Applied Energy 350 (2023) 121696

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Limiting imbalance settlement costs from variable renewable energy sources in the Nordics: Internal balancing vs. balancing market participation

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ARTICLE INFO

Keywords:
Variable renewable energies
Imbalance settlement
Forecast errors
Nordic energy markets

ABSTRACT

Due to the market gate closures in the Nordic energy markets, producers with variable renewable energy (VRE) assets, e.g., PV and wind power plants, must forecast their production prior to delivery, leaving room for significant forecast errors. These forecast errors can lead to imbalances between the contractual market agreements and physical delivery, which have to be financially accounted for through the imbalance settlement. The increasing shares of VREs in the Nordic energy mix and the increasing variability in the price of regulating the imbalances, can lead to potential large revenue losses for the producers.

This study investigates how different producer balancing strategies can limit the uncertainty and potential revenue losses in the imbalance settlement. The study focuses on available balancing measures the producers are able to use in the period starting from the last energy market gate closure, i.e., the manual Frequency Restoration Reserve (mFRR, tertiary reserves) balancing market, and throughout the subsequent settlement period. During this settlement period, producers have the option within the Nordic imbalance settlement framework to prevent VRE imbalances by performing internal balancing, i.e., ramping up or down their dispatchable assets which are located in the same bidding area as the VRE assets. However, this study shows both theoretically and quantitatively that such internal balancing is not economically beneficial compared to offering this regulating energy to the mFRR market.

1. Introduction

The shares of Variable Renewable Energy (VRE) technologies, like wind and solar power, are increasing in the Nordic energy mix. When bidding with these weather dependent technologies in the energy markets, deviations, or imbalances, between the contractual agreement and physical delivery for a settlement period occur. During dispatch of the settlement period, the Transmission System Operators (TSOs) activate the required balancing energy market products in order to correct for these imbalances and other grid disturbances. This is done to ensure a stable system frequency of 50 Hz. After the end of the settlement period, the activated reserves are then financially settled with the market participants causing the imbalances through the so-called imbalance settlement [1].

The outcome of the imbalance settlement introduces uncertainty and can create potential revenue losses for the energy producers. The regulating price, which determines the cost of the imbalances, is set during operation of the given settlement period by the activated reserves in the manual Frequency Restoration Reserves (mFRR, tertiary reserves) balancing energy market [2]. Hence, the potential producer revenues or losses from the imbalance settlement are only determined after the end of the given settlement period. Profit maximizing market operation strategies are thus hard to determine due to the regulating price stochasticity.

It is the net imbalances within a bidding area that the producers have to settle [1]. Thus, the producers can reduce their net imbalances by ramping their dispatchable assets up or down during the settlement period, compensating for the VRE forecast errors. Such internal balancing can thus be performed after the market gate closures, when the updated VRE forecasts are more accurate and the imbalances easier to predict. However, if this internal balancing operating strategy is chosen, there will be less available regulating volumes to be offered to the balancing markets, e.g., the mFRR market. Thus, producers aiming

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https://doi.org/10.1016/j.apenergy.2023.121696
Received 31 March 2023; Received in revised form 18 June 2023; Accepted 28 July 2023
Available online 10 August 2023

to maximize their profits must compare the value of offering their regulating energy volumes in the balancing markets to allocating the volumes to the settlement period for the purpose of internal balancing.

Under the current Nordic imbalance settlement structure, VRE imbalances can generate additional revenues for a producer compared to providing perfect forecasts to the markets. However, in Klyve et al. it was demonstrated that the imbalances induced from Photovoltaic (PV) power plants operating in the day-ahead and intraday markets in Scandinavia are generally related to a revenue loss [3]. Moreover, as the wind penetration is far greater than the PV penetration in the Nordics, it is likely that the correlation between forecast errors and unfavourable regulating prices is higher for the wind assets than for the PV assets. This means that the revenue losses from the imbalance settlement for Scandinavian PV producers demonstrated in Klyve et al. would likely be higher for producers with mainly wind power assets. Thus, there is a need to investigate measures to limit the imbalance settlement revenue losses, beyond improving the VRE forecasts.

Co-operating dispatchable power plants with VREs for internal balancing have been studied for different markets [4–7]. In naive approaches, where dispatchable assets are used for internal balancing at no cost, it is often concluded that internal balancing is beneficial. Angarita et al. demonstrate how correcting wind power day-ahead forecast errors with dispatchable hydropower under the Spanish regulations can increase revenues with up to 46% [4]. Holttinen and Koreneff report a far more modest (2%), but still significant gain, for internal balancing of wind- and hydro power in Finland for 2004, when wind penetration still was low [5].

Assuming no cost for the usage of a dispatchable asset is a simplification, which makes internal balancing seem overly attractive. Holttinen and Koreneff acknowledge this and therefore calculate the cost of internal balancing when the flexibility of hydro power is valued at the imbalance price, as an upper bound on the internal balancing cost [5]. However, this is also a misconception, as the dispatchable asset should be valued at its marginal cost and not the market clearing price. Riddervold et al. conclude that internal balancing can be a profitable strategy compared to clearing the forecasted imbalances through trades in the Nordic continuous double auction intraday market. This is a valid conclusion when the mFRR market is neglected, and the price of buying deficit energy through the intraday market is higher than the cost of ramping up the producers own dispatchable assets, and vice-versa when selling energy surpluses [6]. However, this article also takes into account the pay-as-cleared mFRR market which has its gate closure after the intraday market. By including the mFRR market to the analysis, we aim to show that internal balancing is not beneficial when the dispatchable assets are priced at their true alternative costs and when the dispatchable assets can participate in the mFRR market.

The imbalance settlement structure influences the market participants' market bidding behaviour and incentive to provide accurate schedules [3,8–12]. When demonstrating the impact of such regulations, care must be taken to comply with the full set of regulations. Bottieau et al. demonstrates how optimal real-time dispatch of a battery system can be done to achieve additional revenues through the single price imbalance settlement structure [12], but forming such systematic imbalances are clearly prohibited under Nordic market regulations.

Please note that the scope of this work is the handling of imbalances after all commitments in other markets than the mFRR market, having the last gate closure for a settlement period, are sealed. There is a body of literature on how anticipation of market outcomes in the balancing market can lead to more profitable commitments in the day-ahead-market, but this topic falls out of the scope of this article (interested readers are referred to [13,14] for intermittent assets and [15–20] for dispatchable assets).

The present work gives a thorough summary of the new Nordic imbalance settlement structure and regulations introduced in November 2021, in order to summarize which types of operating strategies which are possible under Nordic market regulations. In addition, recent and future energy market updates are presented, to show under which market conditions the conclusions of this work are valid. The novelty of this study is the theoretical analysis and demonstration of why performing internal balancing during a settlement period with the use of dispatchable energy is not an economically feasible operating strategy under Nordic market conditions. Moreover, the study shows how the uncertainty and potential revenue losses from the imbalance settlement can be mitigated, by active participation in the mFRR market.

2. Theory

This section summarizes key properties of the Nordic energy markets and imbalance settlement. The different energy and balancing market products will be presented, demonstrating how producers commit to schedules in order to maximize their profits across the day-ahead, intraday and balancing markets. As the Nordic energy and balancing markets are in the process of harmonizing with the Central European markets, anticipated market changes will be presented as well. The energy market products and related gate closures are given in Fig. 1, using the Norwegian markets per February 2023 as example. It should be noted that imbalances from bilateral trades are also settled through the same imbalance settlement process.

2.1. Bidding areas

There are 12 bidding areas in the Nordics, 2 in Denmark, 1 in Finland, 5 in Norway and 4 in Sweden [21]. The bidding areas are defined by the local TSO based on the physical transmission grid and common bottlenecks. Thus, generally there are few congestions within a bidding area, while inter-area congestions often occur. When the energy market prices are calculated the bidding areas are taken into account and since the power cannot freely flow between them, the prices will differ between the areas as well. Differentiating the prices between the bidding areas incentivizes market participants to increase consumption in areas of low prices and high power supply, and oppositely increase production in areas of high prices and high power demand. Thus, the market participants can contribute to reducing the inter-area congestions over time.

2.2. Energy mix

In Fig. 2, the shares of the actual generation per production type in each of the Nordic bidding areas for 2018–2022 are given. The data is collected from the European Network of Transmission System Operators for Electricity (ENTSO-E) transparency platform [22], except for the data of the Swedish bidding areas which is collected from the Swedish TSO [23]. For the Norwegian and northernmost Swedish bidding areas, i.e., SE1 and SE2, the energy mixes are dominated by hydropower. According to IEA, hydropower has both the shortest start-up time as well as the highest ramp rate [%/min] compared to all of the other dispatchable generating units [24], which have historically ensured low balancing energy costs for the Nordic region [25].

In Denmark and in the south of Sweden, i.e., DK1, DK2 and SE4, wind power is the dominating energy source, but all bidding areas, except NO5, have had a noticeable increase in the shares of the VRE generation from 2018 to 2022.

2.3. Day-ahead market

The day-ahead market is the main energy trading platform clearing 90% of the consumption in the Nordics [26]. The day-ahead market is cleared at a daily auction at 12.00 CET D-1 (day before delivery) for the complete following day [27]. Hence, at 12.00 CET producers must forecast how much energy they will generate, and for what prices they are willing to sell the energy, for the following 12 to 36 h.

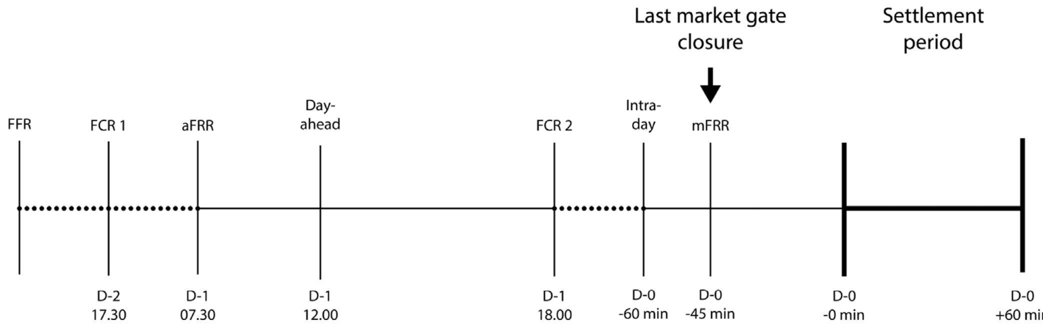

Fig. 1. Timeline showing the Norwegian energy market products (per February 2023) and their respective gate closures for a given settlement period. In Norway, the FCR (primary reserves) market has two gate closures. Common for all the Nordic energy markets are the gate closures for the day-ahead, intraday, aFRR (secondary reserves) and mFRR markets (tertiary reserves). In Finland, intraday trading is possible within the Finnish bidding area until the beginning of the settlement period, i.e. at D-0 -0 min.

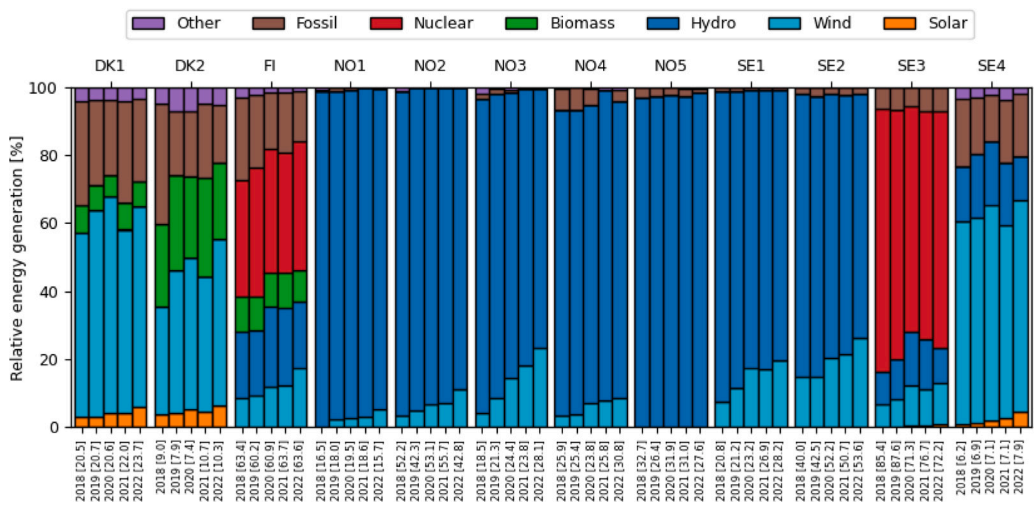

Fig. 2. The actually generated energy from each production type in all of the Nordic bidding areas for 2018–2022. The total yearly generated energy (in TWh) is given in the brackets. For the Swedish bidding areas, Fossil represents all thermal generation (not nuclear).
Source: The figure is adapted from Klyve et al. [3].

The total energy price and volume are found at the intersection between the aggregated supply and demand curves across the participating Nordic bidding areas, as well as the other European countries through the Single Day-Ahead Coupling (SDAC) [28]. The market is cleared on merit-order and with a pay-as-cleared structure, meaning the production units with the lowest marginal cost are dispatched first and the cost of the last production unit which clears the consumption is price setting for all producers and consumers in the market. The cross-border bidding area transmission capacities are implicitly auctioned, such that the power flows between the bidding areas are cost-optimally allocated at the same time as the inter-area congestions are considered [27].

Per February 2023, the market is cleared for settlement periods on hourly intervals. However, before January 1. 2025, the market will be cleared on 15 min intervals [29].

2.4. Intraday market

In the intraday market, market participants can trade with each other to reschedule their day-ahead committed schedules in order to (1) correct for forecast errors or unforeseen events, or (2) for the purpose of energy arbitrage. The intraday market is organized as a double auction pay-as-bid market with hourly products, opening at 14.00 CET D-1 and closing an hour prior to the beginning of a settlement period [30]. In Finland market participants can internally intraday trade until the start of the settlement period [31]. Intraday trades can be performed with other European countries through the Single Intraday Coupling (SIDC) [32]. By Q2 2024, the Nordic intraday market will include 15 min trading products as well as intraday auctions [29].

2.5. Balancing markets

The purpose of the balancing markets is to ensure availability of reserves to maintain the system frequency at 50 Hz, despite unforeseen faults, outages or forecast errors in the energy system. The balancing products are differentiated in the terms of their activation time, durance and remuneration. The activated reserves are considered as scheduled energy when deriving the net imbalances in the imbalance settlement [1].

2.5.1. Fast Frequency Reserves (FFR)

The fastest product in the Nordic balancing markets is the FFR (inertial response) with activation time of 0.7–1.3 s [33]. The acquisition and remuneration are not coordinated among the TSOs. FFR is sold as a capacity product, meaning market participants only get paid for making this capacity available for the decided period, not for the final dispatched energy.

2.5.2. Frequency Containment Reserves (FCR)

The FCR (primary reserves) capacities are settled pay-as-cleared by each local TSO without a common gate closure. However, the products are in the process of being harmonized (except for DK1 connected to the Central European synchronous area [34]). FCR is split into two products (except in DK1), i.e., FCR-N (normal operation) and FCR-D (disturbances) [35]. The activated up- and down-regulating energy during the FCR-N service are compensated for with the mFRR market cleared up- and down-regulating price respectively [36–39].

2.5.3. automatic Frequency Restoration Reserves (aFRR)

From Q4 2022, a common Nordic aFRR (secondary reserves) pay-as-cleared capacity market was introduced [40,41]. The gate closure for the market is at 07.30 CET D-1, and clears the aFRR capacity for each bidding area, each up- or down-regulation direction and each hour the following day. As for FCR-N, the dispatched energy during aFRR operation is compensated for by either the mFRR market cleared up- or down-regulating price, corresponding to the direction of the activated aFRR bid. By Q2 2024, the Nordic aFRR market is planned to be integrated with the European aFRR market through the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO), where aFRR energy activation on 15 min intervals will be traded [42].

2.5.4. manual Frequency Restoration Reserves (mFRR)

The mFRR energy activation balancing market is coordinated between the TSOs [43]. The gate closure is 45 min prior to dispatch of the given settlement period, thus being the market product with the latest gate closure (except for the local intraday market in Finland). In this regard, the mFRR market has previously been more important than the intraday market, as traditional generating units could settle their expected imbalances by offering them to the mFRR market close to dispatch [30].

During operation of a settlement period, the TSOs activate the required mFRR energy bids to control the system frequency. The mFRR energy market is split into two markets, one for up- and one for down-regulation. When offering up-regulation the producers bid how much energy their generating units can additionally dispatch and for what price they are willing to sell this up-regulation energy. Oppositely for down-regulation, the producers pay the TSO to reduce their energy output for a given settlement period. The prices for up- and down-regulation are set according to a pay-as-cleared structure, meaning the price of the last activated balancing unit is price setting for all activated up- and down-regulating mFRR bids respectively [2].

By Q4 2023, the Nordic TSOs will organize a common mFRR capacity market, ensuring that there is enough mFRR capacity available in the mFRR market to regulate the energy system [44]. By Q2 2024 the mFRR market will be connected to the common European mFRR energy activation market through the Manually Activated Reserves Initiative (MARI) platform, clearing the market on 15 min resolution [42].

2.5.5. The single regulating price

The regulating price used for the imbalance settlement is based on the outcome of the mFRR energy market, meaning market participants who provide imbalances pay the market price of clearing them. If the TSO activates net up-regulation in the mFRR market, the single regulating price is set equal to the up-regulation price for the given bidding area and settlement period, and vice-versa with net activated down-regulation. For settlement periods without any activated mFRR bids for a given bidding area, the single regulating price is set equal to the day-ahead price.

The box plots of the difference between the regulating prices and the day-ahead prices relative to the day-ahead prices for the different Nordic bidding areas in 2018–2022 are given in Fig. 3. As shown in Fig. 3, the market regulating price for all bidding areas, except NO1, NO2, and NO5, has had an increasing spread around the day-ahead price for 2020–2022 compared to 2018–2019. When the spread of the market regulating price around the day-ahead price increases, the uncertainty of the imbalance settlement outcome increases as well. It should be noted that before November 1. 2021, the regulating price was under the dual-price structure, meaning there were one up- and one down-regulating price respectively based on the mFRR market outcome. Thus, for 2018–2021 the dual regulating prices have been reconstructed to represent the single-price structure, by setting the single regulating price equal to the up-regulation price in settlement periods with net system up-regulation activation and vice-versa with net activated down-regulation.

Currently, the price setting of the single regulating price is under revision and a new model to calculate this price will likely be introduced after the unification of the European balancing markets has been conducted [45].

2.6. Imbalance settlement

As previously mentioned, when market participants have deviations between the contractual agreements and physical delivery, this imbalance has to be financially accounted for in the imbalance settlement. The imbalance settlement in the Nordics is coordinated by the TSOs through their commonly owned company, eSett. eSett provides handbooks describing the imbalance settlement in detail [1]. As for the markets, the imbalance settlement is in an ongoing transition, and as mentioned in Section 2.5.5 the imbalance settlement was conducted with a dual-price settlement structure until November 1. 2021 [47,48]. More details about the previous dual-price imbalance settlement can be found in Klyve et al. [3]. In addition, from the end of May 2023 the imbalance settlement will be conducted on 15 min intervals instead of 60 min intervals [49].

2.6.1. BRP

The imbalance settlement is conducted between eSett and a Balancing Responsible Party (BRP), on behalf of the energy consumers, producers or traders. Market participants with a high consumption or production generally provide their own BRP services, but market participants can also have agreements with third-party BRPs who settle the imbalances with eSett on their behalf.

The BRP is accountable for the net imbalance of its portfolio of production and consumption units within a bidding area for each settlement period. In practice, this means that a power plant with an energy surplus in relation to its schedule can compensate for another power plant's energy deficit for the same settlement period, if both power plants have the same BRP and are situated in the same bidding area.

The BRPs are obligated to aim for balance for each settlement period. If the BRP anticipates imbalances, e.g., by having updated forecasts with improved accuracy closer to or during a settlement period, the BRP has the option to deviate from the market committed schedules of their individual power plants, but only if it reduces the net imbalances of the portfolio within the bidding area. BRPs can also reduce imbalances by trading bilaterally, and the gate closure for reporting these trades are 45 min before the settlement period in Norway and Sweden, and 20 min before the settlement period in Denmark and Finland.

Throughout this study, it is assumed that the producers are providing their own BRP services, and the BRPs are thus only referred to as producers.

2.6.2. BSP

A Balancing Service Provider (BSP) has an agreement with a TSO and eSett regarding provision of balancing services to the TSO, e.g., up- and down-regulation. The BRP can also provide BSP services, and the provided balancing energy is thus included as contractual agreed delivery for the net portfolio imbalance calculation. Thus, if a BRP has initially a net deficit of energy for a settlement period and one of its power plants is activated for regulation, the total net deficit of the portfolio remains the same as before the activation of the regulation, since the market commitment of the BRP changed correspondingly to the activated reserves.

In this study it is assumed that the producers also provide BSP services. Thus, only the term producers will be used for providers of both BRP and BSP services.

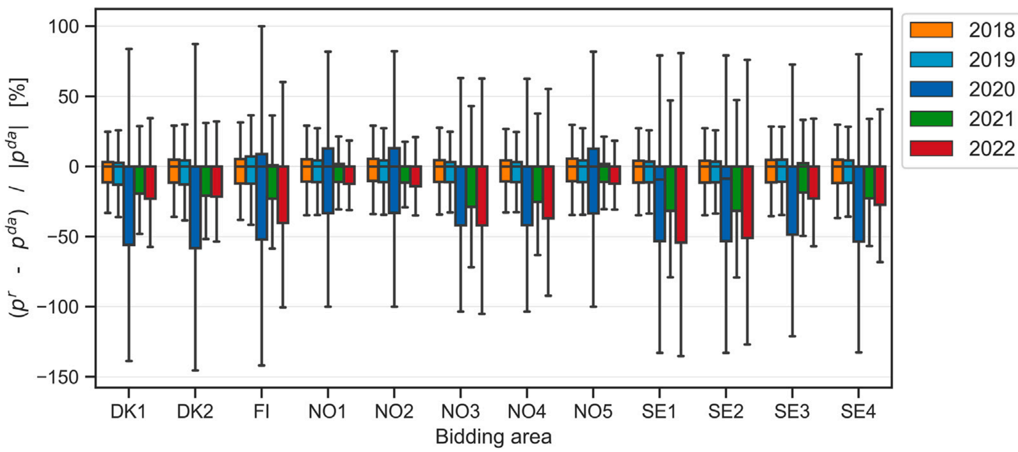

Fig. 3. Box plots of the difference between the market regulating price, p^r, and the day-ahead price, p^{da}, relative to the day-ahead price for each hour in the Nordic bidding areas for 2018–2022 [46]. The box plots with the outliers are given in Fig. A.1.

2.6.3. Imbalance pricing

The imbalance settlement cost is determined by the single regulating price cleared from the mFRR energy market, in addition to an imbalance fee. eSett also issues weekly and volume fees, as well as a peak load reserve fee in Sweden. However, as these fees are not influenced by the amount of provided imbalances, these are neglected in this study.

The day-ahead market forecasted and contractual VRE generation, $\hat{E}_v^{da}$, is equal to the difference between the physically delivered net VRE generated energy, E_v, and the VRE imbalance, E_v^{imb}, as given in Eq. (1). The VRE imbalance is defined as being positive when the VREs have provided an energy surplus compared to the contractual agreements of delivery.

$$\hat{E}_v^{da} = E_v - E_v^{imb} \tag{1}$$

If a producer has an energy deficit for a settlement period it buys balancing energy from eSett to the market cleared regulating price, p^r. For a settlement period with an energy surplus the producer sells this additional energy to eSett also to the market cleared regulating price. If the dominating direction of the energy system is down-regulation and the producer provides an energy deficit, the producer can buy the energy deficit from eSett to a lower price than what the producer sold it for in the day-ahead market, and thus making a profit through the imbalance settlement. Correspondingly, for settlement periods where the producer has an energy surplus and the energy system is in a state of up-regulation, the producer can profit from selling the imbalance to a higher price to eSett than what this additional energy would have achieved through the day-ahead market.

Regardless of whether the producers provide an energy deficit or surplus, they will have to pay an imbalance fee, p^f, for the provided imbalance energy volume. Per February 2023, the imbalance fee is 1.15 €/MWh in the Norwegian, Swedish and Finnish bidding areas, and 0.13 €/MWh in the Danish ones [50]. The imbalance settlement income, Π, can be formulated as in Eq. (2) [3].

$$\Pi = E_v^{imb} p^r - |E_v^{imb}| p^f \tag{2}$$

How the VRE forecast errors can lead to additional revenues or costs compared to providing perfect forecasts to the day-ahead market is visualized in Fig. 4.

Despite producers being able to generate higher profits in the imbalance settlement compared to through the day-ahead market, purposely forming imbalances during a settlement period in order to maximize profits in the imbalance settlement would breach the contract with eSett and such behaviour can lead to exclusion from the energy markets [1]. This means that strategically under- or over-bidding in the markets is a contract breaching action.

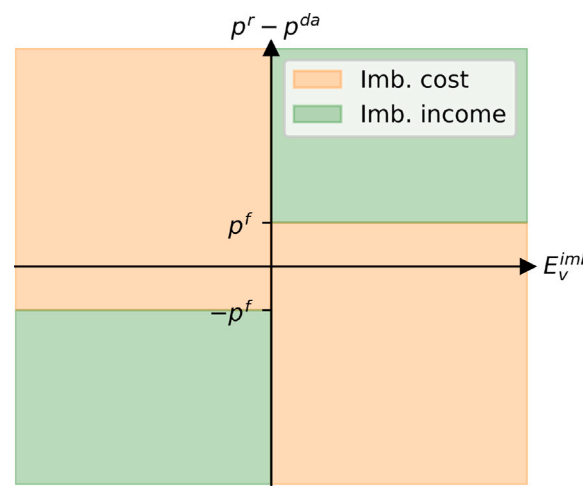

Fig. 4. A VRE energy imbalance, E_v^{imb}, for a given settlement period can provide both an additional cost (yellow area) or income (green area) compared to providing a perfect forecast in the day-ahead market. This depends on the market cleared regulating price, p^r, the day-ahead price, p^{da}, the imbalance fee, p^f. When $p^r - p^{da} > 0$, the power system is in a net up-regulation state and when $p^r - p^{da} < 0$, in a net down-regulation state.

2.6.4. Market surveillance

In order to assure that the market participants are following their contract with eSett, eSett perform market surveillance. Key Performance Indicators (KPIs) are calculated to make sure that the net imbalances, but also the imbalances for each power plant are within predefined limits. If not, eSett can take actions which in worst case can lead to exclusion from the energy markets [1].

3. Method

At the last market gate closure and throughout the settlement period, there are still opportunities to influence the imbalance settlement income losses, and this section compares the two possible strategies to do so, i.e., internal balancing and mFRR market participation. A combination of these strategies is presented in the Appendix A.1 and a discussion on curtailment is given in Section 4.4.

For simplicity, only revenues from the day-ahead and the mFRR market are considered, meaning the day-ahead market represents all types of market committed energy in this analysis. This is done as the conclusions on optimal operation strategy from the last market gate closure throughout a settlement period do not change if including more market products.

The imbalance settlement is carried out as for Eq. (2). The day-ahead net VRE forecasted and thus net VRE market committed energy, $\hat{E}_{v}^{da}$, is defined as in Eq. (1). Due to the low marginal cost of VREs and the merit-order structure of the day-ahead market, it is assumed that the VRE energy is always dispatched in the day-ahead market. The power plants are assumed to have individual connection points to the grid, meaning that hybrid power plants, e.g. combined PV and battery power plants where the battery represents the dispatchable asset, are not considered in this work. In addition, it is assumed that the dispatchable generation units only operates for two different loading levels, at two different constant marginal operating costs, $p^{m,d}$, $p^{m,u}$, which later will correspond to the marginal down- and up-regulating costs respectively. Furthermore, the lowest marginal operating cost, $p^{m,d}$, is lower than the cleared day-ahead price p^{da}, such that the dispatchable generation units are dispatching energy to the day-ahead market equal to E_{d}^{da} for the given settlement period and bidding area. This represents the lumpy nature of a set of discrete production units in the form of a step-wise supply curve. Changing the assumption to smooth, convex supply curve will not alter the conclusions in this exposition.

The revenues from the dispatchable assets in the day-ahead market are thus given by $(p^{da}-p^{m,d})E_{d}^{da}$, where p^{da} is the day-ahead price for a given settlement period and bidding area. Moreover, it is assumed that the dispatchable assets do not provide any imbalances, and the VRE assets are not performing any balancing services. For the main analysis, the day-ahead price and market regulating price, p^{r}, are considered to be positive. How these assumptions influence the conclusions are discussed in Section 4.

3.1. Internal balancing

The producers have the possibility to reduce their net imbalances by compensating for a VRE energy surplus, $E_{v}^{imb} > 0$, or deficit, $E_{v}^{imb} < 0$, with their available dispatchable energy during a settlement period. Increasing the generated energy in order to compensate for a VRE energy deficit is related to a fuel cost, or loss of hydro resources, and the cost is assumed to be the marginal up-regulating cost, $p^{m,u}$. Reversely, the producer can save fuel by performing down-regulation, and the saved costs correspond to the marginal down-regulation cost, $p^{m,d}$.

The closer the producers are to the settlement period, the more accurate their VRE forecasts are likely to be. It is thus assumed that the producers have the option to provide accurate enough forecasts to completely clear the net imbalance in their portfolios within a settlement period, given the required dispatchable regulating energy for the specific up- or down-regulation direction of the producer is greater than the imbalance. When the producer's available dispatchable energy volume is less than the VRE imbalance, the imbalance will not be completely cleared, but only reduced corresponding to the producer's available dispatchable energy.

The total income, Π^{ib}, for the VRE and dispatchable units operating in the day-ahead market and performing internal balancing (emphasized by the superscript *ib*) can be found in Eq. (3).

$$\begin{aligned}\Pi^{ib} =& \hat{E}_{v}^{da}p^{da} + (E_{v}^{imb} + E_{d}^{r,ib})p^{r} - |E_{v}^{imb} + E_{d}^{r,ib}|p^{f} \\ &+ (p^{da} - p^{m,d})E_{d}^{da} - p^{m}E_{d}^{r,ib}\end{aligned} \tag{3}$$

The dispatchable regulation energy volumes, $E_{d}^{r,ib}$, used for internal balancing need to be equal to the negative of the VRE imbalance volume, in order to prevent any imbalances. Moreover, the regulation volume is limited by the available up- and down-regulation volumes, E_{d}^{u}, E_{d}^{d}, respectively. This is summarized in Eq. (4). The value of $E_{d}^{r,ib}$ is defined to be negative when the producers provide down-regulation.

$$E_{d}^{r,ib} = \begin{cases} E_{d}^{u} & \text{if } E_{d}^{u} < -E_{v}^{imb} \\ E_{d}^{d} & \text{if } E_{d}^{d} > -E_{v}^{imb} \\ -E_{v}^{imb} & else \end{cases} \tag{4}$$

Finally, the marginal regulating cost of the producer, p^{m}, is equal to the marginal up-regulating cost, $p^{m,u}$, and marginal down-regulating cost, $p^{m,d}$, in settlement periods of up- and down-regulation respectively, as given in Eq. (5).

$$p^{m} = \begin{cases} p^{m,u} & \text{if } E_{d}^{r,ib} > 0 \\ p^{m,d} & \text{if } E_{d}^{r,ib} \le 0 \end{cases} \tag{5}$$

The internal balancing operating strategy is illustrated in Fig. 5(a). It should be noted that for settlement periods where $p^{r} - p^{da} < 0$ the energy system is in a down-regulation state, and in an up-regulating state for $p^{r} - p^{da} > 0$.

3.2. mFRR market participation

For the mFRR market participation strategy, the VRE imbalance is sent to the imbalance settlement regardless of how much energy which is dispatched through the mFRR market. However, from the pay-as-cleared mFRR market, the producer will achieve the market cleared regulating price for the mFRR market dispatched energy, meaning revenue losses in the imbalance settlement are compensated for by revenue gains in the mFRR market.

The total income, Π^{mp}, for producers with VRE and dispatchable assets operating in the day-ahead market and relying on mFRR market participation (emphasized by the superscript *mp*) is given in Eq. (6).

$$\begin{aligned}\Pi^{mp} =& \hat{E}_{v}^{da}p^{da} + E_{v}^{imb}p^{r} - |E_{v}^{imb}|p^{f} \\ &+ (p^{da} - p^{m,d})E_{d}^{da} + (p^{r} - p^{m})E_{d}^{r,mp}\end{aligned} \tag{6}$$

For this strategy, the producer commits its available up- and down-regulation energy volumes to the mFRR market to the marginal up- and down-regulation price respectively. Thus, the offered regulating energy is only dispatched as long as the market regulating price becomes equal or greater than the producer's marginal up-regulating price, or equal or lower than the producer's marginal down-regulation price regardless of the size and sign of the VRE imbalance and the day-ahead price, as given in Eq. (7).

$$E_{d}^{r,mp} = \begin{cases} E_{d}^{u} & \text{if } p^{r} \ge p^{m,u} \\ E_{d}^{d} & \text{if } p^{r} \le p^{m,d} \\ 0 & else \end{cases} \tag{7}$$

The producer's marginal regulating cost, p^{m}, is given as in Eq. (5), but defined with $E_{d}^{r,mp}$ instead of $E_{d}^{r,ib}$. An illustration of the mFRR market participation strategy is given in Fig. 5(b).

3.3. Quantitative demonstration

In order to quantitatively demonstrate the theoretical result that the mFRR provision strategy is always superior to the internal balancing strategy, a simple hypothetical case study is carried out. In this case study, we assume that a producer operates a series of 10 MWp PV power plants which are active in the day-ahead markets in each of the Nordic bidding areas. Moreover, in each of the bidding areas, the producer has a 1 MW, 1 MWh battery system. We consider two different operating strategies for the battery assets: (1) the battery system performs internal balancing, i.e., correcting for the forecast errors of the PV power plant within the same bidding area; and (2) the battery system sells mFRR regulating energy to the mFRR market in the bidding area it is located in. Meteorological weather data from professional weather stations, weather forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF), as well as actual day-ahead and mFRR prices are used for this analysis. The data comprise the period from 2018 throughout 2021, but for NO2 we note that data is only available for the period 2020 throughout 2021. All the data are on hourly resolution. An optimization problem is formulated in order to achieve the battery schedules for the internal balancing and mFRR provision strategies, as will be explained in Section 3.3.3. These

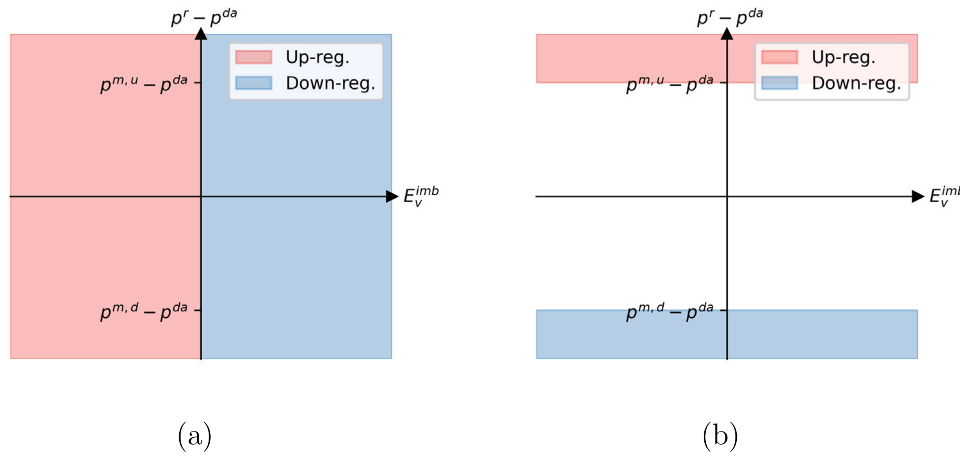

Fig. 5. (a) For the internal balancing strategy, the producer's dispatchable production units are providing up-regulation when the VRE imbalance is negative (energy deficit) and providing down-regulation when the VRE imbalance is positive (energy surplus). (b) For the mFRR market participation strategy, the producer's dispatchable production units are providing up-regulation when the market regulating price is equal or higher than the producer's marginal up-regulating cost and providing down-regulation when the market regulating price is equal or lower than the producer's down-regulating cost.

battery schedules are then used as input to Eqs. (3) and (6), when estimating the relative income gain from adding the batteries to the producer portfolios. For this analysis it is assumed that the producer is a price taker in the day-ahead and mFRR market, and that there are no minimum volume sizes for the market bids. Inflation occurring in the four year period is neglected.

3.3.1. PV power plants

As there are limited numbers of utility-scale PV power plants in some of the 12 Nordic bidding areas, one 10 MWp synthetic PV power plant for each of the bidding areas is modelled from meteorological data. The methodology to generate PV energy production data, E_v, the day-ahead energy forecasts (based on ECMWF data), $\hat{E}_v^{da}$, and thus the related PV energy imbalances, E_v^{imb}, is thoroughly explained in Klyve et al. [3]. The locations and key properties of each of the synthetic PV power plants can be found in Table A.1 in Appendix.

3.3.2. Battery system

For this example, a simple 1 MW, 1 MWh battery system is modelled, only performing either internal balancing or providing mFRR energy to the mFRR market. For simplicity, the battery is considered to be lossless and not to be experiencing any operating costs. Moreover, it is assumed that the battery does not participate in the day-ahead market, i.e., in Eqs. (3) and (6) $p^{m,d} = p^{m,u} = 0$ and $E_d^{da} = 0$. The battery can be completely discharged within an hour, i.e., having a C-rate equal to 1, and the battery can operate with a state of charge (SOC) between 0%–100% without experiencing any degradation or damage. However, as the battery dispatching schedules have an impact of the lifetime of the battery, this indirect operating cost is modelled equally between the operating strategies by setting an upper bound of 730.5 cycles which the battery can perform in the four year period it is implemented. This amount of cycles corresponds to performing half a cycle per day on average, or a total of 730.5 MWh which can be discharged and charged during the modelled four year period.

3.3.3. Optimizing battery schedules

The charging and discharging schedules of the battery systems are determined by solving a simple linear optimization problem on hourly resolution. The objective of the optimization problem is to dispatch the battery systems in such a way that the total system costs of the optimization problem are minimized in the considered four year period. Under both strategies, the optimization model has perfect foresight for the complete modelled period, such that the optimal battery schedules to either minimize the PV power plant imbalances or to maximize the revenues in the mFRR market are achieved.

When solving the optimization model for the internal balancing strategy, the practical goal is to assure battery schedules which minimize the imbalances of the PV power plants, as expressed in (8). Thus, the negative of the modelled imbalances from the PV power plants are given as a load obligation in the optimization model and the battery has to be dispatched to clear this load obligation, cf (9). However, if the battery is not able to clear the imbalances due to its SOC, (b^{SOC}), or cycle limitations, the required energy to cover the load obligation can be bought or sold from the grid, but to a high penalty, C^{grid}. The penalty is constant and higher than all market prices, thus the battery is incentivized to dispatch ($b^{charge}, b^{discharge}$) such that the interaction with the grid is limited and the PV power plant imbalances are compensated for by the battery system. The number of cycles is limited by (13), where $B^{maxcycles}$ represent the total amount of energy that can be discharged over the period.

$$\min \sum_t C^{grid} e_{t,tot}^{imb} \tag{8}$$

subject to

$$e_{t,tot}^{imb} = -E_{t,v}^{imb} - b_t^{discharge} + b_t^{charge} \quad \forall t \tag{9}$$

$$b_t^{discharge} \leq b_t^{SOC} \quad \forall t \tag{10}$$

$$b_{t-1}^{SOC} + b_t^{charge} \leq B^{SOCmax} \quad \forall t \tag{11}$$

$$b_{t-1}^{SOC} - b_t^{discharge} + b_t^{charge} = b_t^{SOC} \quad \forall t \tag{12}$$

$$\sum_t b_t^{discharge} \leq B^{maxcycles} \tag{13}$$

For the mFRR provision strategy, the optimization has no load obligation. The battery has the option to dispatch energy to the mFRR market, but only in periods where the energy system was in a historical up-regulation state, cf (15), and vice version to charge energy for hours where the system was in a historical down-regulation state, cf (16). The battery considers the values of the historical mFRR prices p^r, such that battery schedules which maximize the profits in the mFRR market are achieved.

Thus, for the mFRR provision strategy the objective changes to maximizing income from the mFRR market:

$$\max \sum_t p_t^r (b_t^{charge} + b_t^{discharge}) \tag{14}$$

The battery will only be activated in the mFRR market for up- and down regulation if the system state requires it.

$$b_t^{charge} = 0 \iff p_t^r - p_t^{da} > 0 \tag{15}$$

$$b_t^{discharge} = 0 \iff p_t^r - p_t^{da} < 0 \tag{16}$$

The physical restrictions of the battery, (10)–(13) naturally applies to this optimization problem as well.

The optimal internal balancing and mFRR provision battery schedules on hourly resolution are then exported from the optimization model, by setting $E_d^{r,ib} = b^{discharge} - b^{charge}$ and $E_d^{r,mp} = b^{discharge} - b^{charge}$ for each timestamp of the respective solved models. These schedules are then used as input when calculating the total hourly income for the PV power plants and battery systems using Eqs. (3) and (6), together with the modelled PV power plant day-ahead forecasts, $\hat{E_v^{da}}$, day-ahead prices p^{da}, PV power plant imbalances, E_v^{imb}, regulating prices, p^r, imbalance fees, p^f.

4. Results and discussion

4.1. Optimal balancing strategy

Two cases are considered in order to assess whether internal balancing is beneficial or not: one where the VRE imbalance is supporting the total system energy balance and one where it is not.

If the VRE imbalances support the total energy system balance, performing internal balancing would increase the total system imbalance, opposing the TSOs' effort for frequency stability. In these cases, internal balancing also deprives the producer of the additional income that the single-price imbalance settlement grants when an imbalance is helping the total system being in balance. This means that when the imbalances are supporting the energy system balance, internal balancing is neither beneficial for the TSOs nor for the producers.

In the cases where VRE imbalances induce a revenue loss for the producer, the dispatchable assets could have been used to reduce the portfolio imbalances. However, when $E_v^{imb} < 0$ and $p^r < p^{m,u} - p^f$, or $E_v^{imb} > 0$ and $p^r > p^{m,d} + p^f$, the imbalance settlement costs for the VRE imbalance would be smaller than the costs related to the internal balancing. When participating in the mFRR market, the up- or down-regulating volumes are only dispatched when the market regulating price is higher or lower than the producers' marginal up- or down-regulating prices, respectively, preventing the producers to dispatch regulating energy when the market regulating price is cheaper than the price of the producers' own dispatchable assets. As the mFFR market is a pay-as-cleared market, the mFRR dispatched energy is remunerated with either its marginal regulating price or higher for the up-regulation, or its marginal regulating price or lower for the down-regulation.

Moreover, as long as regulating energy is only dispatched through the mFRR market, it will not be possible for the producers to dispatch regulating energy which is unfavourable for the system balance. The TSOs should have a better overview of the present and future system balances, and letting them handle the system stability through the balancing markets should be beneficial for all actors. In the mFRR market the producers also have the ability to dispatch all their regulating energy volumes, i.e., E_d^u or E_d^d, not only volumes equal to the negative of their portfolio imbalances, i.e., $-E_v^{imb}$, as for the internal balancing strategy. This implies that more regulating energy will be available in the energy system if the producers are not performing internal balancing.

Finally, by allocating more regulating volumes to the mFRR market instead of offering it to the other energy and balancing markets, the risk of achieving large imbalance costs due to high VRE imbalances and intermittent regulating prices can be reduced. As long as the offered mFRR market volumes are equal or greater than the VRE imbalance volume, any extraordinary high regulating price, and thus, imbalance settlement cost, would be compensated for by an extraordinary mFRR market income. The only additional cost for the producer would be the cost related to the imbalance fee for the VRE imbalance.

4.2. Quantitative case comparison

Firstly, it should be emphasized that the generality of the mFFR provision strategy being superior to the internal balancing strategy under the current Nordic market conditions is already theoretically explained in Section 4.1. Thus, this case study involving a PV power plant and a battery system for each of the Nordic bidding areas is quantitatively demonstrating an already proven point. However, the case study is of interest as it quantifies the economic benefit of using a battery system for mFRR provision instead of internal balancing.

In Fig. 6 the relative income gain for a producer when adding a battery system to its portfolio consisting of a 10 MWp PV power plant is given. From the figure it can be seen that the relative income gain for the mFRR strategy (2.9 – 5.5%) is greater than for the internal balancing strategy (−0.1 – +0.2 %) for all of the modelled PV and battery systems across the Nordic bidding areas, as expected from the theoretical analysis. For the mFRR provision strategy, the relative income gain differs between the bidding areas due to different mFRR market prices between the areas, as well as PV energy forecast errors. When performing internal balancing of the imbalances from the Danish PV power plants, the total income from the PV and battery system is reduced. This is due to the fact that the battery cleared imbalances which would have generated additional revenues for the producer, i.e., for regulating prices and imbalances corresponding to the green area in Fig. 4. Dispatching energy from the battery which results in being economically unfavourable for the producer is not possible under the mFRR provision strategy, as discussed in Section 4.1.

It should be noted that since the amount of energy the battery can discharge and charge is smaller than the total PV power plant imbalances, there are several battery schedule solutions minimizing the PV forecast errors, and there might exist a schedule clearing the same amount of imbalances which would have achieved a more economically favourable imbalance settlement. In addition, for a producer portfolio with wind power assets, instead of PV assets, it is likely that the relative income gain would have been higher under the internal balancing strategy (but not greater than the mFRR provision strategy). This is due to the higher wind than PV power penetration in the Nordics, such that the correlation between forecast errors and unfavourable regulating prices are likely higher for wind assets than for PV assets in the Nordics.

4.3. Combining the internal balancing and mFRR market participation strategies

As discussed in Section 4.1, the mFRR market participation strategy is more beneficial for both the producers and TSOs compared to the internal balancing strategy. However, for the special case of $E_v^{imb} < 0$ and $p^r > p^{m,u} - p^f$, or $E_v^{imb} > 0$ and $p^r < p^{m,d} + p^f$, the internal balancing strategy in combination with the mFRR market participation strategy would maximize the revenues, since the cost related to the imbalance fee could be prevented. In order to successfully operate with the combined strategy, the producers must at the gate closure of the mFRR market accurately allocate the required internal balancing volumes and offer the rest of the regulating volumes to the mFRR market. This means that the producers would have to perfectly forecast both the VRE imbalance as well as the system regulating price at the gate closure of the mFRR market. Moreover, the only saved costs from using the combined strategy compared to the pure mFRR market participation strategy would be the costs of the imbalance fee, i.e., the product of the absolute value of the net VRE imbalance and the imbalance fee. As mentioned, the imbalance fee per February 2023 equals 1.15 €/MWh for Finland, Norway and Sweden and 0.13 €/MWh for Denmark. Thus, not only is the combined strategy challenging to accomplish, there are also limited revenues to gain from it. More details about the combined strategy are given in the Appendix A.1.

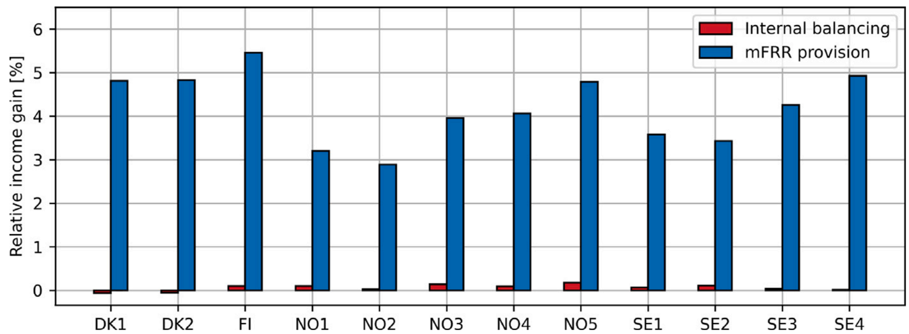

Fig. 6. The relative income increase for a producer operating a 10 MWp PV power plant in addition to a lossless 1 MW, 1 MWh battery system performing internal balancing or providing mFRR services, compared to operating the PV power plant alone. Meteorological data, forecasts generated from the ECMWF, day-ahead and regulating prices for each of the bidding areas and specific PV power plant locations from 2018 throughout 2021 are used (for NO2: 2020 throughout 2021).

4.4. Curtailment of VRE surplus imbalances

For settlement periods where the VRE physical delivery is larger than the contractual agreement, curtailing this additional VRE energy is a possible measure to reduce the imbalance of the settlement period. However, if the single regulating price for the given settlement period is greater than the imbalance fee, curtailing this energy is related to an economic loss as the producer would have been paid for the dispatched energy with the price of the single regulating price in the current imbalance settlement structure. In the period 2018 throughout 2022, DK1 experienced the most negative single regulating prices, i.e., 3.5% of the time. Thus, curtailing the VRE surplus imbalances are generally not profitable, and the producer could rather offer down-regulation to the balancing markets and curtail its VRE assets when it is economically feasible for the producer to do so.

4.5. VREs in the mFRR market

For this analysis, it has been assumed that the VRE assets are not participating in the mFRR market, but if the down-regulating price is equal or less than zero, curtailing the VRE assets can be cost efficient. However, some producers might be willing to produce regardless of negative down-regulation prices if they are receiving additional revenues for their production, e.g. through support schemes like green certificates. Oppositely, some producers might be willing to curtail their production for down-regulating prices above zero, if operating costs or costs related to degradation can be prevented.

Providing up-regulation would require the VRE assets to continuously curtail in normal operation, by operating the assets in regions where they are less efficient and then release this additional energy when the TSOs activate the up-regulating energy. Another possibility would be to underbid in the other energy and balancing markets and allocate some of the forecasted VRE energy generation as mFRR bids, hoping to be activated during operation. However, these strategies are related to a risk since producers must aim for being in balance for each settlement period as stated by the BRP agreement, and it is not given that the TSO will activate the mFRR bids. Thus, additional imbalances can occur [51].

Since negative down-regulation prices are in general required for it to be profitable for VRE assets to provide mFRR regulation, it is judged to be a valid assumption that the VREs are primarily not operating in the mFRR market in this study. However, if producers have VRE assets which have been qualified to provide balancing services, some of the imbalance settlement costs could be avoided by offering the forecasted imbalances just before the mFRR gate closure to the mFRR market at the day-ahead price. If the imbalances are then activated in the mFRR market, the producer can prevent paying the cost related to the imbalance fee. This corresponds to always achieving an imbalance income either when $E_v^{imb} < 0$ and $p^r - p^{da} < 0$ or when $E_v^{imb} > 0$ and $p^r - p^{da} > 0$. In Fig. 4, this could have been illustrated by each of the green areas reaching the x-axis.

4.6. Portfolio diversification

The producers can also reduce their net portfolio imbalances without using their dispatchable assets, but with proper portfolio management in terms of technological and geographic diversification. Since there often is an anti-correlation between wind and PV energy resources [52], diversifying the portfolios with PV and wind technologies can reduce the net imbalances. E.g., for a settlement period with lower wind production than forecasted, it is likely that the PV production is greater than anticipated, and thus reducing the net imbalances compared to only having wind assets in the portfolio. In this regard, issuing combined PV and wind forecasts, taking the potential anti-correlation into account, could reduce the net VRE forecast errors [53]. In terms of geographic diversification, spreading out the weather dependent assets of the same technology over a larger area within the bidding area can reduce the net imbalances. Oppositely, if all assets of a specific technology would be co-located, a local forecast error could lead to great imbalances.

5. Conclusion

In this study, the Nordic energy and balancing markets have been presented, emphasizing how the market gate closures provoke imbalances between contractual agreements and physical deliveries, due to the VRE production stochasticity. The regulations on how these imbalances have to be financially settled through the Nordic single-price imbalance settlement have been thoroughly described. The shares of VREs in the Nordic energy mix are growing at the same time as the market regulating prices have an increasing variability around the day-ahead price, making the outcome of the imbalance settlement increasingly uncertain. At the last energy and balancing market gate closure, i.e., for the mFRR balancing market, a producer has the option of allocating regulating energy volumes for the purpose of internal balancing, or commit these volumes to the mFRR balancing market.

Generally, internal balancing is not a profit maximizing strategy, and should thus be avoided. Producers aiming to reduce their imbalance settlement revenue losses should rather allocate more regulating volumes to the mFRR market, since any extraordinary imbalance settlement cost will be compensated for by an extraordinary mFRR market income. This was also quantitatively demonstrated in each of the Nordic bidding areas by modelling a 10 MWp PV power plant and a 1 MW, 1 MWh battery system either performing internal balancing or providing mFRR balancing energy to the market. The results show that the revenues would be relatively unaffected by the internal balancing strategy (−0.1 – +0.2 % increase), but experiencing a reasonable increase by the mFRR provision strategy (2.9 – 5.5% increase), compared to the achieved income when operating the PV power plants alone.

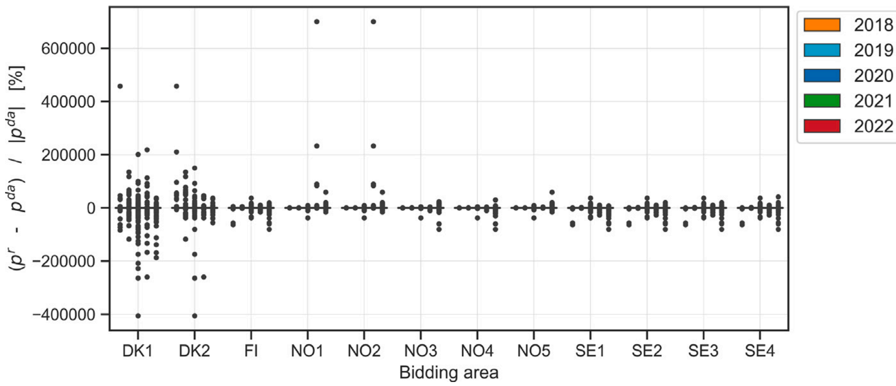

Fig. A.1. Box plots of the difference between the regulating price and the day-ahead price relative to the day-ahead price in each of the Nordic bidding areas. As the outliers have high values compared to the boxes themselves, the boxes are not visible in this figure, but the box plots without the outliers are given Fig. 3.

Only when the producer is able to accurately forecast its net imbalance as well as the market regulating price for a given bidding area and settlement period, can internal balancing in combination with mFRR market participation maximize the profits. Since this combined strategy is challenging to achieve, only committing to the mFRR balancing market is advised.

As these conclusions are based on the current Nordic markets and regulations, producers operating in other regions could assess their specific energy market and imbalance settlement regulations in order to reevaluate their operation strategies accordingly. In this manner, producers can ensure that their VRE assets are experiencing as little imbalance settlement costs as possible, and thus maximizing the value of the generated VRE energy. Future work should investigate optimal balancing strategies for producers which operates hybrid power plants, e.g., when production and storage assets share the same grid connection point.

CRediT authorship contribution statement

Øyvind Sommer Klyve: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Gro Klæboe:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Magnus Moe Nygård:** Supervision, Writing – review & editing, Data curation. **Erik Stensrud Marstein:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Open source data given in references.

Acknowledgments

The authors acknowledge funding from the Research Council of Norway (KSP HydroSun, grant no. 328640).

Appendix

A.1. Combined internal balancing and mFRR market participation strategy

Internal balancing can be beneficial when performed in combination with mFRR market participation. In Fig. A.2, the striped areas represent the conditions where internal balancing is optimal. It should be noted that it is only an energy volume equal to the VRE imbalance which should be internally balanced, while the rest of the producers' up- and down-regulating energy volumes should be offered to the mFRR market to the producer's marginal up- and down-regulating price respectively. The equations corresponding to the combined strategy are given in Eqs. (A.1), (A.2), (A.3), (A.4):

$$\begin{aligned}\Pi^{cs} =& \hat{E}_v^{da} p^{da} + (E_v^{imb} + E_d^{r,ib}) p^r - |E_v^{imb} + E_d^{r,ib}| p^f \\ &+ (p^{da} - p^{m,d}) E_d^{da} - p^m E_d^{r,ib} + (p^r - p^m) E_d^{r,mp}\end{aligned} \tag{A.1}$$

$$E_d^{r,ib} = \begin{cases} E_d^u & \text{if } E_d^u < -E_v^{imb} \ \&\ p^r > p^{m,u} - p^f \\ E_d^d & \text{if } E_d^d > -E_v^{imb} \ \&\ p^r < p^{m,d} + p^f \\ -E_v^{imb} & \text{if } E_v^{imb} < 0 \ \&\ p^r > p^{m,u} - p^f \\ -E_v^{imb} & \text{if } E_v^{imb} > 0 \ \&\ p^r < p^{m,d} + p^f \\ 0 & else \end{cases} \tag{A.2}$$

$$E_d^{r,mp} = \begin{cases} E_d^u - E_d^{r,ib} & \text{if } p^r \geq p^{m,u} \\ E_d^d - E_d^{r,ib} & \text{if } p^r \leq p^{m,d} \\ 0 & else \end{cases} \tag{A.3}$$

$$p^m = \begin{cases} p^{m,u} & \text{if } E_d^{r,ib} + E_d^{r,mp} > 0 \\ p^{m,d} & \text{if } E_d^{r,ib} + E_d^{r,mp} \leq 0 \end{cases} \tag{A.4}$$

where Π^{cs} is the total income in the day-ahead and mFRR market under the combined strategy, and $\hat{E}_v^{da}$, p^{da}, E_v^{imb}, p^r, p^f, $p^{m,d}$, $p^{m,u}$, E_d^{da}, E_d^u and E_d^d are defined as in Section 3. $E_d^{r,ib}$ and $E_d^{r,mp}$ are the regulating volume used for internal balancing and mFRR market participation respectively. p^m is the producer's marginal regulating cost.

A.2. Meteorological weather stations

The locations and key properties of the meteorological weather stations used to model PV power plants in the Nordic bidding areas are given in Table A.1. When modelling the PV power plant in the Finish bidding area, GHI and wind speed data are collected from the weather station given in the table, while the ambient temperature is collected from the Helsinki Kaisaniemi weather station located at latitude 60.18, longitude 24.94 and altitude 3. Details about the modelling of the other PV power plants can be found in Klyve et al. [3].

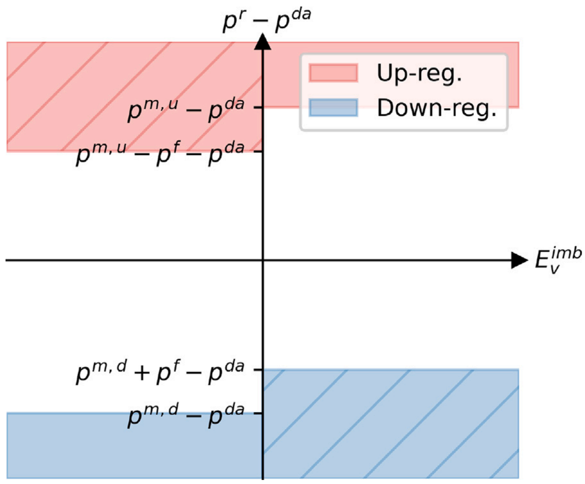

Fig. A.2. If the producers are able to correctly forecast the market regulating price and the VRE energy imbalance volume for a given settlement period, combining the internal balancing and mFRR market participation strategies provide the most revenues. However, internal balancing is only beneficial in the striped areas, i.e. (1) when there is a VRE energy deficit, $E_v^{imb} < 0$, and the market regulating price is higher or equal to the producer's marginal up-regulating price minus the imbalance fee, $p^r > p^{m,u} - p^f$, or (2) when there is an imbalance energy surplus, $E_v^{imb} > 0$, and the market regulating price is lower or equal to the producer's marginal down-regulating price plus the imbalance fee, $p^r < p^{m,d} + p^f$. For all other regulating and day-ahead market prices, p^{da}, only participating in the mFRR market is the cost optimal strategy.

Table A.1
The locations, bidding areas, latitudes (Φ), longitudes (λ), and heights above sea level (H) for the meteorological stations which are used to model the 10 MWp synthetic PV power plant energy outputs. The tilt angles (β) were selected using the PVGIS tool (V5.2). All locations have the same 180° azimuth angle for the PV modules.

Location	Bidding area	Φ [°N]	λ [°E]	H [m]	β [°]
Mejrup	DK1	56.38	8.67	53	45
Sjælsmark	DK2	55.88	12.41	40	41
Helsinki Kumpula	FI	60.20	24.96	24	44
Oslo	NO1	59.94	10.72	94	45
Grimstad	NO2	58.33	8.58	–	44
Trondheim	NO3	63.42	10.41	60	44
Iškoras	NO4	69.30	25.35	591	50
Bergen	NO5	60.38	5.33	46	40
Luleå	SE1	65.54	22.11	32	48
Umeå	SE2	63.81	20.24	23	49
Borlänge	SE3	60.49	15.43	168	47
Lund	SE4	55.71	13.21	85	45

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