Economic Assessment of Battery Energy Storage Systems Participating in the JEPX Spot Market and Frequency Containment Reserve Market

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***Abstract*—Demand-side resources can participate in daily energy trading through the Japan Electric Power eXchange (JEPX), and the Frequency Containment Reserve (FCR) market, newly established in 2024, provides additional opportunities for frequency regulation. This paper evaluates the economic performance of a battery energy storage system (BESS) on the demand side under joint participation in the JEPX spot market and the FCR market. Three scenarios are assessed: the current market environment, a prospective market reflecting anticipated policy reforms, and a sensitivity case in which the FCR price declines toward levels observed in mature international primary reserve markets. The analysis explicitly considers the impact of market price forecasting methods, examining how the forecast price signals affect the operation and profitability of the target BESS under different scenarios. Profits are quantified through market simulations using actual price data, and battery degradation associated with FCR participation is modeled by simulating a simple proportional controller that satisfies FCR response requirements, with state-of-charge (SOC) cycling estimated from the resulting charge-discharge behavior.**

***Index Terms*—Demand-side Responses, Electricity Market, Primary Frequency Reserve, Price Forecast, Battery Energy Storage System**

I. Introduction

The ongoing deregulation of the Japanese electricity market has reshaped market structures and expanded participation opportunities for diverse resources. The JEPX has operated a day-ahead single-price spot market since 2015. Recently, the FCR market was introduced in 2024 and is organized by the Electricity Power Reserve eXchange (EPRX) to procure primary frequency control capacity. Market participation is open to conventional generators and distributed energy resources, enhancing system flexibility under increasing renewable energy penetration.

Compared with energy arbitrage in the JEPX spot market, FCR provision is particularly attractive for BESS operators. The symmetrical and relatively shallow response requirement results in limited SOC deviation and moderate battery degradation. Meanwhile, due to the currently limited number of market participants and insufficient competition, the FCR market exhibits relatively high prices, making reserve provision highly profitable.

When participating in both markets, a BESS can switch between energy arbitrage and reserve provision to maximize profit. However, optimal operational decisions strongly depend on accurate market price forecasting. A wide range of forecasting methods has been applied to electricity price prediction, including statistical time-series models such as the Seasonal AutoRegressive Integrated Moving Average (SARIMA) model [1] and rapidly developing machine learning approaches such as long short-term memory (LSTM) networks [2]. Forecasting of frequency regulation market prices in different regions has also been investigated in [3], [4].

Conventional forecast evaluation metrics primarily measure numerical error. For example, 27 forecasting methods are compared using symmetric mean absolute percentage error in [5]. However, numerical accuracy alone is insufficient from an economic perspective for energy arbitrage. Previous studies have shown that accurately predicting the timing of price extrema is often more economically valuable than minimizing overall prediction error in energy arbitrage, particularly for distributed resources [6], [7].

Although prior research has examined the economic assessment of simultaneous participation in energy and frequency regulation markets [8], [9], limited attention has been paid to how price forecasting characteristics affect profitability. The main contribution of this paper is to conduct price forecasting for the newly established FCR market in Japan and to identify which forecast characteristics are most critical for maximizing BESS profitability under different market scenarios.

II. The FCR Market in Japan

A. Current Market Conditions

The FCR market in Japan procures primary frequency control reserves to maintain short-term system frequency stability following supply-demand imbalances. Resources providing

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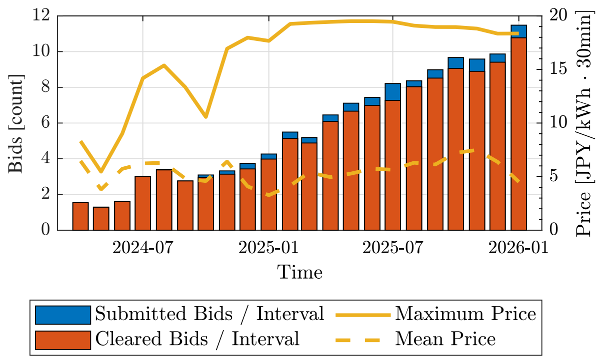


Fig. 1. Monthly average bidding activity and price levels.

this service must respond automatically to frequency deviations without centralized dispatch instructions and, therefore, continuously monitor system frequency and adjust their output proportionally according to a predefined droop characteristic.

Procurement is conducted through competitive weekly auctions, in which qualified resources submit bids specifying capacity (MW) and price with a 3-hour bidding interval. The market follows a multi-price (pay-as-bid) settlement rule, meaning cleared resources are paid their bid prices rather than a uniform clearing price. Cleared resources receive capacity payments for maintaining symmetrical availability of both upward and downward regulation capability, regardless of the actual activation energy.

The monthly average bidding activity and price levels of the FCR market in the Kyushu area are shown in Fig. 1. As a newly established market, the number of market participants and submitted bids remains limited, although it has been continuously increasing. On the other hand, the average price appears relatively stable; however, the maximum price is close to the price cap of $19.51\ \mathrm{JPY/kW \cdot 30min}$ set by EPRX [10]. In more than $90\,\%$ of the bidding intervals, the demanded FCR requirement is not fully met by the submitted bids; therefore, bids are accepted even when submitted at the price cap. The local system operator must compensate for the remaining reserve requirement through non-market measures in such situations.

B. Prospective Market Reform

As the number of participants and submitted bids increases, the high price cap of $19.51\ \mathrm{JPY/kW \cdot 30min}$ may significantly raise the overall system cost of procuring primary reserve. Meanwhile, the current weekly auction framework and 3-hour bidding interval are not aligned with other electricity markets in Japan. Therefore, the Agency for Natural Resources and Energy is discussing reforms to the FCR market in the coming years, including reducing the price cap to $7.21\ \mathrm{JPY/kW \cdot 30min}$ [11], and changing the bidding interval to 30 minutes on a daily basis to align with other markets in Japan [12].

Although no formal discussion has yet addressed the pay-as-bid settlement mechanism, it is reasonable to assume that, with a sufficient number of participants and bids, the system requirement will generally be met and market prices will converge toward the average bid level.

TABLE I
MARKET PRICE COMPARISON

	ENTSO-E DE	Japan Kyushu
Energy Price	$76.28\ \mathrm{EUR/MWh}$	$12.61\ \mathrm{JPY/kWh}$
FCR Price	$4.91\ \mathrm{EUR/[MW \cdot 15min]}$	$8.03\ \mathrm{JPY/[kW \cdot 30min]}$
FCR/Energy in 1 hour	25.74%	127.40%

Accordingly, the following assumptions are adopted for the Prospective Market scenario in this study:

- Scale down the FCR price by a factor of $7.21/19.51$.
- Change the bidding interval from 3 hours to 30 minutes.
- Replace the current multi-price mechanism with a single-price market, where the average price of each bidding interval is taken as the clearing price.

C. Mature-Market Pricing

Table I summarizes the price characteristics from March to September 2025 for the German area (ENTSO-E DE) and the Kyushu area in Japan. Even after being scaled down by a factor of $7.21/19.51$, the FCR price in Kyushu remains relatively high compared with the mature ENTSO-E DE market, with an FCR-to-energy price ratio of $47.08\,\%$, which is nearly twice that observed in ENTSO-E DE.

To simulate a stabilized market environment in the distant future, the Mature-Market scenario further scales down the FCR price by a factor of 0.2, resulting in an FCR-to-energy price ratio of approximately 25.74%. The bidding interval and the clearing mechanism remain identical to those assumed in the Prospective Market scenario.

III. BESS Model

A. FCR Controller

EPRX requires FCR participants to provide full bidding power output when the frequency deviation reaches 0.2 Hz [13], with a deadband of 0.01 Hz. In accordance with this requirement, the FCR controller of the BESS is designed as follows:

$$\Delta P = \begin{cases} 0, & |\Delta f(t)| \leq 0.01, \\ -\dfrac{\Delta f(t)}{0.2} P_{\mathrm{FCR}}, & |\Delta f(t)| > 0.01, \end{cases} \tag{1}$$

where P_{FCR} denotes the bid FCR capacity.

To quantify the impact of FCR participation on BESS degradation, the actual frequency deviation over one week, measured in Tokyo, Japan, is used to simulate the BESS power response. The measured frequency deviation is shown in Fig. 2. The effect of FCR participation on the SOC in one prospective bidding interval ($\Delta T = 30\mathrm{min}$) is modeled as:

$$m = m_0 \cdot \frac{P_{\mathrm{FCR}}}{Q} \tag{2}$$

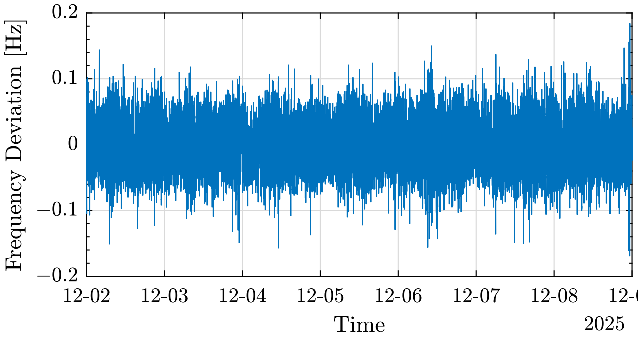


Fig. 2. Measured frequency deviation.

where m represents the absolute total SOC movement caused by continuous charge/discharge under the FCR controller, and Q is the total BESS energy capacity. Based on the measured frequency deviation, m_0 is averagely calculated to be 6.71%. This implies that, under the above FCR controller, a BESS capable of being fully charged within 1 hour would likely experience an SOC movement of only 6.71% when participating in FCR at its maximum output power for one prospective bidding interval. On the other hand, the average net SOC change within a bidding interval is approximately 0.15%, indicating that although FCR operation induces continuous SOC fluctuations, the cumulative effect over each interval is negligible.

B. Operation Optimization

The target BESS participates in the JEPX spot market for energy arbitrage and in the FCR market for the profit of primary reserve provision. The daily operational scheduling of the BESS is formulated as the optimization problem shown in (3).

$$\underset{\substack{State_{\mathrm{JEPX}}(T)\\ State_{\mathrm{FCR}}(T)}}{\text{maximize}} \quad \Delta T P_{\max} \sum_{T} \Big(p_{\mathrm{JEPX}}(T) State_{\mathrm{JEPX}}(T) + p_{\mathrm{FCR}}(T) State_{\mathrm{FCR}}(T) \Big) \tag{3a}$$

$$\text{subject to} \quad -1 \le State_{\mathrm{JEPX}}(T) \le 1, \tag{3b}$$

$$0 \le State_{\mathrm{FCR}}(T) \le 1, \tag{3c}$$

$$SOC(T) = SOC_{\mathrm{initial}} - \Delta T \frac{P_{\max}}{Q} \cdot \sum_{T} State_{\mathrm{JEPX}}(T), \tag{3d}$$

$$\underline{SOC} \le SOC(T) \le \overline{SOC}, \tag{3e}$$

$$|State_{\mathrm{JEPX}}(T)| + State_{\mathrm{FCR}}(T) \le 1, \tag{3f}$$

$$\sum_{T} \Big(|State_{\mathrm{JEPX}}(T)| + m State_{\mathrm{FCR}}(T) \Big) \le 2k(\overline{SOC} - \underline{SOC}) \tag{3g}$$

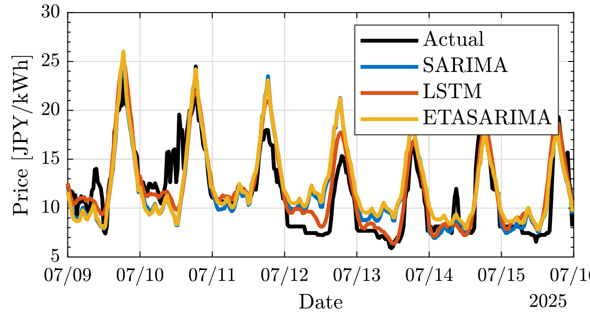


Fig. 3. JEPX spot price forecast results.

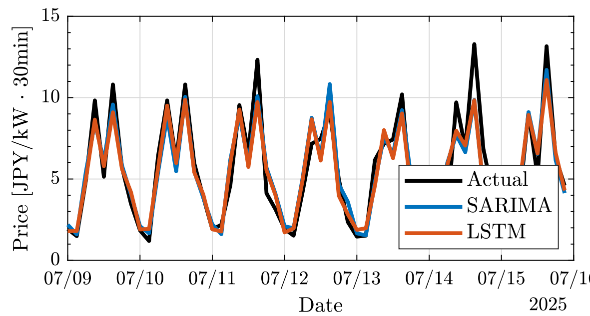


Fig. 4. FCR price forecast results.

The objective function in Eq. (3a) maximizes the BESS's daily profit. p_{JEPX} and p_{FCR} denote the forecast JEPX spot price and FCR price, respectively. $P_{\max}$ represents the maximum power rating of the BESS. $State_{\mathrm{JEPX}}$ and $State_{\mathrm{FCR}}$ indicate the fraction of $P_{\max}$ allocated to the JEPX and FCR markets in each bidding interval. A negative $State_{\mathrm{JEPX}}$ corresponds to charge, whereas a positive value represents discharging.

Eq.(3d) describes the SOC dynamics of the BESS, assuming that the net cumulative effect of FCR participation on SOC within each bidding interval is negligible. $\overline{SOC}$ and $\underline{SOC}$ denote the upper and lower SOC limits, respectively. Eq.(3f) prevents prevents simultaneous bidding in both markets. The number of charging cycles is limited by (3g) to mitigate battery degradation, where k represents the maximum number of charging cycles permitted per day.

IV. Simulation Results

A. Price Forecast

Three forecasting methods are considered in this paper: a statistical time-series SARIMA model, a univariate LSTM model, and a profit-oriented ETA-SARIMA model specifically tuned for JEPX spot price forecasting, as proposed in [6]. Previous studies have shown that, for demand-side resources, accurately predicting the timing of price extrema is more profitable than merely improving numerical forecast accuracy. A portion of the forecasting results for the JEPX spot market and the FCR market in the Kyushu area are presented in Fig. 3 and Fig. 4, respectively.

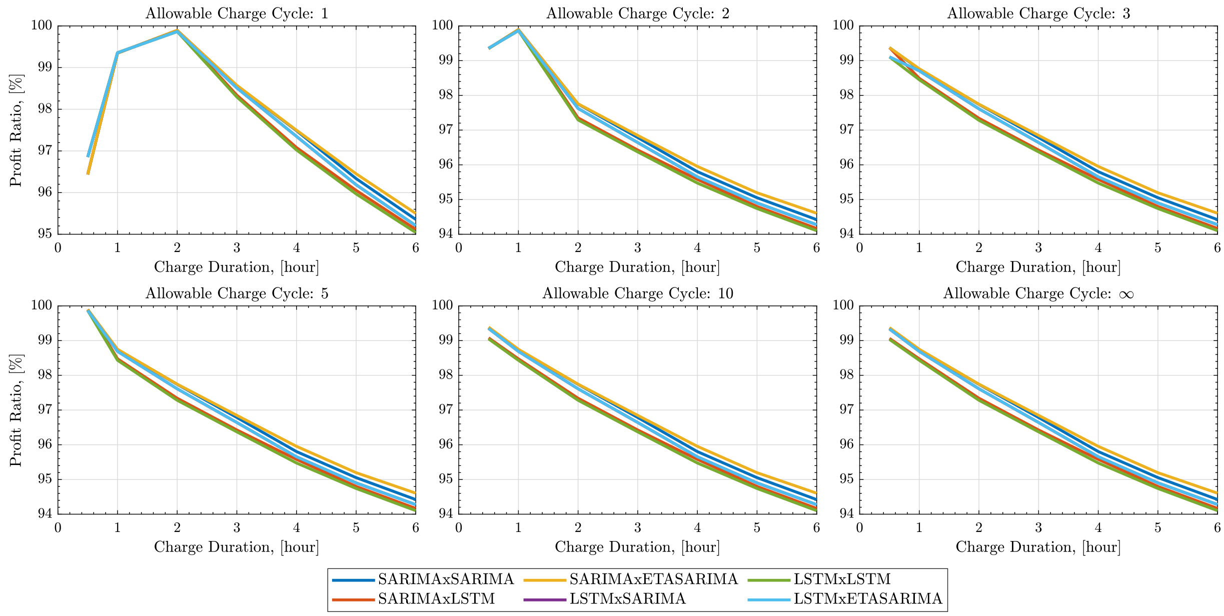


Fig. 5. Profit comparison of forecast method combination in Prospective Market scenario.

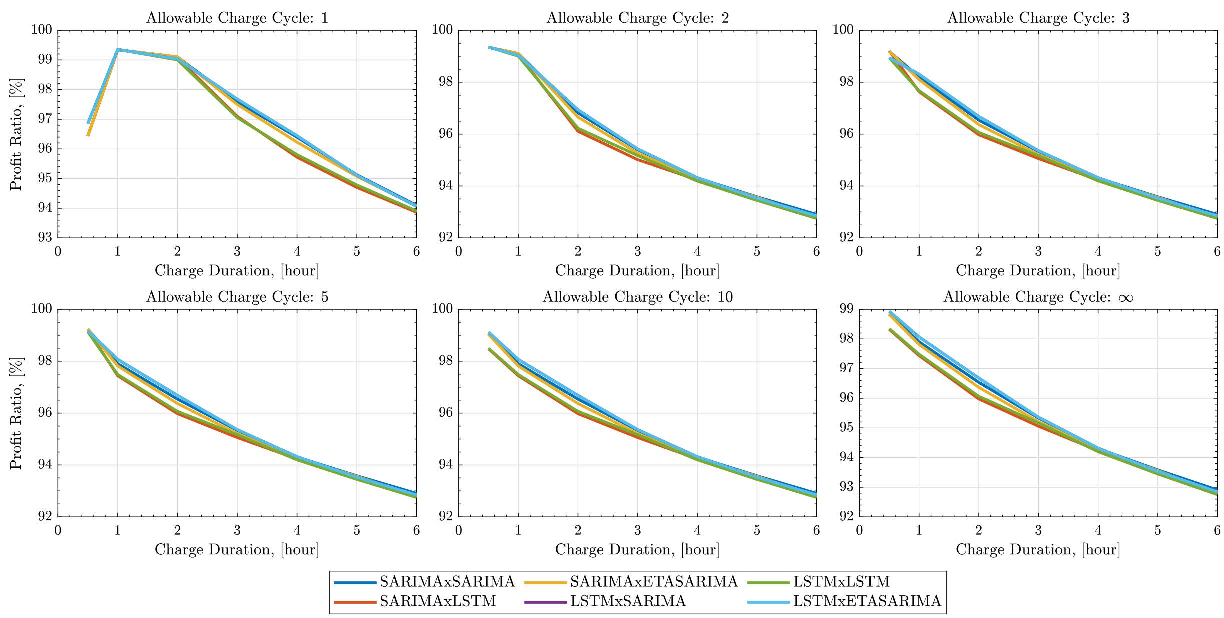


Fig. 6. Profit comparison of forecast method combination in Mature-Market scenario.

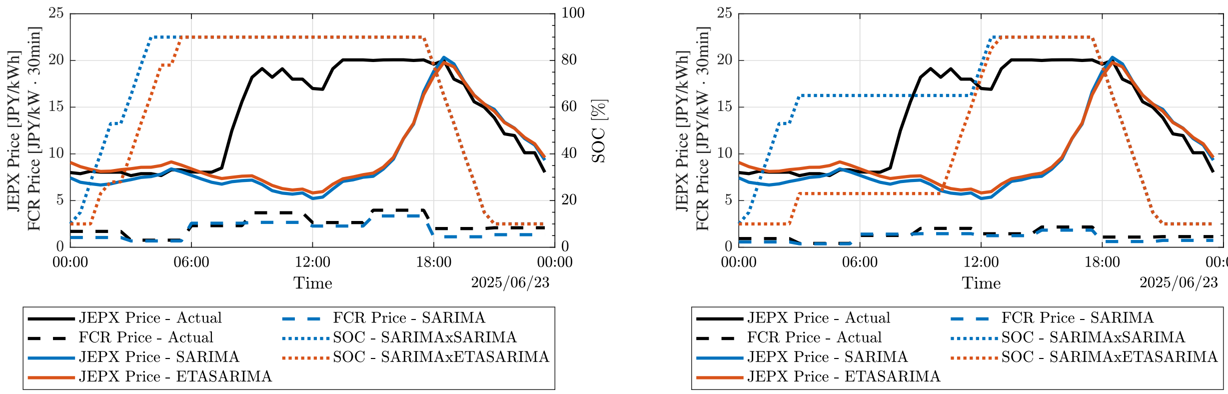
TABLE II
FORECAST EVALUATION

		SARIMA	LSTM	ETASARIMA
JEPX	R^2	0.6084	0.6298	0.5990
	ETA	0.7205	0.6117	0.7378
FCR	R^2	0.8068	0.8119	-
	ETA	0.8800	0.8667	-

The detailed evaluation results are summarized in Table II. In addition to the conventional coefficient of determination (R^2), the forecasts are assessed using the Extremum Timing Accuracy (ETA) metric proposed in [7] as well. ETA evaluates the accuracy of predicted price-extremum timing and reflects the potential profitability of the forecast for demand-side resources engaged exclusively in energy arbitrage.

B. Economic Assessment

The total energy capacity of the target BESS is $10\mathrm{MWh}$, and the maximum power output varies depending on the charging duration, ranging from 0.5 to 6 hours for sensitivity



(a) Prospective Market scenario.

(b) Mature-Market scenario.

Fig. 7. Price and BESS operation detail: SARIMAxSARIMA vs SARIMAxETASARIMA.

analysis. The simulation period spans from April to September 2025.

Under the current market scenario, given the high price cap and the frequent reserve insufficiency in the FCR market, an FCR bid submitted at the cap price is highly likely to be accepted. In this setting, the profit from the FCR market substantially exceeds that from energy arbitrage in the spot market. Consequently, the BESS has almost no incentive to participate in the spot market and can simply submit bids at the cap price in the FCR market. In the most extreme case, where the BESS charging duration is 0.5 hour ($P_{\max} = 20$ MW), the theoretically optimal profit achievable with perfect foresight of JEPX and FCR prices is 3412 million JPY. In comparison, blindly bidding at the cap price in the FCR market yields a profit of 3411 million JPY, which corresponds to 99.98% of the oracle benchmark. Therefore, under the current market design, the BESS can capture nearly the full potential profit without performing any price forecasting.

The profit comparison of different forecast method combinations in the Prospective Market and Mature-Market scenarios is shown in Fig. 5 and Fig. 6, respectively. In the legend, the former method denotes the FCR forecast model and the latter denotes the JEPX forecast model. The BESS is assumed to act as a price taker due to its relatively small capacity compared with conventional generators.

In the Prospective Market scenario, the SARIMA×ETASARIMA combination consistently yields the highest profit, regardless of the allowable charging cycles or charging duration. Notably, this combination achieves the highest ETA rather than the highest R^2. Since the BESS primarily participates in the FCR market and switches to the JEPX spot market only during price peaks and dips, accurate prediction of price-extremum timing is critical to profitability.

In contrast, in the Mature-Market scenario, the most profitable forecast method combination varies. The combinations using LSTM for JEPX forecasting perform worst in most cases, indicating that a sufficiently high ETA remains essential. The operational details are illustrated in Fig. 7. For a given pair of JEPX price peak and dip times, $T_{\max}$ and $T_{\min}$, whether the BESS switches from FCR provision to energy arbitrage depends on

$$p_{\mathrm{JEPX}}(T_{\max}) - p_{\mathrm{JEPX}}(T_{\min}) - 2\big[p_{\mathrm{FCR}}(T_{\max}) + p_{\mathrm{FCR}}(T_{\min})\big]. \tag{4}$$

If (4) is positive, the profit from energy arbitrage exceeds that from FCR provision. In the Prospective Market scenario, p_{FCR} is relatively high compared with $p_{\mathrm{JEPX}}(T_{\min})$. Therefore, the tolerance to inaccuracies in estimating $p_{\mathrm{JEPX}}(T_{\min})$ is relatively large, as the BESS charging time shifts only slightly (see Fig. 7(a)). By contrast, when the FCR price level decreases in the Mature-Market scenario, inaccuracies in estimating $p_{\mathrm{JEPX}}(T_{\min})$ have a much stronger impact. This may lead to incorrect charging decisions and consequently reduced profit, as shown in Fig. 7(b). Therefore, in this scenario, not only a high ETA but also accurate value prediction of the price extrema is crucial for achieving optimal profitability.

V. Conclusions

This paper examined the impact of price forecasting methods on the profitability of a BESS participating in both the JEPX spot and FCR markets under different market scenarios in Japan. The results show that under prospective market structures with relatively high FCR prices, ETA is the dominant factor determining profitability, while conventional accuracy metrics such as R^2 are less relevant. However, as the FCR market matures and price levels decline, not only extremum timing but also accurate prediction of extremum magnitude becomes critical. Future work will focus on developing a combined profit-oriented evaluation criterion for FCR and JEPX price forecasts, as well as forecasting models explicitly designed based on this profit-oriented objective.

References

[1] P. Rajan and K. V. Chandrakala, "Statistical model approach of electricity price forecasting for indian electricity market," in *2021 IEEE Madras Section Conference (MASCON)*. IEEE, 2021, pp. 1–5.

[2] K. Wang, M. Yu, D. Niu, Y. Liang, S. Peng, and X. Xu, "Short-term electricity price forecasting based on similarity day screening, two-layer decomposition technique and bi-lstm neural network," *Applied Soft Computing*, vol. 136, p. 110018, 2023.
[3] S. Cai and R. Matsuhashi, "Model predictive control for ev aggregators participating in system frequency regulation market," *IEEE Access*, vol. 9, pp. 80 763–80 771, 2021.
[4] W. Sai, Z. Pan, S. Liu, Z. Jiao, Z. Zhong, B. Miao, and S. H. Chan, "Event-driven forecasting of wholesale electricity price and frequency regulation price using machine learning algorithms," *Applied Energy*, vol. 352, p. 121989, 2023.
[5] J. Lago, F. De Ridder, and B. De Schutter, "Forecasting spot electricity prices: Deep learning approaches and empirical comparison of traditional algorithms," *Applied Energy*, vol. 221, pp. 386–405, 2018.
[6] S. Cai, M. Mae, and M. Ryuji, "Demand-side response management in electricity markets via a profit-oriented forecasting criterion," *IEEE Access*, 2025.
[7] S. Cai, M. Mae, R. Matsuhashi, T. Masuda, N. Ishibashi, and S. Ikekawa, "Profit-oriented criterion of electricity price forecast considering charging duration of demand-side responses," in *2025 21st International Conference on the European Energy Market (EEM)*. IEEE, 2025, pp. 1–6.
[8] Q. Zhai, K. Meng, Z. Y. Dong, and J. Ma, "Modeling and analysis of lithium battery operations in spot and frequency regulation service markets in australia electricity market," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 5, pp. 2576–2586, 2017.
[9] S. Cai, M. Mae, and R. Matsuhashi, "Cooperative optimal bidding strategy for demand-side responses participating in jepx spot market and replacement reserve market," *IEEJ Transactions on Power and Energy*, vol. 146, no. 3, pp. 194–204, 2026.
[10] Electric Power Reserve eXchange (EPRX), "Upper price limits for the supply-demand reserve market," https://www.eprx.or.jp/information/docs/20260205_%E9%9C%80%E7%B5%A6%E8%AA%BF%E6%95%B4%E5%B8%82%E5%A0%B4%E3%81%AE%E4%B8%8A%E9%99%90%E4%BE%A1%E6%A0%BC%E3%81%AB%E3%81%A4%E3%81%84%E3%81%A6.pdf, Feb 05 2026, accessed: 2026-03-03.
[11] Agency for Natural Resources and Energy, "Overview of the supply–demand reserve market," https://www.meti.go.jp/shingikai/enecho/denryoku_gas/jisedai_kiban/system_review/pdf/108_04_00.pdf, Oct 29 2025, accessed: 2026-03-03.
[12] ——, "Simultaneous market and future roadmap," https://www.meti.go.jp/shingikai/enecho/denryoku_gas/jisedai_kiban/system_design_wg/pdf/005_06_00.pdf, Oct 15 2025, accessed: 2026-03-03.
[13] *Overview of the EPRX Market and Product Requirements*, 7th ed., Electric Power Reserve eXchange (EPRX), 2025, https://www.eprx.or.jp/outline/docs/guide_250401.pdf.