Analysis of Photovoltaic Forecasting for Self-Wheeling Imbalance Management in Japan

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***Abstract*—As Japan's electricity market continues to liberalize and renewable energy adoption accelerates, self-wheeling - the practice of transmitting electricity from privately owned generation sites to distant consumption points - is gaining attention. However, forecast errors in photovoltaic (PV) generation can lead to self-wheeling imbalance, undermining not only power system stability but also the cost-effectiveness of self-wheeling schemes. This study investigates the impact of PV forecast on imbalance management under Japan's current self-wheeling and imbalance penalty framework. Using real-world solar generation data, the imbalance outcomes of a self-wheeling project are compared under different solar forecast conditions. Results show that the Mean Absolute Error (MAE) more accurately reflects the magnitude of imbalance than the Mean Squared Error (MSE), and that the mean of forecast error significantly affects the performance of Battery Energy Storage System (BESS) used for imbalance mitigation. Finally, the defect in the current imbalance penalty system is discussed, and a remedial measure is proposed to improve fairness and operational efficiency.**

***Index Terms*—Renewable Energy, Self-wheeling, Forecast, Battery Energy Storage System**

I. Introduction

The transition to a decarbonized energy system has led to rapid growth in renewable energy adoption worldwide. Among various renewable sources, photovoltaic (PV) power has gained particular prominence due to its modularity, scalability, and declining installation costs. In Japan, PV has become a central component of the national energy strategy, supported by policies such as the Feed-in Tariff (FIT) and Feed-in Premium (FIP) schemes [1].

In this context, self-wheeling has emerged as a flexible mechanism that allows electricity consumers and corporate generators to utilize electricity generated at remote sites for their own consumption. Unlike traditional power purchase agreements or retail contracts, self-wheeling enables entities to generate electricity at one location and transmit it across the grid to another site without selling it into the wholesale market. Under this arrangement, the self-wheeling entity is only required to pay wheeling charges to the transmission system operator (TSO) based on the volume of electricity transmitted [2]. While this scheme promotes decarbonization and enhances energy autonomy, it also introduces new operational challenges, particularly when renewable generation resources are involved, due to their inherent output variability.

Under Japan's current market design, the discrepancy between the day-ahead planned and the real-time energy generation/consumption is defined as the imbalance. The entities in the system are penalized or rewarded according to the imbalance they cause [3]. This mechanism is intended to encourage accurate day-ahead scheduling and reduce the risk of supply-demand mismatches in real-time grid operation. Consequently, for entities operating intermittent renewable generation such as PV, improving forecast accuracy is essential to minimize imbalance penalty charges and contribute to system stability.

Recent advances in PV power forecasting have led to the development of a wide range of methods, broadly classified into physical models, statistical approaches, and hybrid techniques [4]. Physical models rely on meteorological and irradiance data to simulate solar generation, but they often lack adaptability to real-time conditions. In contrast, statistical approaches, including autoregressive time series models and machine learning algorithms, have shown strong performance in capturing complex temporal and spatial patterns in PV output [5]. More recently, hybrid methods that integrate physical insights with machine learning have been reviewed in [6]. While much of the existing literature has focused on minimizing forecast error, emerging studies are increasingly emphasizing the economic implications of forecasting, aiming to optimize profit-oriented decision-making in renewable energy operations [7]–[9].

To date, no studies have specifically addressed the impact of PV forecasting on imbalance management in self-wheeling schemes under Japan's updated imbalance penalty pricing system introduced in 2022 [3]. A related study by Nakamura et al. [10] evaluates the economic benefits of deploying a Battery Energy Storage System (BESS) with simple operational rules based on the predicted direction of forecast error. However, this study was conducted under the previous imbalance pricing regime and does not explicitly examine the influence of PV forecast results on imbalance outcomes.

This paper presents preliminary research on a self-wheeling project that transmits PV electricity from a distant generation site to a university campus in the Tokyo region of Japan as

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part of the university's decarbonization strategy. The primary contributions of this study are to:

- evaluate the impact of PV forecasting methods on imbalance magnitude and associated costs under Japan's updated imbalance penalty framework
- identify a structural defect in the current imbalance penalty system and propose a performance-based remedial measure.

The remainder of the paper is organized as follows: Section II and Section III introduce Japan's imbalance penalty system and the self-wheeling scheme, respectively. Section IV presents a case study based on real-world solar generation and load data, highlighting structural challenges within the current system. Finally, Section V concludes the paper.

II. The Imbalance Penalty System In Japan

Since the deregulation of the electricity industry in Japan in 2016, all entities, including generators and retail companies, are required to submit their day-ahead operation schedules to the TSO in 30-minute intervals. These entities are expected to adhere strictly to their submitted schedules.

An imbalance resulting from actual generation falling short of the scheduled amount or consumption exceeding the scheduled value is defined as a shortage imbalance. Conversely, generation exceeding the schedule or consumption falling below it constitutes a surplus imbalance. The structure of the Imbalance Penalty System is illustrated in Fig. 1. Under this system, the TSO penalizes shortage imbalances and uses the payments to compensate surplus imbalances. The imbalance penalties and rewards are settled ex-post. The residual imbalance that cannot be offset internally is corrected by deploying regulation resources in the system.

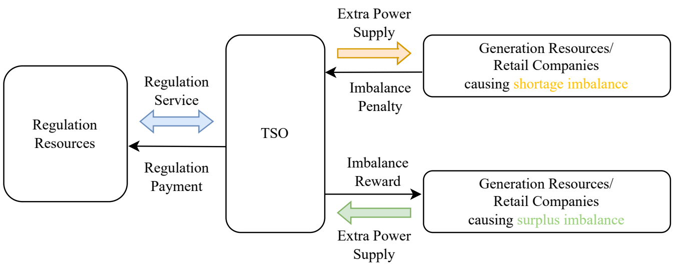


Fig. 1. The imbalance penalty system in Japan.

Under the previous system, imbalance prices were determined as a linear combination of the clearing prices from the day-ahead and intraday energy wholesale markets. However, this approach failed to accurately reflect the regional and temporal value of electricity, as the correlation between imbalance prices and actual system imbalances was shown to be weak [3]. To address these shortcomings, a revised imbalance pricing system was introduced in 2022. With the increasing penetration of renewable energy and its inherent variability, the new system incorporates the risk cost of insufficient supply to better manage potential power shortages. While the imbalance price remains stable under normal conditions, it can rise significantly during periods of tight supply. Conversely, when renewable curtailment occurs, the imbalance price is reduced to zero, thereby discouraging further generation. Additionally, under the new framework, imbalance prices are published in real time, enhancing transparency and responsiveness. Figure 2 illustrates the real-time imbalance prices observed from February 21 to February 28, 2025.

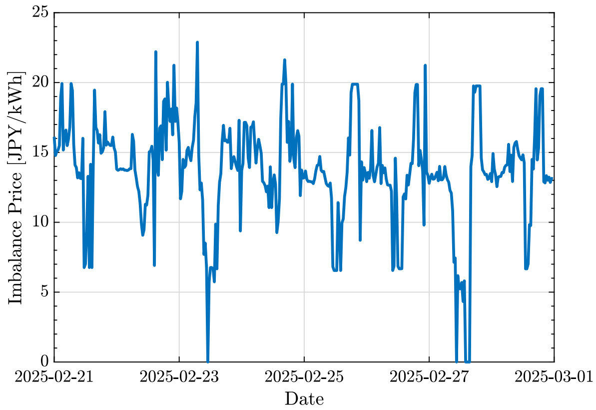


Fig. 2. The new imbalance price from 2025/02/21 to 2025/02/28.

III. The Self-wheeling Scheme

Self-wheeling refers to the practice of transmitting electricity generated at a privately owned facility to a separate location for the same entity's own use, without selling or purchasing the electricity on the wholesale market. In Japan, this approach is increasingly adopted by corporations and institutions aiming to meet decarbonization goals by directly utilizing renewable energy.

One key advantage of self-wheeling is the potential to reduce electricity procurement from retail suppliers, thereby lowering overall electricity costs. Since self-wheeled electricity is supplied from the entity's own generation facilities, it will not be directly affected by fluctuations in wholesale market prices. In addition, electricity used via self-wheeling is exempt from the renewable energy surcharge, which is normally levied on electricity purchased from the grid. As of October 2023, this exemption significantly enhances the cost-effectiveness of self-wheeling, especially for entities that install large-scale renewable energy systems [11].

To utilize the transmission network, self-wheeling entities are required to pay wheeling charges to the TSO based on the volume of electricity transmitted. Unlike conventional retail contracts or third-party Power Purchase Agreements (PPAs), self-wheeling allows electricity consumers to retain control over their generation sources. However, self-wheeling entities must also bear the imbalance risk. They are required to submit a day-ahead transmission schedule to the TSO, and any deviation between the scheduled and actual transmitted electricity results in an imbalance. For entities wheeling variable renewable energy, this imbalance can lead to significant additional costs.

IV. CASE STUDY

The target self-wheeling project aims to transmit electricity from a PV generation site in Utsunomiya, Tochigi, to a university campus in Tokyo, both located within the same TSO service area in the Kanto region of Japan. The PV system has a maximum output capacity of $30\,\text{MW}$, which corresponds to approximately 30% of the campus's peak load. The campus load profile exhibits a pronounced peak around midday and a dip at midnight, aligning well with the generation pattern of PV systems and making it an ideal candidate for PV self-wheeling. A BESS is installed at the PV site to mitigate the imbalance caused by PV orecast errors. The simulation is conducted over a two-month period, from September 1 to October 31, 2023.

A. PV Generation Forecast

Two forecast results are compared in the simulation.

1) MEPS Ensemble Model: The Meso Ensemble Prediction System (MEPS) is a high-resolution, ensemble-based numerical weather prediction model developed and operated by the Japan Meteorological Agency [12]. MEPS produces short-term forecasts by performing multiple simulations with slightly perturbed initial conditions to capture the uncertainty inherent in atmospheric dynamics. It covers the Japanese archipelago with a spatial resolution of $5\,\text{km}$ and provides data on variables such as temperature, wind speed, and solar radiation at a 3-hour interval. For each forecast point, MEPS outputs a set of 21 ensemble members. In this study, the location of the PV site is shown in Fig. 3, and the ensemble forecast is calculated as the average of the forecasts from the four nearest MEPS grid points.

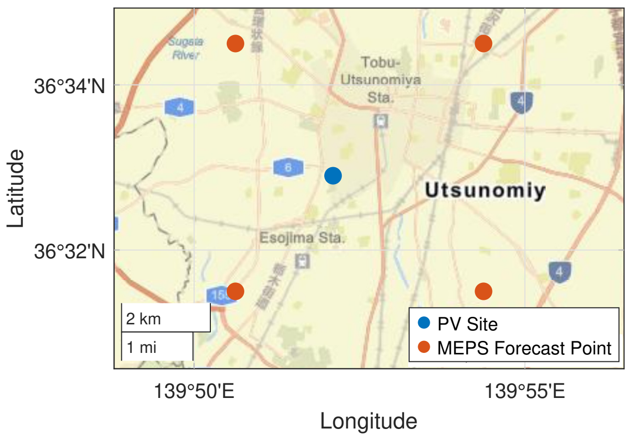


Fig. 3. The location of the PV site and the nearst MEPS forecast points.

2) SARIMA Model: The Seasonal Auto-Regressive Integrated Moving Average (SARIMA) model is a time series forecasting method that incorporates seasonal components [13]. It is a statistical model derived directly from historical values, making it effective for capturing trends and repeating daily patterns in solar radiation. Due to its simplicity and interpretability, SARIMA is widely used for forecasting PV generation [14], [15].

The PV forecast results are given in Table I and a fraction of it as depicted in Fig. 4.

TABLE I
THE PV FORECAST RESULT.

	MSE	MAE	Error Mean
MEPS	3.22	1.12	-0.01
SARIMA	3.56	0.98	-0.16

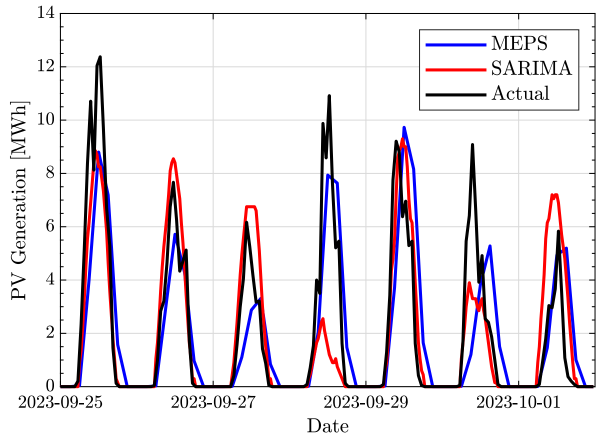


Fig. 4. The PV forecast result from 2023/09/25 to 2023/10/01.

B. Impact on Imbalance Management

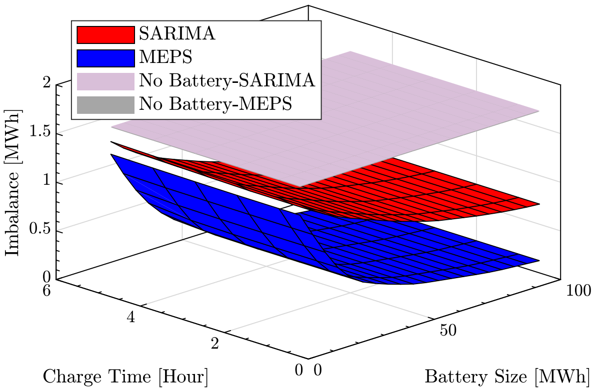
Two operation patterns of the BESS are compared in this section:

- Minimize the total imbalance magnitude
- Minimize the total imbalance penalty (assuming perfect forecast on imbalance price to focus on the impact of PV forecast)

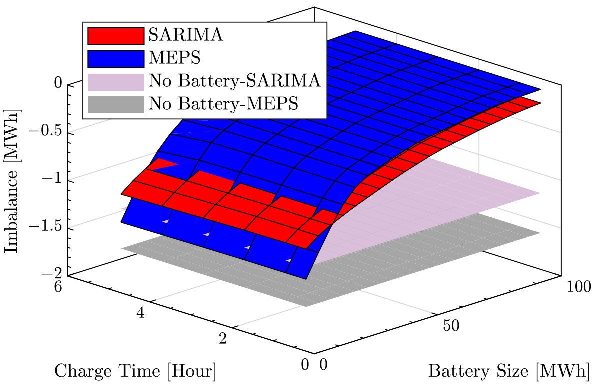
The simulation results of the above operation patterns with varying BESS sizes and charging times are shown in Fig. 5 and Fig. 6, respectively.

The flat surfaces represent benchmark cases without BESS implementation. In the absence of BESS, the total surplus imbalance is nearly identical for both PV forecasting methods. However, the SARIMA forecast results in a smaller shortage imbalance compared to the MEPS forecast, leading to a lower overall imbalance magnitude. This occurs despite the SARIMA forecast having a higher MSE, because its MAE is lower. The key reason lies in the nature of the MSE: for a given actual value $\rho > 0$, MSE penalizes forecasts more heavily only when the predicted value exceeds 2ρ or becomes negative: situations that are highly unlikely in PV forecasting. As a result, MAE serves as a more appropriate metric than MSE for evaluating forecast performance in terms of imbalance magnitude.

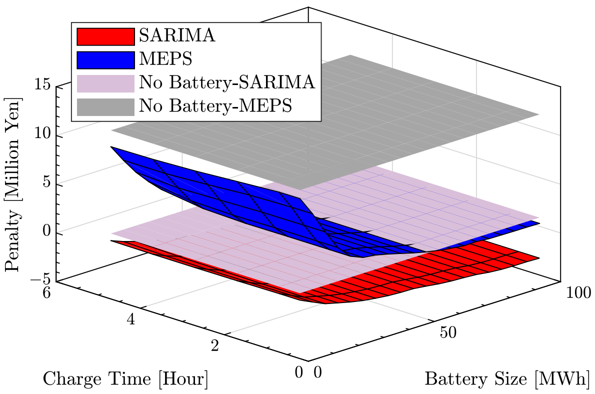
When the BESS is implemented, the MEPS forecast results in more effective imbalance mitigation. This is because the mean of its forecast error is closer to zero, allowing the BESS more balanced opportunities to both charge and discharge. In



(a) Surplus Imbalance.

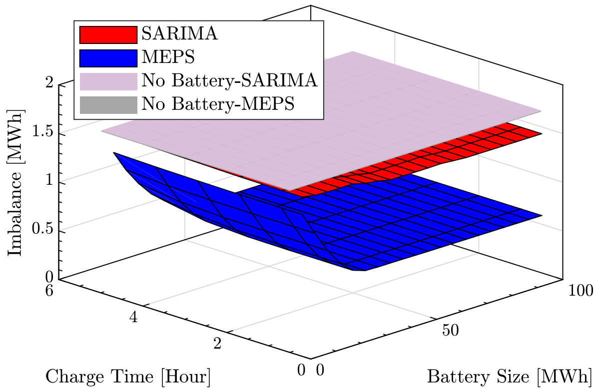


(b) Shortage Imbalance.

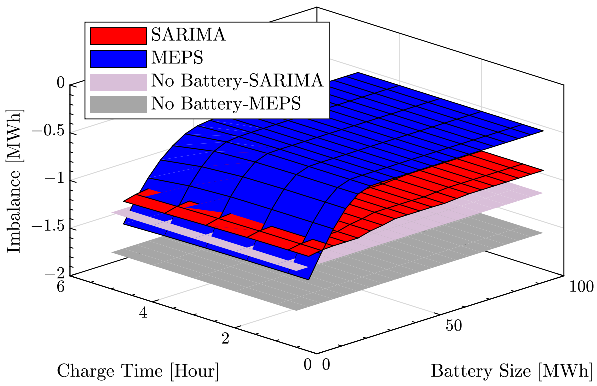


(c) Imbalance Penalty.

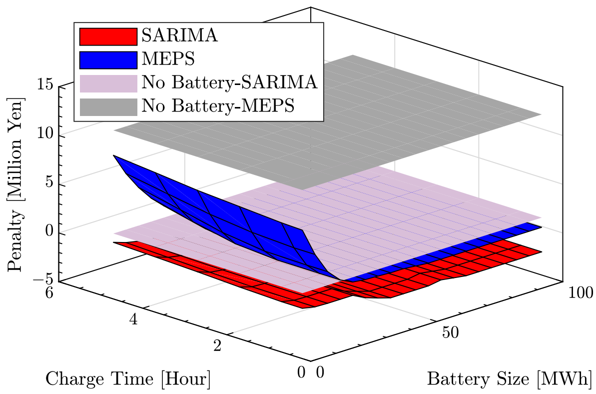
Fig. 5. Minimize the imbalance magnitude.



(a) Surplus Imbalance.



(b) Shortage Imbalance.



(c) Imbalance Penalty.

Fig. 6. Minimize the imbalance penalty.

contrast, with the SARIMA forecast, the BESS struggles to compensate for surplus imbalance. This is due to the forecasted values frequently underestimating actual generation, resulting in fewer opportunities to discharge and thus limiting their ability to offset the imbalance.

C. Defect in the Current System

As the SARIMA forecast frequently leads to surplus imbalances, the resulting imbalance penalty often becomes negative, indicating that the target self-wheeling scheme is, in fact, profiting from the imbalance penalty system. Furthermore, when the BESS is operated with the goal of minimizing the imbalance penalty, mitigation reaches a plateau despite further increases in BESS capacity. This implies that the self-wheeling scheme is deliberately allowing a certain level of imbalance to persist, as it yields economic benefits.

While the updated imbalance pricing mechanism is designed to reflect the real-time value of electricity in the system and thus justifies rewards for surplus generation during periods of system-wide shortage, it opens the door to exploitation. A self-wheeling entity could intentionally under-report its schedule, submitting values significantly lower than the expected generation (in the extreme case, submitting a zero-generation schedule), and profit from the guaranteed purchase of excess generation by the TSO. This effectively allows the imbalance penalty system to be used as a "riskless market" for selling electricity, undermining the original intent of maintaining supply-load balance.

Such behavior runs counter to the foundational goals of both the imbalance penalty framework and the self-wheeling scheme, which are intended to promote system stability and responsible forecasting. To prevent this type of gaming, a performance-based metric could be introduced. For example:

$$k_i = \frac{\sum_n MAE_n/n}{MAE_i} \quad (1)$$

where MAE_i is the MAE of the ith entity. The imbalance reward for surplus generation by the ith entity is scaled by multiplying the original imbalance price by k_i. When the entity's forecasting performance is worse than the system average, k_i drops below 1, thereby reducing the imbalance reward. Assuming the average MAE across all entities is 0.9, the resulting surplus imbalance under the MEPS forecast is shown in Fig. 7. With the performance-based adjustment in place, the total surplus imbalance is further reduced compared to the baseline scenario without this mechanism.

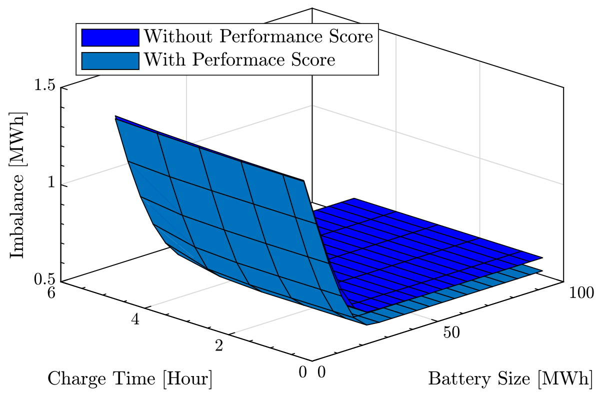


Fig. 7. Surplus imbalance for the MEPS forecast with performance score adjustment.

V. Conclusions

This study investigated the impact of PV forecasting on imbalance management in a self-wheeling project under Japan's updated imbalance penalty framework. Through a comparison of two forecasting approaches, we found that MAE is a more relevant metric than MSE for assessing imbalance magnitude. Furthermore, forecasts with a more balanced error distribution enable more effective BESS operation for mitigating imbalances.

A structural defect in the current imbalance penalty system is also identified: under certain forecast conditions, an entity may profit from deliberate under-scheduling. Such behavior undermines the intended purpose of the system and raises concerns regarding operational efficiency and fairness.

Future work will focus on developing PV forecasting models that achieve both low MAE and unbiased error distributions. In addition, while this study proposes a preliminary approach to mitigating system misuse, more robust and well-validated solutions are needed to ensure the integrity of the imbalance penalty system.

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