

Operational Planning of a Home Energy Management System Using Regional Weekly Weather Forecasts to Mitigate Surplus Electricity

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Abstract—Photovoltaic (PV) systems often generate surplus electricity during daytime when production exceeds demand. To address this, existing studies optimize energy storage and heat-pump (HP) water heater operations but typically focus only on same-day forecasts. This study proposes using regional weekly weather forecasts to enhance PV surplus management. Solar irradiance is estimated via machine learning trained on historical data, using daily and weekly forecasts as inputs. Predicted irradiance informs PV generation forecasts, guiding optimal operational planning for battery storage and HP water heaters through linear programming. Plans are adjusted based on actual generation data. Results indicate that perfectly accurate weekly forecasts could reduce surplus electricity by 16% compared to same-day forecasts. Even with estimated irradiance, integrating next-day forecasts reduces surplus by 0.66% relative to same-day predictions alone.

Index Terms—energy management, HEMS, surplus electricity, photovoltaic system, weather forecast

I. INTRODUCTION

The use of renewable energy sources has gained momentum in response to environmental and energy sustainability concerns. Among these, residential photovoltaic (PV) systems have seen significant adoption. Home Energy Management Systems (HEMS) play a key role in optimizing household energy use, particularly electricity generated by PV systems. While solar power reduces environmental impact and reliance on grid electricity, it also poses a challenge: mismatches between supply and demand can lead to surplus electricity, especially due to seasonal and daily fluctuations.

As a result, recent research has focused on effectively utilizing surplus electricity. This issue is important for two main reasons. First, from a technical perspective, imbalances between supply and demand can cause voltage and frequency fluctuations, threatening grid stability—an issue expected to grow with increased residential PV adoption. Second, from an economic perspective, maximizing self-consumption of surplus electricity reduces reliance on purchased power, lowering energy costs. Inefficient use, on the other hand, may result in financial losses.

To effectively address these challenges, two primary methods have been proposed for utilizing surplus electricity: em-

ploying storage batteries in conjunction with solar power generation, and operating heat pump (HP) water heaters during periods of peak solar generation [1]–[3]. Optimizing the operation of storage batteries and HP water heaters can significantly reduce surplus electricity. Existing research has developed and implemented optimal operational strategies for storage batteries and HP water heaters by predicting future solar generation output and household electricity demand [4], [5].

However, current research typically considers only the forecasted electricity generation and demand for the operational day itself when planning the use of storage batteries and HP water heaters. Consequently, these approaches do not incorporate forecasts beyond the immediate day, which can result in suboptimal use of surplus electricity. Without considering predictions for subsequent days, there is an increased risk of surplus electricity remaining unused and ultimately being wasted.

To address this limitation, this study proposes a method that incorporates regional weekly weather forecasts into the operational planning of storage batteries and HP water heaters. The proposed method consists of the following four steps. First, the amount of insolation is estimated using weekly weather forecasts. Linear regression analysis is conducted based on historical weather data, and the resulting model is utilized alongside regional weekly forecasts to estimate insolation. Second, electricity generation is estimated from the predicted insolation using a standard approximation formula. Third, operational plans for storage batteries and HP water heaters are formulated using linear programming based on predicted electricity generation and household electricity demand, aiming to minimize surplus electricity throughout the week. Fourth, the operational plans are adjusted and executed. Because operational plans are initially based on predicted generation values, daily adjustments are necessary to accommodate actual generation levels. The execution occurs only for the initial step of the plan, after which updated operational plans are prepared daily.

Given the limited accuracy of weekly weather forecasts,

incorporating forecast data for days further in the future does not necessarily lead to improved planning performance. To evaluate the effectiveness of the proposed method, simulations were conducted to compare the following four planning approaches and a greedy approach:

- **Week-Ahead Approach:** Utilizes the full weekly weather forecast.
- **3-Day-Ahead Approach:** Uses forecasts for the day of operation and the following two days.
- **2-Day-Ahead Approach:** Uses forecasts for the day of operation and the following day.
- **Day-Ahead Approach:** Uses only the forecast for the day of operation.
- **Greedy Approach:** Does not rely on any forecasts; decisions are made based solely on present conditions.

These simulations were conducted under various conditions, including different PV system capacities and battery storage sizes.

First, a reference simulation was conducted using the actual amount of insolation instead of predicted values, assuming perfect weather forecast accuracy. The simulation results show that the Week-Ahead Approach can reduce the average surplus electricity rate by 48.1% compared to the Greedy Approach and by 16% compared to the Day-Ahead Approach under conditions of a $4kW$ system capacity and $8,000Wh$ storage battery capacity. When using actual insolation values, it was observed that the greater the number of forecast days used, the lower the average surplus electricity rate. But notably, the Week-Ahead and 3-Day-Ahead Approaches yielded approximately equivalent average rates of surplus electricity. When using predicted values, the average surplus electricity rate for the Week-Ahead Approach exceeded that of the Day-Ahead Approach due to forecast inaccuracies. Nevertheless, even with forecast errors, the average surplus electricity rate decreased from 19.71% to 19.58% when comparing the Day-Ahead and 2-Day-Ahead Approaches, corresponding to a relative reduction of 0.66%. It was also confirmed that when actual insolation data is used, the efficiency gap between the Week-Ahead and Day-Ahead Approaches becomes more pronounced as PV system capacity and storage battery capacity increase.

The rest of this paper is organized as follows. Section II describes the background knowledge, and Section III describes the related research. Section IV describes the proposed method. Section V presents the experiments and their results, and Section VI summarizes this paper.

II. BACKGROUND

A. Home Energy Management System

Home Energy Management System (HEMS) is a system for optimizing energy management within the home. It visualizes energy usage and supports to use energy efficiently. In particular, by linking with solar power generation and storage batteries, it is possible to make effective use of surplus electricity and optimize power consumption. HEMS architecture consists of components as shown in Figure 1.

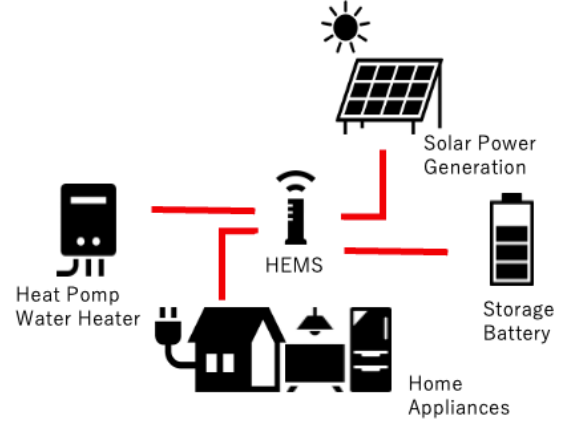


Fig. 1. Home Energy Management System

B. Surplus electricity

Surplus electricity refers to the amount of electricity generated that exceeds the amount of electricity demand. The generation of surplus electricity can not only lead to the waste of energy resources and financial losses, but also have a negative impact on the stability of electricity supply. Therefore, it is important to utilize surplus electricity without waste.

The amount of electricity supplied must always match the amount of electricity demanded. If the balance between supply and demand is disrupted, it will be impossible to maintain the utility frequency and electricity will not be supplied normally. Electricity companies have a Central Power Supply Control Center, which maintains the balance between the amount of electricity demanded and the amount of electricity supplied. At present, surplus electricity is absorbed by being supplied to the power grid. When there is surplus electricity and it is supplied to the power grid, the Central Power Supply Control Center maintains the balance between supply and demand by either increasing demand or reducing the output of thermal power generation.

In recent years, with the spread of solar power generation, there is often surplus electricity in spring and autumn, when there is little demand for air conditioning. If the surplus electricity is continually supplied to the power grid, there is a possibility that the situation will occur where the supply will not be able to meet demand, even if the amount of electricity generated by thermal power generation is reduced.

If surplus electricity is not utilized efficiently, there is a possibility of financial loss. By utilizing surplus electricity and increasing the rate of self-consumption, it is possible to reduce the amount of electricity purchased from the power company and keep electricity costs down. Although surplus electricity can be sold, the purchase price of electricity is higher than the selling price of electricity. Therefore generating surplus electricity is a financial loss.

III. RELATED WORKS

In recent years, the utilization of renewable energy sources has been actively promoted to address environmental concerns

and energy sustainability. Renewable energy encompasses various sources, such as solar power, hydropower, and wind power. Among these, the deployment of residential photovoltaic (PV) systems has shown notable progress. A Home Energy Management System (HEMS) is a technology designed to efficiently manage household energy consumption—including electricity, gas, and water—while facilitating optimal energy utilization. In particular, electricity produced by residential PV systems can be effectively controlled and optimized through the use of HEMS. Employing solar power generation systems not only significantly reduces environmental impact but also decreases dependence on externally purchased electricity. However, a critical challenge associated with solar power generation is the intermittent imbalance between electricity supply and demand. Depending on seasonal variations and daily fluctuations, PV systems may produce electricity in excess of household consumption, resulting in surplus electricity.

Consequently, recent research has focused on methods for effectively utilizing this surplus electricity. Two primary technologies have received significant attention: storage batteries and heat pump (HP) water heaters. Storage batteries can store surplus electricity for use during periods of low generation, enhancing self-sufficiency and self-consumption. Previous research demonstrated that the use of storage batteries significantly improves self-consumption rates. Emil Nyholm et al. [1] used energy consumption data from detached houses in Sweden that use solar power generation systems to investigate the extent to which storage batteries contribute to improving the rate of self-consumption of solar power generation. According to the research, if the capacity of storage batteries (kWh) is 2.5 to 4.0 times the annual amount of solar power generation (MWh), it is possible to improve the self-consumption rate of solar power generation by 18 to 48%. To meet these conditions, a storage battery with a fairly large capacity is required. According to the simulation analysis of Yamada et al., it is possible to raise the average rate of electricity self-sufficiency from 29% to 46% by using a storage battery with a capacity of $4kWh$. In addition, using a storage battery with a capacity of $10.8kWh$ can raise the electricity self-sufficiency rate up to 68%. HP water heaters also directly utilize surplus electricity by shifting operation times to daytime. Sebastian [3] conducted a one-year simulation combining HP water heaters and solar power generation, improving self-consumption rates by approximately 11% monthly. The combined use of both storage batteries and HP water heaters further enhances efficiency by strategically managing energy flows.

Prior studies have developed various operational planning strategies for these technologies, primarily based on short-term forecasts of electricity demand and generation. For instance, Hatta et al. proposed operational planning methods using day-ahead forecasts, achieving up to 65% utilization of surplus electricity [4]. Nawata et al. explored the combined use of electric vehicle batteries and HP water heaters, achieving reductions in surplus electricity of up to 46% [5]. There are many other research that use storage batteries and HP water heaters to utilize surplus electricity [6]. However, these

strategies generally do not consider forecasts beyond the immediate day, potentially leading to suboptimal utilization of surplus electricity.

IV. PROPOSED METHOD

This study addresses these limitations by proposing a method that integrates regional weekly weather forecasts into operational planning. The method comprises four steps: estimating insolation using regression analysis, predicting electricity generation, formulating operational plans using linear programming, and daily adjustments based on actual generation data. The procedure is shown below.

- 1) Estimate insolation from regional weekly weather forecasts.
- 2) Predict the amount of electricity generated.
- 3) Make an operation plan for storage batteries and HP water heaters using a mathematical optimization model based on the amount of electricity generated and electricity demanded.
- 4) Adjust and execute the operation plan.

An operation plan up at most a week ahead is formulated to minimize surplus electricity, considering predicted generation and demand data. This plan is updated daily, incorporating the latest forecasts and actual generation data. By iteratively refining the plan, we aim to optimize electricity utilization in real-time.

A. Prediction of insolation

In this study, regional weekly weather forecasts are used to estimate insolation over a week. A linear regression model, trained on historical weather data, is applied to the forecast inputs. The estimation granularity depends on the resolution of the weather forecast, and finer intervals allow for more precise planning. Possible weather features used in the model include date, time zone, temperature, humidity, precipitation, cloud cover, atmospheric pressure, and wind speed—all of which influence solar irradiance and its variability.

There is a strong correlation between the amount of electricity generated by solar power and the amount of insolation. The amount of electricity generated by solar power is approximately calculated by using the following equation.

$$E = H \div 3.6 \times K \times P \div G \times 1000$$

where E is the amount of electricity generated by solar power (Wh /hour), H is insolation per hour (MJ/m^2 /hour), K is the loss coefficient ($=73\%$)¹, P is the system capacity (kW), and G is insolation intensity under standard test conditions ($=1$) (kW/m^2).

B. Operational planning through mathematical optimization

The optimization problem addressed here is a linear programming problem, in which the objective function and constraints are all expressed in terms of linear functions.

The problem is formulated as follows. Here parameters are:

¹https://www.maff.go.jp/j/biomass/b_21hosei/pdf/taiyo_panf2.pdf

$E_{hp_capacity}$	Maximum amount of heat that can be stored in HP
$P_{hp_demand}[t]$	Heat consumption of HP
$E_{hp_lower_lim}$	Minimum remaining heat storage in HP
$E_{system_capacity}$	System capacity of solar panel
$P_{pv_predicted}[t]$	Amount of electricity generated by solar power
$P_{demand_predicted}[t]$	Amount of electricity demanded
$E_{battery_capacity}$	Storage battery capacity,

and variables are:

$P_{battery_charge}[t]$	Amount of electricity supplied/discharged to storage batteries
$P_{battery_discharge}[t]$	Amount of electricity discharged from storage batteries
$E_{battery_storage}[t]$	Amount of electricity stored in storage batteries
$P_{hp_supply}[t]$	Amount of heat supplied to HP
$E_{hp_status}[t]$	Amount of heat stored in HP
$P_{grid_purchase}[t]$	Amount of electricity purchased
$P_{pv_actual_curtail}[t]$	Actual amount of electricity generated (after curtailment).

Constraints on storage battery and HP are:

$$\begin{aligned}
P_{battery_charge}[t] &\leq E_{battery_capacity} - E_{battery_storage}[t-1] \\
P_{battery_discharge}[t] &\leq E_{battery_storage}[t-1] \\
E_{battery_storage}[t-1] + P_{battery_discharge}[t] &\geq 0 \\
E_{battery_storage}[t] &= E_{battery_storage}[t-1] \\
&\quad + P_{battery_charge}[t] - P_{battery_discharge}[t] \\
E_{hp_status}[t] &= E_{hp_status}[t-1] + P_{hp_supply}[t] - P_{hp_demand}[t].
\end{aligned} \tag{1}$$

Constraints on electricity supply and demand are:

$$P_{pv_actual_curtail}[t] + P_{grid_purchase}[t] + P_{battery_discharge}[t] = P_{demand_predicted}[t] + P_{battery_charge}[t] + P_{hp_supply}[t]$$

and other constraints are:

$$\begin{aligned}
E_{hp_status}[t] &\geq E_{hp_lower_limit} \\
P_{pv_actual_curtail}[t] &\leq P_{pv_predicted}[t] \\
E_{hp_status}[t] &\leq E_{hp_capacity}.
\end{aligned}$$

In addition, the obvious constraint that all parameters and variables are positive is imposed.

The objective function is:

$$\min \frac{\sum (P_{pv_predicted} - P_{pv_actual_curtail})}{\sum P_{pv_predicted}}. \tag{2}$$

C. Adjustment of operational planning

Although the operational plan is based on the predicted amount of electricity generated by solar power, the predicted amount of electricity generated by solar power and the actual amount of electricity generated by solar power are different. Therefore, it is necessary to adjust the operational plan for one step to be executed to match the actual amount of electricity generated by solar power.

The adjustment of operational planning at time t is performed as follows. If the actual amount of electricity generated by solar power is less than the predicted amount of electricity generated by solar power and the plan is executed as planned, the amount of electricity used will exceed the amount of electricity supplied. Therefore, the plan is adjusted by either reducing usage or increasing supply. The adjustment is made in the order of reducing the usage and then increasing the supply.

- 1) If the actual amount of electricity generated by solar power at time t ($P_{pv_predicted}[t]$) is less than the predicted amount of electricity generated by solar power at time t ($P_{pv_real}[t]$), the plan is adjusted. (If the actual amount of electricity generated by solar power at time t is greater than the predicted amount of electricity generated, the plan is executed as planned.)
- 2) If the amount of electricity supplied to the storage battery at time t ($P_{battery_charge}[t]$) is more than 0, reduce $P_{battery_charge}[t]$.
- 3) If the amount of heat supplied to HP water heater at time t ($P_{hp_supply}[t]$) is more than 0, reduce $P_{hp_supply}[t]$. However, reduce it so that it does not fall below the minimum remaining heat storage capacity of HP water heater.
- 4) If the amount of electricity stored in the storage battery at time $t-1$ ($E_{battery_storage}[t-1]$) is more than 0, increase the amount of electricity discharged from the storage battery at time t ($P_{battery_discharge}[t]$).
- 5) If it is still necessary to adjust the plan, increase the amount of electricity purchased at time t ($P_{grid_purchase}[t]$).

V. EXPERIMENT

We have conducted experiments to confirm how the use of regional weekly weather forecast for operational planning contributes to utilizing surplus electricity effectively.

For comparison with the method that uses the regional weekly weather forecast (Week-Ahead Approach), we conducted experiments using the method that uses only the forecast for the day of operation (Day-Ahead Approach), method that uses the forecast for the day of operation and the following day (2-Day-Ahead Approach), method that uses the forecast for the day of operation and the following two days (3-Day-Ahead Approach) and the method that does not use any forecast (Greedy Approach). There is difference between the predicted amount of electricity generated and the actual amount of electricity generated. Therefore, in order to evaluate the maximum performance of the Week-Ahead Approach, we also conducted a experiment in a simulation using the actual amount of electricity generated by solar power. We also changed the storage battery capacity and the system capacity of the solar panels to check how these capacity parameters affect the utilization of surplus electricity.

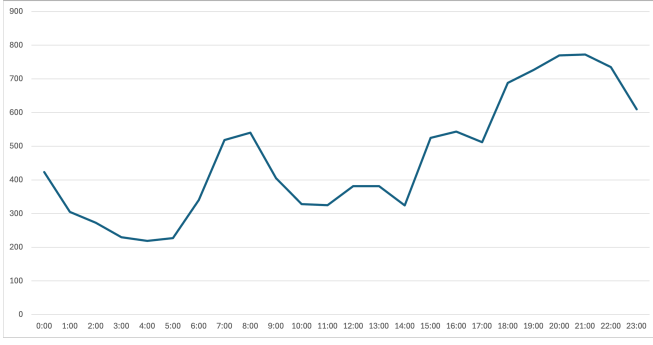


Fig. 2. The estimated amount of electricity consumed by time

A. Settings

In this study, simulations are performed based on meteorological data and weather forecasts for Fukuoka City, Fukuoka Prefecture. For machine learning to estimate insolation, meteorological data for March to May in 2021 to 2023 is used. Simulations using weather forecasts are conducted from March to May in 2024. Regional weather forecasts and regional weekly weather forecasts are used for the weather forecasts, and these are explained in detail in Section V-B. The amount of electricity demanded is assumed to be known and we have used an estimation in ed the spring season (March to May), during which air conditioner usage is assumed to be minimal, shown in in Figure 2. The operational plan is made so that the rate of the surplus electricity for 7 days is minimized. The parameters used in the linear programming are as follows: $E_{hp_capacity} = 4,000Wh$, $P_{hp_demand} = 375Wh$, $E_{hp_lower_lim} = 1,000Wh$. Hot water demand per day is assumed to be $3kWh$ based on related studies [4]. Since at least $1kWh$ is left to prevent HP water heater from running out, the heat storage capacity of the HP is assumed to be $4kWh$. It is also assumed to consume $375W$ since the daily hot water demand is $3kWh$.

B. Prediction of the amount of insolation based on data published by the Japan Meteorological Agency

To improve the accuracy of operational planning, shorter time intervals for estimated insolation are preferred. Accordingly, regional weather forecasts, which provide 3-hourly data, are used to estimate insolation up to the following day in 3-hour intervals. For periods beyond the following day, daily estimates are obtained using regional weekly weather forecasts. The 3-hourly forecast issued at 5:00 on the day of operation and the weekly forecast issued at 17:00 on the preceding day are utilized for this purpose.

Linear regression analysis was conducted to estimate insolation using meteorological data from March to May during 2021–2023. The input features from regional forecast data include month, day, time, temperature, and weather conditions, with insolation as the target variable.

The average absolute error when using regional weather forecasts for March to May in 2024 is shown in (a) of Table I, and the average absolute error using regional weekly weather

TABLE I
ACCURACY OF INSOLATION FORECAST

(a) Forecast until the next day in 3-hour increments		(b) One-week forecast by day	
MAE		MAE	
1st day	1.38	3rd day	4.02
2nd day	1.26	4th day	4.42
(Unit: MJ/m^2)		5th day	4.6
		6th day	5.07
		7th day	5.21
		(Unit: MJ/m^2)	

forecasts for March to May in 2024 is shown in (b) of Table I.

C. Greedy Approach

As a comparison with Week-Ahead Approach, simulations are performed using a method that controls according to a rule base without considering future demand and supply (Greedy Approach). The following procedure is used to allocate electricity. This method allocates electricity in the following order of priority, demand, storage batteries, then HP water heaters.

If the amount of electricity demanded at time t ($P_{demand_predicted}[t]$) is made up for by the actual amount of electricity generated at time t ($P_{pv_actual_curtail}[t]$). If the amount of electricity generated is not enough to cover the demand, the electricity is discharged as much as possible from storage batteries to make up the shortfall. If it is still not enough, the amount of electricity purchased ($P_{pv_purchase}[t]$) is increased.

If there is surplus electricity, it is first supplied to storage batteries. Charge as much as possible until exceeding the capacity of the storage batteries ($E_{battery_capacity}$). When the storage batteries are fully charged, the remaining surplus electricity is supplied to HP water heater. Heat is also supplied as much as possible until exceeding the capacity of the HP water heater ($E_{hp_capacity}$). When the HP water heater is also fully charged, the remaining power is disposed of as surplus electricity.

Since future demand and supply are not taken into account, it is undetermined when there is surplus electricity to be supplied to the HP water heaters. Therefore, to prevent running out of hot water, the system stores heat ($3kWh$) at 6:00 every day which is enough to cover the amount of heat consumed per day.

D. Results of experiments

The average rate of the surplus electricity for each method is shown in Table II. The lower row shows the case where the amount of insolation was estimated, and the upper row shows the case where the amount of insolation was known. Experiments were conducted with a system capacity of $4kW$ and a storage battery capacity of $8,000Wh$, which is equivalent to a typical residential solar generation system.

Week-Ahead approaches are more effective than Day-Ahead approaches in reducing surplus electricity when using actual measured values. The surplus rate drops from 13.56% to 11.39%, representing a 16% relative decrease. The more days

TABLE II
AVERAGE RATE OF SURPLUS ELECTRICITY

	Week-Ahead	3-Day-Ahead	2-Day-Ahead	Day-Ahead	Greedy
Actual Value	11.39	11.32	11.45	13.56	21.96
Predicted Value	19.81	19.79	19.58	19.71	21.96

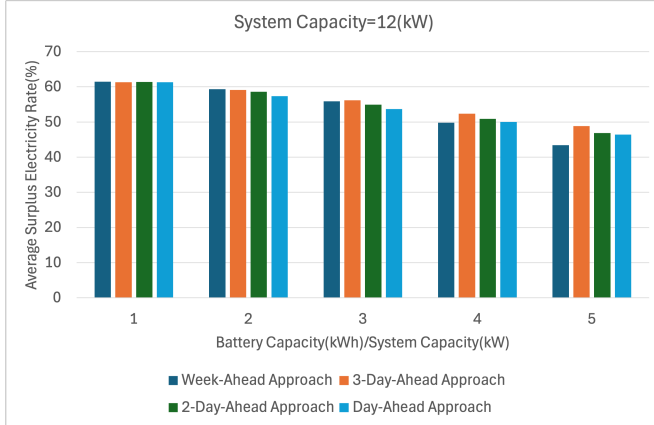


Fig. 3. Average Rate of Surplus Electricity (System Capacity: 12kW)

used, the smaller the average rate of the surplus electricity when using the actual measured values, but the average rate of the surplus electricity of Week-Ahead Approach and 3-Day-Ahead Approach is roughly equivalent.

When using the predicted values, the average surplus electricity rate of Week-Ahead Approach is larger than the average surplus electricity rate of Day-Ahead Approach, probably due to the low accuracy of weather forecasts. However 2-Day-Ahead Approach is more effective than Day-Ahead Approach in reducing surplus electricity. The average rate of the surplus electricity drops from 19.71% to 19.58%. This is probably because the weather forecast for the second day is in 3-hour increments, and insolation can be estimated with higher accuracy at finer time increments than when using the weekly forecast.

We have also evaluated the impact of varying system and storage battery capacities. Figure 3 shows the average rate of surplus electricity when the system capacity is fixed at 12kW and the battery capacity is varied. The battery capacities are 12kWh, 24kWh, 36kWh, 48kWh, and 60kWh from left to right. The difference in surplus electricity rates between the Week-Ahead and other approaches increases with larger battery capacities. For instance, with a system capacity of 12kW and a battery capacity of 60kWh, the surplus electricity rate is 43.4% for the Week-Ahead Approach and 46.43% for the Day-Ahead Approach. When the battery capacity is increased to 120kWh, the rates are 22.34% and 27.00%, respectively.

VI. CONCLUDING REMARKS

This study proposed an operational planning method for solar power systems that reduces surplus electricity by leveraging

regional weekly weather forecasts and machine learning-based insolation prediction, examining its effectiveness through simulation under various system and storage capacities. As a result, the simulations showed that if weekly forecasts were perfectly accurate, surplus electricity could be reduced by up to 16%. While the current improvement is modest due to the limited accuracy of actual weather forecasts, using forecasts for two days ahead still offers better performance than relying solely on same-day forecasts.

In this study, estimated fixed demand data was used, but actual electricity demand varies with factors such as weekdays, holidays, and temperature. Incorporating daily demand fluctuations and applying existing demand forecasting methods, such as neural networks [7] or Kalman filters [8], would enable more realistic evaluations. Furthermore, surplus electricity could be further reduced by employing additional supply—demand adjustment methods. For example, IoT appliances—despite their small individual consumption—can collectively contribute to demand creation, and their increasing prevalence makes them promising for demand response applications [9].

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