the need for SOFC operations. Residences with high SOFC utilisation exhibited lower battery usage because of a high base load exceeding the rated generation capacity of 0.7 kW, preventing surplus generation. This observation indicates the importance of demand-side measures to reduce the base load for optimal use of the three-battery hybrid system. Community optimisation also achieved high-efficiency SOFC operation but distributed the load more evenly. Consequently, the required SOFC units were approximately 0.8 units lower than in household optimisation, with a smaller standard deviation. This indicates that power-sharing enables SOFCs to operate at a rated capacity with fewer units, thereby distributing the generated power across multiple households. Consequently, power-sharing is effective in reducing the number of operating SOFC units.

Future Estimation

In the future, Japan aims for the decarbonisation of grid electricity through the increased adoption of renewable energy. This section evaluates the impact of these societal changes on the operation of a three-battery hybrid system. As shown in Table 7, the CO_2 emissions for the BAU and household optimisation increased in the future estimates compared with the current estimates. This is because of the reduced impact of CO_2 emissions owing to the reverse power flow to the grid. Promoting consumption within residences and communities is more crucial than the reverse power flow. Compared to the BAU scenario, CO_2 emissions in household and community optimisations were reduced by 8.9% and 16%, respectively, demonstrating greater reduction effects than the current estimates (Figure 5).

Table 6: Current estimation results.

	BAU	Optimized Household	Optimized Community	Unit
CO2 emission	7.20	6.97	6.81	kg-CO2/day/house
Peak/average grid load	2.75/0.356	1.99/0.192	2.25/0.219	kW/house
Cost	12.6	12.3	13.2	K yen/house/mo
P2P	-	-	0.83	kWh/day/house
Battery charge /discharge	7.91	9.62	2.84	kWh/day/house
required SOFC	9.03±1.25	6.34±3.39	5.56±2.78	Unit
SOFC efficiency	43.1	46.6	46.8	%

Table 7: Future estimation results.

	BAU	Optimized Household	Optimized Community	Unit
CO2 emission	8.06	7.34	6.78	kg-CO2/day/house
Peak/average grid load	2.75/0.356	1.51/0.190	1.99/0.167	kW/house
Cost	12.6	12.4	16.0	K yen/house/mo
P2P	-	-	0.95	kWh/day/house
Battery charge /discharge	7.91	11.3	0.93	kWh/day/house
required SOFC	9.03±1.25	5.00±3.39	0.55±0.23	Unit
SOFC efficiency	43.1	46.3	46.4	%

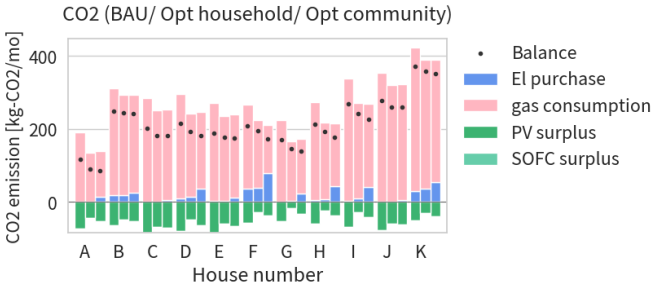

Figure 4: CO_2 emission evaluation in current estimation.

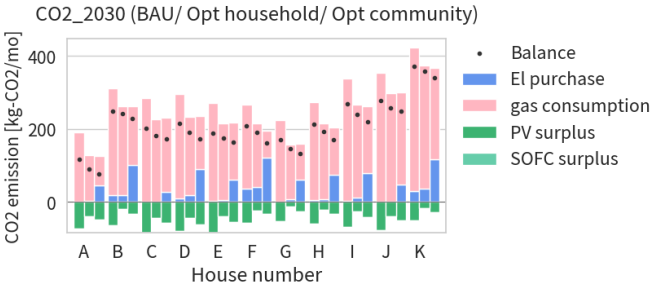

Figure 5: CO2 emission evaluation in future estimation.

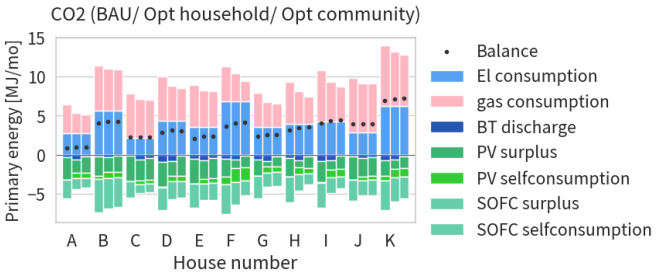

Figure 6: Energy breakdown in current estimation.

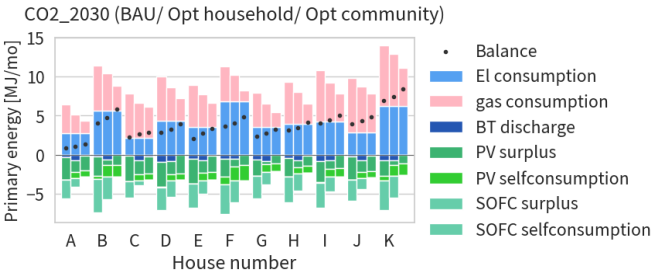

Figure 7: Energy breakdown in future estimation.

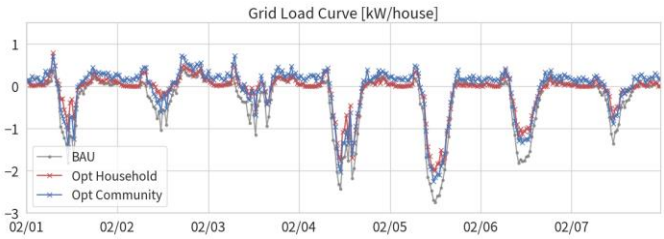

Figure 8: Grid load curves in current estimation.

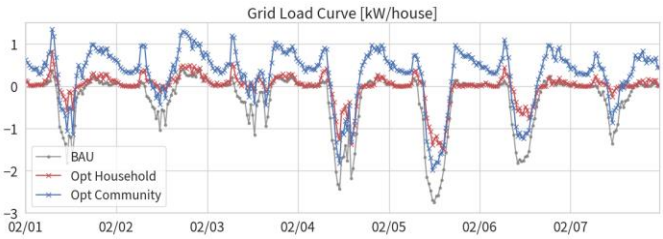

Figure 9: Grid load curves in future estimation.

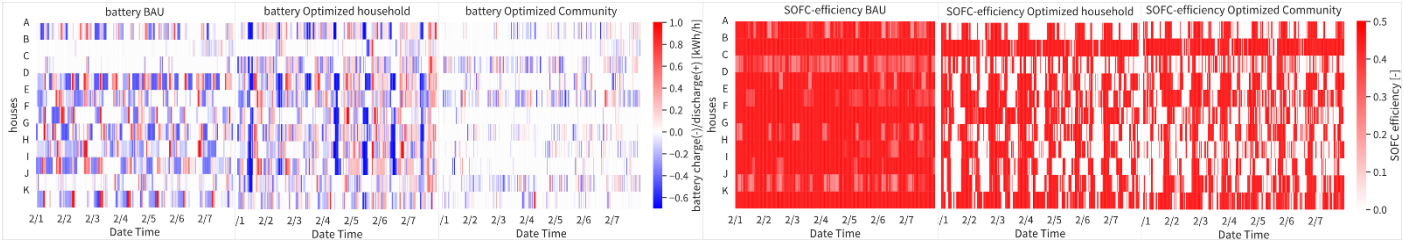

Figure 10: Battery/SOFC states in current estimation (BAU, household optimization, community optimization).

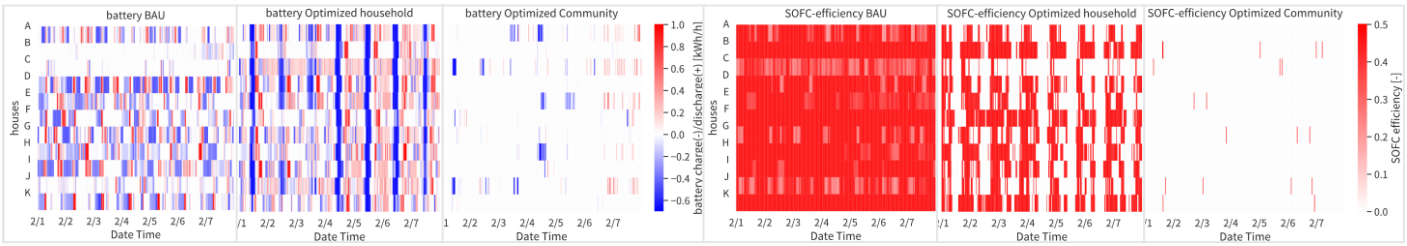

Figure 11: Battery/SOFC states in future estimation (BAU, household optimization, community optimization).

The breakdown of the primary energy supply and demand indicates that SOFC generation almost ceased during community optimisation (Figure 7). The grid load was lower than that in the BAU case (Figure 9). In community optimisation, electricity was actively purchased from the decarbonised grid, fully leveraging the benefits of grid decarbonisation and demonstrating high adaptability to societal changes. The cost for the BAU case was 12,600 yen/house/month, while household optimisation slightly reduced costs, and community optimisation increased costs by about 27% to 16,000 yen/house/month. Utilizing the three-battery hybrid system for community benefits presents practical challenges due to increased costs.

Figure 11 illustrates the operating states of the batteries. In household optimisation, the charge–discharge volume increased. The temporal usage trends of charging during the day and discharging from evening to night became more pronounced. Consequently, in residences such as Residence C, where battery use was minimal in the BAU case, the usage increased. In contrast, in districts allowing power sharing, battery charging–discharging was minimal at 11% of the BAU case. This is because decarbonised grid electricity reduces CO_2 emissions through battery usage, leading to electricity purchases that cover power shortages. The control was implemented to minimise CO_2 emissions. However, maintaining the state of charge of the battery above a certain level is crucial for disaster preparedness and ensuring the peace of mind of the residents.

Figure 11 also illustrates the operating states of the batteries. The generation efficiency during the operation did not change significantly, but the generation volume varied. In household optimisation, daytime SOFC operation almost ceased, with limited nighttime operation in Residences A and C. Combined with battery behaviour, indicating that the control maximises PV self-consumption by charging the battery during the day. Consequently, the number of required SOFC units was reduced by 1.3. In community optimisation, SOFC operation was minimal, prioritising electricity purchases from the decarbonised grid. However, considering the smart communities' goal of energy self-sufficiency, future studies should also explore operational strategies focusing on independent power management through SOFC utilisation.

CONCLUSIONS

Previous research on decentralised energy systems has primarily focused on optimising PV-battery systems for households and communities. However, there has been limited research on three-battery hybrid systems that integrate fuel cells and have the flexibility to generate power. In the present work, simulations were performed using a three-battery hybrid model to determine optimal system control. simulated the power and thermal supply of a three-battery hybrid system.

We expanded the control strategies comprehensively and utilised a GA to explore the optimal combinations of the control cases. This study examined both household and community optimisation, considering P2P energy trading, and projected future scenarios involving the decarbonisation of grid electricity. Several significant findings have emerged from these results.

- Household and community optimisations achieved significant CO_2 emission reductions, with community-level optimisation providing a stronger decarbonisation effect owing to power-sharing capabilities.
- Future scenarios indicated CO_2 emission reductions of 8.9% and 16% for household and community optimisations, respectively, compared with current estimates. This underscores the increased

importance of implementing optimal control and power sharing in the future.

- Differences in the use of batteries and SOFCs were observed between household and community optimisation. Household optimisation increased planned battery usage compared with the BAU case. On the other hand, community optimisation utilised the battery more supplementarily. Both optimisations operated the SOFCs more efficiently than in the BAU case; however, community optimisation was effective in reducing the total number of SOFCs required.
- Optimising CO_2 emissions also led to a reduction in grid load.
- Future estimates on household optimisations showed pronounced trend of charging the battery during the day and discharging it from the evening to night. Community optimisation actively purchased grid electricity, demonstrating strong adaptability to societal changes.
- Considering CO2 minimization and electricity sharing, resident utility costs increased, presenting practical challenges.

These findings underscore the potential of three-battery hybrid systems for enhancing urban sustainability and offer critical insights into smart community development.

FUTURE WORK

Optimisation

In this study, we explored control cases aimed at minimising CO_2 emissions. However, significant cost increases were observed when implementing power sharing. Therefore, future research will include analysing multi-objective optimal control that simultaneously minimizes both costs and CO2 emissions. Additionally, it is necessary to optimise the number of SOFC units for continuous operation and develop matching algorithms for P2P energy trading. Furthermore, we analyse a multistage optimisation approach incorporating demand response methods suited to a three-battery hybrid system.

HEMS Measurement Data

The duration and variety of the HEMS data can be expanded. By extending the learning and data acquisition periods and increasing the number of households, we aim to investigate a three-battery hybrid system considering seasonal variability and differences in residents' lifestyles.

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