A Comparative Analysis of the Market Bidding Decisions of Operational PV Plants during Near-Zero Prices in the Spanish Electricity Markets

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***Abstract*—Nowadays, Day-Ahead market price cannibalization particularly affects photovoltaic (PV) plants, as this phenomenon impacts the revenue per unit of energy. However, renewable assets can participate in balancing services to increase their market revenues. Despite many research articles proposed complex optimization techniques, the market bidding of operational PV assets remains unsophisticated nowadays. This article studies and compares the market strategies of PV plants during near-zero price days in Spain, highlighting how these PV plants, despite having similar characteristics, operate with significantly different market decisions. It concludes that participation in balancing markets increases solar value by capturing higher revenues. Solar trackers also enhance daily solar generation. In the future, market agents of PV systems should adjust their operations to multiple energy markets and trends in market prices to optimize revenue stacking.**

***Index Terms*—Balancing Services, Electricity Markets, Near-Zero Prices, Market Revenue Stacking, Photovoltaic Plants**

I. Introduction

In recent years, the increasing market penetration of zero-marginal cost variable Renewable Energy Sources (RES) has caused several market distortions, once certain RES penetration thresholds are exceeded as suggested by [1]. These market distortions include a reduction in the average price on the energy markets such as Day-Ahead market (DAM), increased volatility in daily peak and off-peak prices [2], and even price cannibalization in some countries. As indicated by [3] and [4], the negative effects of solar penetration on solar value are more pronounced than those of wind, due to the high temporal concentration of solar generation around midday hours.

Further research should explore the deployment of Energy Storage Systems (ESS), real participation in multiple markets, and grid support services [5], as well as optimized asset management to enhance the value of RES energy into the market. For example, [6] proposed a centralized market operation of PV, wind, and multiple ESSs in the Day-Ahead Market (DAM), Continuous Intraday Markets (ICM), and automatic Frequency Restoration Reserve (aFRR), focusing on portfolio scheme maximization and ESS degradation minimization. Similarly, [7] proposed a multi-stage stochastic bidding strategy in day-ahead, intraday, and balancing markets (BM) for wind, PV, and storage technologies. Authors in [8] investigated the techno-economic assessment of PV+ESS plants for DAM and FCR in the Swedish and German markets during 2023. Indeed, as indicated by [9], PV inverters can provide balancing services and react even faster to frequency deviations than conventional power plants, without the need to upgrade hardware. Focusing on social welfare, [10] aimed at the equilibrium of producers' profits in multiple markets.

The combined operation of energy markets including BM is also addressed by electric vehicles and demand response aggregators [11] and hydrogen-integrated virtual power plants [12]. Previous research has demonstrated that optimization techniques improve RES profitability and effectively manage the multi-settlement bidding in multiple markets, even with daily operational uncertainties. However, the practical operation of RES assets diverges significantly from the theoretical approaches proposed in academic literature.

Moreover, recent market trends, such as price cannibalization, exacerbate these challenges. Price cannibalization leads to a higher occurrence of near-zero prices in the DAM, and even negative prices, especially during midday hours. Consequently, price cannibalization seems to affect mostly to PV assets, as their captured price is lower than the weighted average price settled in the DAM. Therefore, real PV systems should adjust their operations to capture greater market value.

To the best of the authors' knowledge, these market strategies have not been widely validated for days with near-zero prices, in real-world operational assets. This article aims to analyze the strategic market operations of six PV assets with varying characteristics in the Spanish electricity market.Their market participation is compared to understand their strategic market bidding across multiple markets, especially during periods of near-zero DAM prices. This study presents how each plant, participates in different markets and optimizes its strategic bids, including whether the submitted bids were matched or unmatched. The article discusses and highlights how these PV plants, despite having very similar characteristics, operate with significantly different decisions.

Finally, an economic assessment is provided for a typical summer day with near-zero prices, and the market revenues

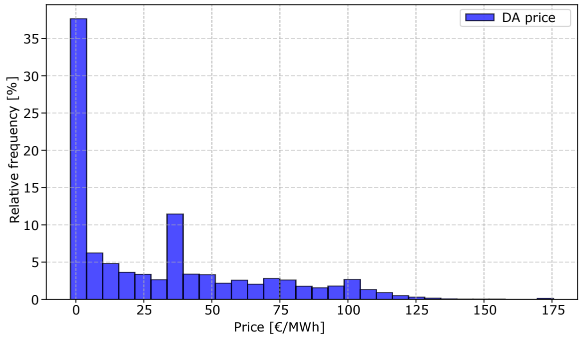

Figure 1. Relative Frequency Distribution [%] of hourly prices in the Spanish DAM from March to June

for each PV agent are discussed.

II. Case Study and Market Design

The present study evaluates the market strategies of PV plants during near-zero price days in Spain. The periods when DAM prices approach zero typically occurring during midday hours due to high solar generation. As illustrated in Fig. 1, DAM prices ranged from -2 to 4 €/MWh in over 37% of the hours from March to June. For this analysis, six operational PV assets were selected, as detailed in Table I. These assets, representative of the broader Spanish PV market with diverse locations and sizes, have their market participation analyzed and compared to understand their strategic bidding in multiple markets during days with near-zero DAM prices.

One of the assets (FBHIBHV) comprises a hybrid PV system with a 5 MW battery and four hours of energy storage capacity (20 MWh). Additionally, the six assets can be distinguished by whether they have a solar tracking system or not, simply by observing their generation patterns offered to the DAM and the declared asset technologies. Knowing in advance which assets have solar tracking systems is crucial, as it significantly impacts their profitability [13]. Solar trackers enhance profitability by increasing PV production during sunrise and sunset, when prices tend to be higher.

An exploratory data analysis is employed, using data published by OMIE, the Nominated Electricity Market Operator (NEMO), which operates the Iberian Electricity Market (MIBEL), and data published by REE, the Spanish Transmission System Operator (TSO) responsible for the balancing services. Regarding market data, OMIE publishes the offers submitted and matched by each unit in the various markets, which are publicly available through the OMIEData service [14].

For balancing services, the data comes from REE, which provides public information through the *i90* files. Prices are also published by REE through its ESIOS service [15]. Once data are downloaded and preprocessed, the offers submitted by these assets and the resulting market matches can be analyzed, with a three-month data delay to be published. These trading results facilitate the evaluation of the strategies employed by these assets and enables an economic assessment of the revenue per unit of energy generated or traded in the market [€/MWh] and per nominal power of the plant [€/MW].

Regarding the multiple markets covered and analyzed under MIBEL, the DAM bids must be submitted by 12:00 on the day before delivery (D-1), with remuneration based on a pay-as-clear mechanism. The Intraday Auction Market (IDM) features multiple sessions with specific gate closure times throughout the day, allowing for near to real-time adjustments, and also operates on a pay-as-clear basis. In contrast, the Continuous Intraday Market (ICM) allows for continuous trading up to one hour before delivery, with a pay-as-bid remuneration.

Balancing services in Europe are evolving into European balancing platforms. Spain will join the PICASSO platform for aFRR in 2025. Consequently, the market period discussed in this article refers to the market design prior to November 2024, prior to the national PICASSO implementation. This past market design is described in [16].

The aFRR auction, that closes at 16:00 on day D-1, negotiates reserve for the entire day D. Participants offer their reserve capacity to be activated by the TSO if needed for frequency regulation, with pay-as-clear remuneration for the reserve capacity. They must be able to deliver up to its maximum reserve. The allocation of aFRR reserve is typically informed at 16:30 at day D-1. Throughout the day of delivery (D), pay-as-clear payments are made for the actual energy provided in case of upward or downward activation. The energy is proportionally activated across all BSPs in accordance with the reserve allocation. Economic remuneration is provided for upward activation, while a cost is incurred for downward [16].

TABLE I
Summary parameters of the analyzed assets

Asset code	Pnom [MW]	Technology	Trackers	BM
FBHIBHV	80 + 5	PV+BESS	NO	NO
PREAL1	110	PV	NO	NO
CLIFV41	38.4	PV	YES	NO
FLLANO1	42.2	PV	YES	YES
FTORD3	11.5	PV	YES	YES
FALMANS	45.1	PV	YES	YES

III. Market Participation Results

Section III presents the market schedule of each PV asset, detailing whether the submitted bids were matched or unmatched, along with their offer prices. Their strategic market operations are compared and discussed. Finally, an economic assessment is provided to analyze the market revenues for each PV agent for a typical summer day with near-zero prices.

Fig. 2 presents the DAM offers submitted by the FBHIBHV asset on June 22 2024, with zero prices during the midday hours. Fig. 2 also shows the offer prices made by the asset, the DAM clearing price, and the matched and non-matched DAM energy. For this particular asset, some offers are fully matched, while others are partially matched when the price drops to zero over several hours. Additionally, some energy is contracted under a Power Purchase Agreement PPA, whose details (price and conditions) are not publicly available and, therefore, remain unknown. Anyway, setting the PPA at midday would increase the probability of this hybrid plant, capturing higher PPA prices. It can also be observed that the battery is planned to be discharged at the end of the day, between period H21

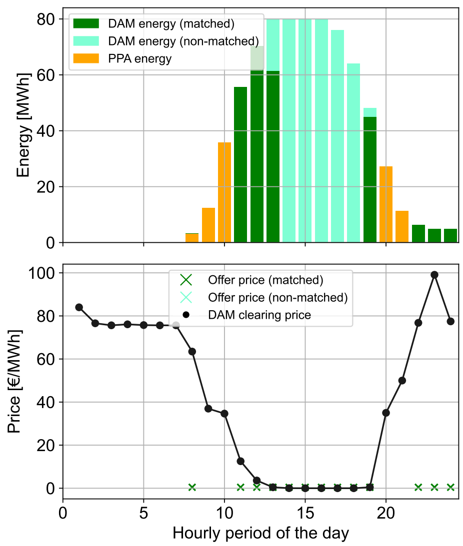

Figure 2. FBHIBHV DAM schedule on 22-06-2024

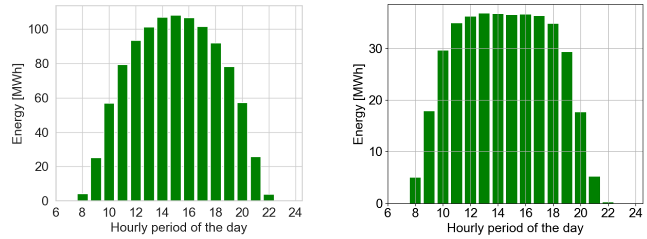

Figure 3. (a) PREAL (b) CLIFV41 DAM schedule on 22-06-2024

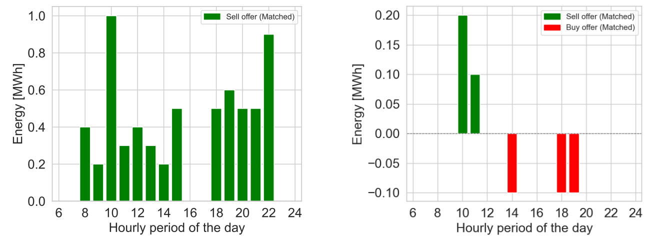

Figure 4. (a) PREAL (b) CLIFV41 IDM schedule on 22-06-2024

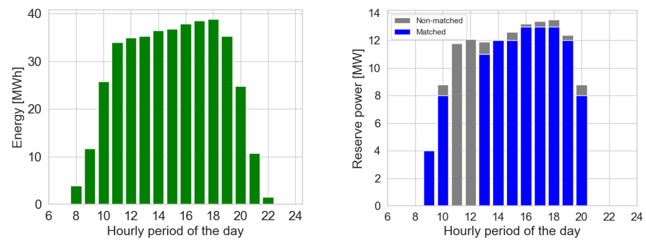

Figure 5. (a) DAM (b) aFRR schedule of FLLANO1 on 22-06-2024

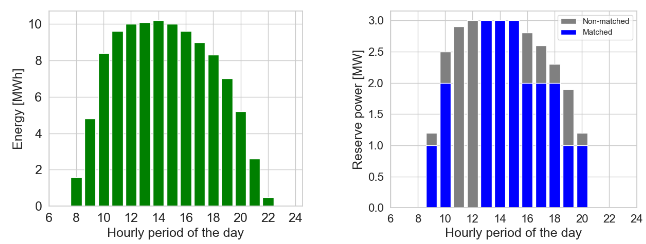

Figure 6. (a) DAM (b) aFRR schedule of FTORD3 on 22-06-2024

to H24, when the price rises again. For the purpose of this analysis, it is assumed that the energy has been placed on the market at the DAM clearing price. This assumption allows for an equitable analysis for market revenues, as if this plant did not have a PPA. The remaining assets of Table I offer at negative prices, which ensures that all DAM bids are matched.

Currently, the design of the European electricity market enables the participation of RES in multiple energy markets, including balancing services. Intraday markets, such as the IDM and ICM, allow them to buy and sell energy, either to compensate for actions not taken in the DAM or to adjust their positions in response to significant changes in their generation forecasts. The FBHIBHV, PREAL1, and CLIFV41 assets operate in these IDM and/or ICM markets. The hybrid asset FBHIBHV attempts to sell the energy that was not successfully sold in the DAM on the IDM, but without success (unmatched bids from H15 to H18). In contrast, PREAL1 and CLIFV41 do not perform any significant operations; they only slightly adjust their market schedules by buying and selling small amounts of energy in the IDM, as observed in Fig. 4.

Additionally, RES can participate in the BM, such as aFRR, which provides a strategic market operation to increase both energy traded and market revenues, particularly on days with zero prices. Hereafter, the strategic bidding of the FLLANO1, FTORD3 and, FALMANS assets is analyzed, which participate in DAM, IDM/ICM and balancing markets. Fig. 6 and Fig. 5 illustrate the bids submitted and matched by the FLLANO1 and FTORD3 assets, respectively, for the DAM and aFRR reserve markets. DAM bids are fully matched, while the aFRR market bids are partially matched (in periods H11 and H12 are not matched at all). This is because aFRR reserve bids are matched in whole MW units; the mechanism does not allow fractional MW to be cleared.

Regarding the quantity of aFRR bids compared to the DAM schedule, FTORD3's aFRR bids are typically between 25% and 30% of the DAM schedule, while FLLANO1's aFRR bids are around 35%.

Similarly, Fig. 7 illustrates the bids submitted and matched by the FALMANS asset for the DAM and aFRR reserve market. The FALMANS asset participates in the aFRR market during daytime hours in which also has a DAM schedule. Generally, the aFRR bids are placed between 37% and 42% of the DAM schedule, which comprise both upward and downward reserve. The hourly clearing prices of the aFRR reserve auction are also indicated in Fig. 8, along with its offered prices. Most of the FALMANS's reserve bids are matched due to lower offered prices than the clearing reserve price, with only a small portion remaining unmatched.

Participation in the aFRR capacity auction requires availability for both upward and downward regulation upon real-time activation. This activation can be managed at the portfolio level of the Balancing Service Provider (BSP), rather than for each individual PV installation. Assuming that the PVs

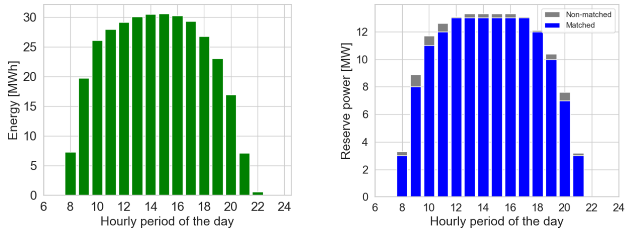

Figure 7. (a) DAM (b) aFRR schedule of FALMANS on 22-06-2024

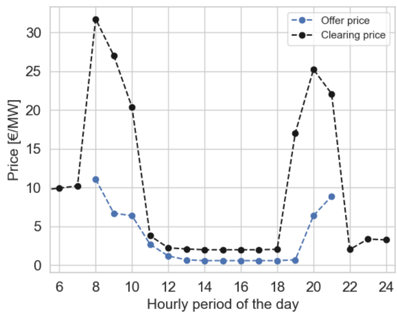

Figure 8. FALMANS aFRR offer and clearing prices on 22-06-2024

should respond to their aFRR services, they need to maintain a margin between their energy generation, DAM schedule, and potential aFRR activation. In this sense, downward activation is generally not a concern, as it can be technically satisfied by reducing energy below the DAM schedule. However, upward activation poses a challenge, as the assets lack additional energy between the forecasted energy and the DAM schedule. At that point, PVs need to purchase energy in the IDM or ICM markets. Fig. 9 and Fig. 10 illustrate the strategic bidding of each PV asset on the second auction of the IDM.

As explained in Section II, the allocation of aFRR reserve is published at 16:30 on day D-1. After this, assets can adjust their market schedule during IDM Session 2 (IDM-2), which closes at 22:00 on day D-1 before delivery Since the prices in the DAM and IDM markets are highly correlated [17], the cost of this purchase is relatively small, particularly during H10 to H16, in which the IDM-2 clearing price is also zero.

FALMANS and FTORD3 submit an IDM-2 bid slightly higher than the DAM to establish a final energy schedule that enables both upward and downward provision by themselves. In contrast, FLLANO1 submits an IDM-2 bid higher compared to the DAM, which reduces its final energy schedule to a great extent. At all times, it ensures there is sufficient margin in case it is required to provide 100% of the energy whether it is for upward or downward regulation in the aFRR service.

Fig. 11 indicates the economic settlement of each market of the FALMANN asset. As illustrated, energy is purchased in the IDM+ICM to correct forecast deviations, but primarily to achieve an intermediate energy schedule that enables participation in the aFRR market in both upward and downward directions. The aFRR market includes a reserve payment and an activation payment if the assets are activated for providing upward energy, as well as an activation cost for providing downward energy. BSPs that participate in the aFRR reserve

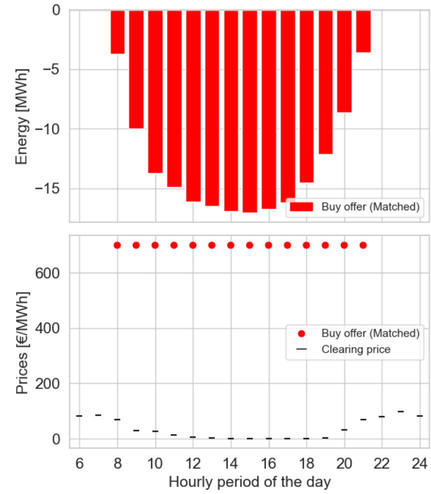

Figure 9. FALMANS IDM-2 puchase bids on 22-06-2024

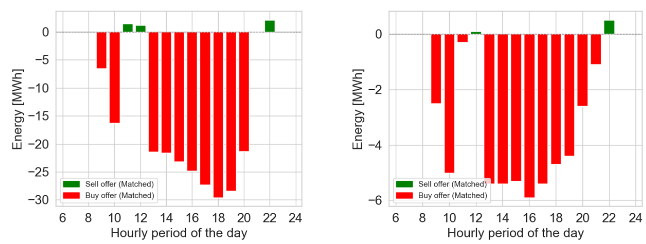

Figure 10. (a) FLLANO1 and (b) FTORD3 IDM-2 bids on 22-06-2024

market can be activated for either upward or downward energy interchangeably depending on the system needs. On this specific day, the few downward activations incurred minimal costs. As a result, the market costs from purchasing energy in the IDM and/or ICM are counteracted by the revenues obtained in the aFRR market (both reserve and upward activation).

The daily profits per MWh generated are displayed in Fig. 12 for each market and PV asset. The figure is a waterfall chart that illustrates the final market revenues and the individual contributions of each market (whether revenues or costs), with each bar starting from the final value of the previous bar. Table II shows also the economic results obtained after analyzing how each asset operates in each market.

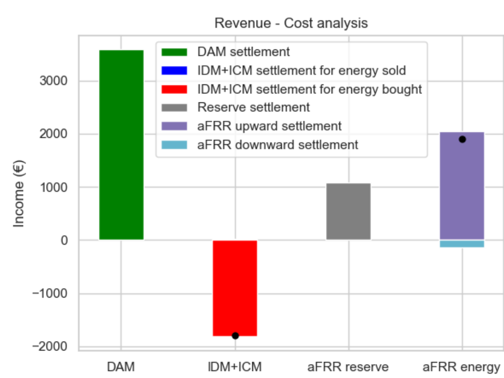

Figure 11. Economic market assessment of FALMANS on 22-06-2024

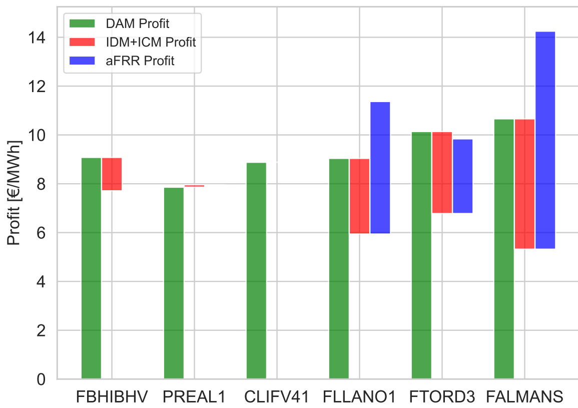

Figure 12. Summary of revenues for analyzed assets for day 22-06-2024

The solar value per energy generated (€/MWhg) represents the daily revenue earned for each MWh of solar energy produced, while the weighted price per energy traded (€/MWhtr) shows the average price received for each MWh of energy traded in the market, adjusted for the volume of matched bids, reflecting the market value of the traded energy.

Firstly, the use of trackers increases revenue (CLIFV41, FLLANO1, FTORD3, and FALMANS), seems to capture more DAM revenues, as during the first and last hours of sunlight, when prices have not yet fallen to zero, trackers enable to trade more energy when prices are still in the tens of €/MWh. FBHIBHV obtains moderate revenues in the DAM due to the usage of the battery at nighttime hours, when DAM prices are higher. However, FBHIBHV has not been able to sell all of its energy in the DAM. In contrast, PREAL1 earns the worst revenues due to the lack of solar trackers or storage systems. Its generation pattern looks like an Normal-shape, which fails to capture the non-zero prices at sunrise and sunset.

Looking at PV assets without participation in the aFRR services, like FBHIBHV, PREAL, and CLIFV41, they participate in the IDM+ICM to adjust their market schedule in accordance to their forecast and to sell energy that was not able to trade in the DAM, with little impact of the economic schedule. FBHIBHV has the worst daily revenues in the energy market, as it is unable to trade all the PV generation either in the DAM or in the IDM. Moreover, the IDM capture price is even lower that the one that it would be able to capture in the DAM, resulting in lower market revenues and solar value. The capacity of the battery to shift generation to night-time compensates for the losses caused by the inability to inject all the energy during central hours, but does not provide a higher solar-value over plants providing aFRR services.

Alternatively, the effective and strategic participation in other markets, such as the aFRR, enabling optimized energy trading and increased revenues. Even among assets that participate in the aFRR market, the profitability of each unit of energy traded in electricity markets varies. Multi-market revenues primarily depend on the strategic adjustment of energy rebought in IDM+ICM or left unsold to participate in the aFRR market, the price captures in the reverse auction,

TABLE II
REVENUES OF PV ASSETS ON A ZERO-PRICE DAY, JUNE 22, 2024.

Asset Code	BM	Day-ahead solar value, in €/MWhg	Multi-market solar value, in €/MWhg	Weighted price in €/MWhtr	Weighted price in €/MWnom
FBHIBHV	NO	9.08	7.91	10.48	73.33
PREAL1	NO	7.86	7.96	7.96	75.47
CLIFV41	NO	8.88	8.89	8.92	90.86
FLLANO1	YES	9.04	11.37	20.53	109.45
FTORD3	YES	10.14	9.84	16.00	91.50
FALMANS	YES	10.66	14.25	23.61	106.14

the activation of the aFRR service, and the fulfillment level of each PV asset. In fact, it depends on the ability to participate in the aFRR market during hours when upward energy is paid the most or when there is high activation for upward balancing. In the opposite direction, it is crucial to participate when downward energy costs the least, or when there is low demand for downward balancing, which represents a cost.

The market revenues of FLLANO1, FTORD3, and FALMANS increase by 25.8%, -2.9%, and 33.7%, respectively, in terms of revenues per unit of energy generated (€/MWh) on a zero-price day. As observed, while FLLANO1 and FALMANS achieve higher final market revenues, FTORD3's aFRR revenues are lower than the costs incurred in ICM+IDM. This is due to FTORD3's lower participation in the aFRR market, which involves fewer bid quantities and more non-matched bids (see Fig. 6), lower upward activations, combined with a high volume of IDM buying bids.

As can be concluded, FLLANO1 and FALMANS achieve the best incomes in terms of energy generated and traded in the market. Both have solar trackers, participate in multiple markets, place aFRR bids in the range of 35-42%, and use ICM+IDM to adjust their final energy schedules, successfully responding to aFRR activation. FALMANS stands out because it successfully matched nearly all its bids in the aFRR reserve auction, unlike the other PV assets. Looking at the results in terms of installed power (€/MWnom), similar conclusions can be drawn, although it also depends on the specific irradiance relative to the installed power and grid access.

IV. CONCLUSIONS

This article discusses the market strategies of PV plants during near-zero price days in Spain. It concludes that participation in BM increases the solar value by capturing a higher weighted price per energy traded. On the day under study, FALMANS achieved higher final market revenues. This PV asset benefits from solar trackers, effective schedule adjustments in IDM+ICM, and successful aFRR provision. Beyond this analysis, it has been observed that aFRR reserve prices are also being cannibalized at midday by the entrance of PV. While their market bidding is not very sophisticated nowadays, market agents may increasingly adapt their strategies to multiple markets (such as the BM), specially during near-zero prices.

On days without near-zero prices, participation in the BM offers limited potential. However, on near-zero price days, the opportunity for increased profits is significantly enhanced. Moreover, the strategy of participating in balancing services is applicable across Europe, where zero-price days are becoming increasingly common.

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