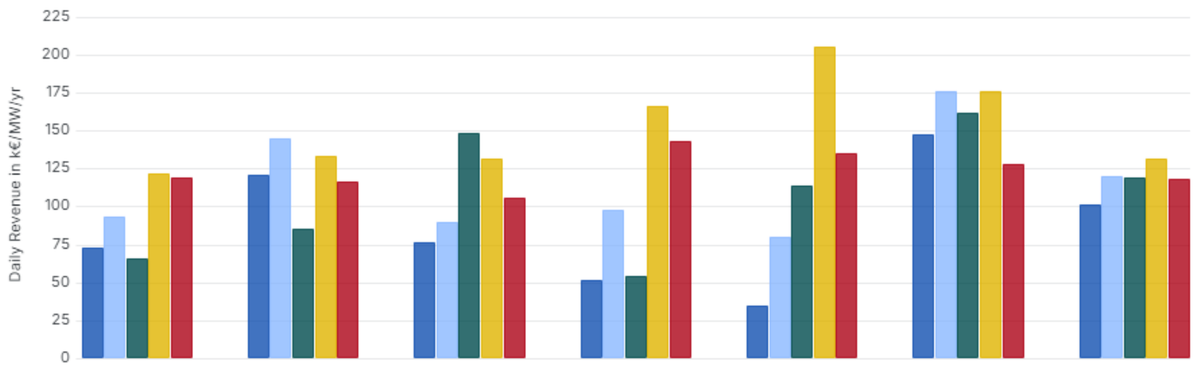

Battery Revenue Index

by ISEA RWTH Aachen

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1. Configuration

Prior to utilisation, the battery system and all markets must be configured. The tables below illustrate the parameters that can be modified by the user.

Table 1: Battery configuation

Parameter	**Unit**	**Description**
Energy	MWh	Installed capacity of the battery system
Power	MW	Available power for charging and discharing including inverter
Cycle limit	/	Equivalent full cycles per day
Service life	Years	Expected lifetime of the system. Will be used for calculating ageing costs
Efficiency	p.u.	Round-trip efficiency of the system
SOC (min, max, init)	p.u.	State-of-charge limits and initial value
DoD	p.u.	Maximum allowed depth of discharge (DoD)
Costs	€/kWh	System costs incl. Inverter, installation etc. Will be used for calculating ageing costs

Table 2: Market configuration

Parameter	**Unit**	**Description**
Delivery time	h	Delivery duration in h for the products in this market
Power share	p.u.	Share of the installed battery power that is allowed to be used for this market
Capacity share	p.u.	Share of the installed battery capacity that is allowed to be used for this market
Capture rate	p.u.	A factor used to weight the daily results for each market to consider that not every best trade can be done by a real asset

2. Single Market Results

In order to ascertain the results of the Single Market, it is first necessary to calculate the daily profits for each market individually, based on the price information available. Therefore, the initial step is to read the price information for the specific date from the relevant market folders, which can be found in the "Market data" folder. With these prices, the daily revenues are calculated using a different procedure for each market. The following subsections explain how the calculation is performed for each market in turn.

Wholesale

This section explains the wholesale markets considered in this index being the Day-ahead market (DA), Intraday Auctions (IDA1) & Intraday Continuous (ID1). The Day-Ahead and Intraday Auctions are closed on the day before delivery and the prices from the index can really be traded. The ID1 index is the weighted average price of all continuous trades executed within the last trading hour of a contract. This index serves to streamline the process of continuous Intraday trading, whereby bids and asks are matched on a second-by-second basis.

Get price information

The Table 3 lists the data that is used for modelling each markets prices per day.

Table 3: Data for wholesale markets

Market	Product duration	Source	Description
Day-Ahead	1h	ENTSO-E[1]	Bidding zone DE-LU
IDA1	15 min	EPEX Spot[2]	IDA1 is regarded as the Intraday auction held at 3 p.m. on the day before deliver
ID1	15 min	EPEX Spot[2]	Market area DE-LU. Weighted average price of all continuous trades executed within the last trading hour of a contract.

Calculate Revenues

With this step we calculate the daily revenue for the wholesale markets. Figure 1: Algorithm for calculating the daily profits for wholesale markets.Figure 1 shows the steps taken to calculate the daily profits. The general idea here is to calculate the best trading profile based on the available price spread on each day.

For each trade it is assumed that the full marketable power is used. The marketable power depends on the available nominal power of the battery and allowed DoD given in the battery configuration.

$$P_t = \min\left(\frac{DoD * E_{nom}}{t_{market}}, P_{nom}\right)$$

[1] ENTSO-E Tranparency platform
[2] EPEX Spot https://www.epexspot.com/en/market-data

We differentiate between traded energy and SOC change in the battery. Both values differentiate due to efficiency losses. The calculation can be seen in Table 4.

Table 4: Calculation of trading volumes and battery (dis)charge energy.

	Buy	**Sell**
Market	$E_{buy} = \frac{P_{t_{buy}} * \Delta t_{market}}{\eta_{Bat}}$	$E_{sell} = P_{t_{sell}} * \Delta t_{market} * \eta_{Bat}$
Battery (SOC)	$\Delta SOC_t = \frac{P_{t_{buy}} * \Delta t_{market}}{E_{bat}}$	$\Delta SOC_t = \frac{-P_{t_{sell}} * \Delta t_{market}}{E_{bat}}$

As shown in the flowchart, the code iterates through all possible trades in descending order based on the available price spread. For the single market results, the first available trade is always taken as no conflicts with other battery activity can occur. Then, iterating through the trade list, a virtual SOC profile is calculated, that would apply if that trade would be executed. Then we check multiple conditions that have to be fulfilled to make sure we only trade feasible trades without exceeding constraints from the given battery configuration.

Condition 0) Is the profit from this trade large enough to cover ageing costs of the battery?

The ageing costs are calculated simply by dividing the battery costs given by the service life. Both parameters are given in the battery configuration.

$$c_{aging} = \frac{c_{bat}}{life_{Bat} * cycles_{day} * 365} \; in \; \frac{€}{MWh}$$

Condition A) Does the SOC always stays within the given limits?

$$SOC_t = SOC_{t-1} + \Delta SOC_t + SOC_t^{fixed} - SOC_{t-1}^{fixed}$$

$$minSOC \leq SOC \leq maxSOC$$

Condition B) Is the SOC at the beginning of the day the same as in the end?

This condition acts as a feasibility check that every opened trade is also closed in the end.

Condition C) Is the given maximum allowed DoD not exceeded?

By calculating the SOC changes between each timestep, we only allow this trade if the maximum DoD is not exceeded.

Condition D) Does this trade not exceed the maximum marketable power for the battery and this market?

Finally, based on the calculated SOC curve, the SOC changes in the profile are calculated. These are then converted into power values.

$$\Delta P = diff(SOC_t) * \frac{E_{bat}}{\Delta t_{market}}$$

We then check that the absolute power usage never exceeds the marketable power.

$$\Delta P \leq P_t$$

When all conditions are fulfilled, the trade is executed and the revenue through this trade is added to the daily revenue. The revenue is the difference between the product of discharged energy and wholesale market price during the time of the sell t_{sell} and the product of charged energy and price at the time of the buy side of the trade t_{buy}. The battery efficiency η is used in the revenue calculation to consider efficiency losses.

$$R_{day} += p_{t_{sell}} * P_{t_{sell}} * \Delta t_{market} * \eta_{Bat} - p_{t_{buy}} * P_{t_{bux}} * \Delta t_{market} * \frac{1}{\eta_{Bat}}$$

Finally, he revenue for this day is weighted with the given capture rate from the market configuration $cr^{market}$to consider non ideal trading.

$$R_{day}^{market} = cr^{market} * R_{day}$$

Frequency Containment Reserve (FCR)

Calculating Frequency Containment Reserve (FCR) revenues takes the 6 prices (one for each 4h block) from the results of the daily auction and multiplies them with the marketable power of the battery for this market. More information for this market can be found on the website of the German TSO TransnetBW[3].

Get price Information

The prices are published every day by the Transmission System Operators[4]. The auction works with a pay-as-cleared mechanism and therefore, there exists one price for the whole market area. Each participants offers FCR services in both direct in parallel and therefore only one price for each block exists. We use the column GERMANY_SETTLEMENTCAPACITY_PRICE_[EUR/MW] from the published excel sheet.

Calculate Revenues

The 6 prices are multiplied with the marketable power for FCR. The marketable power is limited to 80% of the nominal power of the battery system as stated in the prequalification documents (PQ-Conditions[5]) chapter. The battery operator as to reserve 25% of the nominal battery power for SOC management. Thus, the marketable power P_t is calculated as follows.

$$P_t = \frac{P_{bat}}{1.25} = 0.8 * P_{bat}$$

The daily revenue is the calculated as the sum of all 4h blocks considering the capture rate cr^{FCR}.

$$r_{day}^{FCR} = cr^{FCR} * \sum_{i=1}^{6} p_i * P_t$$

Automatic Frequency Restoration Reserve (aFRR)

In this market a battery system can be active in two markets. In the capacity market the battery only offers to reserve power for frequency restauration mechanisms. In the energy market, all participants offer their service to actively use energy to restore the 50 Hz in cases of frequency deviations. At this point in time, we only consider the capacity market. At this

[3] https://www.transnetbw.de/de/strommarkt/systemdienstleistungen/regelreserve
[4] regelleistung.net
[5] PQ conditions page 69

stage of the revenue index, we will include the energy market as well. More information for this market can be found on the website of the German TSO TransnetBW[6].

Symmetrical bidding is assumed for the positive and negative capacity market (state of charge: 50%). We assume that the marketable power is reserved for 1h delivery. Thus, a 2h-system can offer 0.5 MW in each direction while the 1h-system offers 0.25 MW. The market entry barrier of 1 MW is neglected.

Get price Information

The prices are published every day by the Transmission System Operators[7]. The auction works with a pay-as-bid mechanism and therefore, there exist multiple prices for the whole market area. We use the column GERMANY_AVERAGE_CAPACITY_PRICE_[(EUR/MW)/h] from the published excel sheet. This column includes the prices for aFRR capacity prices in positive and negative directions because in this market each participant can choose the directions of bidding (in contrast to FCR). Each price is given as per MW and 4h block. The given prices have to be multiplied with 4 to get the prices per MW per hour. We assume parallel bidding in both directions. Therefore, we will use both prices in the following revenue calculation.

$$p_t^{+/-} = 4 * p_{4h\ Block}$$

Calculate Revenues

The 12 prices (6 in each direction) are multiplied with the marketable power for aFRR. To calculate the marketable power for this market one finds information in chapter 2.7 of the PQ conditions[8]. A battery system operator only must reserve 1h of power delivery if an energy management system exists that can secure 4h of aFRR delivery by shifting the announced operating point of the systems grid access point towards the TSO e.g. through wholesale trades. In that case costs for these trading activities would occur. Without these SOC management operations, the battery system would have to reserve the full 4h of power delivery through capacity reservation. In that case the system could in theory deliver the aFRR service for 4h without any wholesale trades. As the final maximum marketable power of the system depends on the specific system under consideration, we consider a 2h power reservation as a compromise of both options.

Additionally, to these reservations, we can only offer at most half of the battery's capacity in each direction as we want to be offer in both directions in parallel. Therefore, the final marketable power P_t^{aFRR}can be calculated as follows:

$$P_t^{aFRR} = \min(\frac{E_{Bat}}{2} * \frac{1}{2h}, P_{bat})$$

The daily revenue is the calculated as the sum of all 4h blocks including the capture rate cr^{aFRR}:

$$r_{day}^{aFRR} = cr^{aFRR} * \sum_{i=1}^{6} p_i^+ * P_t^{aFRR} + p_i^- * P_t^{aFRR}$$

[6] https://www.transnetbw.de/de/strommarkt/systemdienstleistungen/regelreserve
[7] regelleistung.net
[8] PQ conditions Chapter 2.7

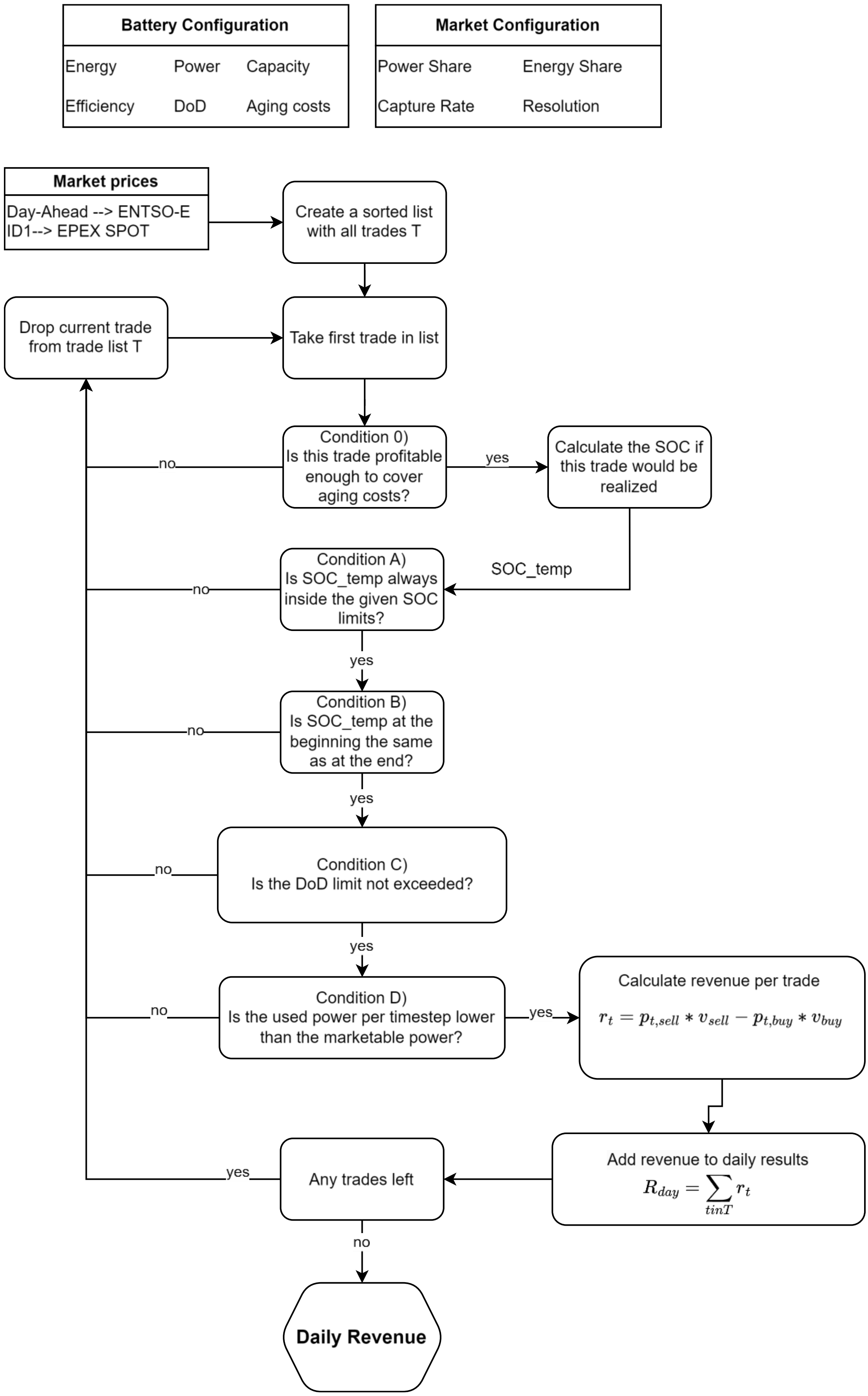

Figure 1: Algorithm for calculating the daily profits for wholesale markets.

3. Cross-market trading

With this approach we combine revenues from offering aFRR capacity in both direction in parallel plus wholesale market trading. For wholesale market trading we can assume trading first at the Day-Ahead (Day-Ahead) market and afterwards, considering the results from DA, trade the rest of the capacity at the Intraday market (ID1). The overall workflow of this trading is shown in Figure 2.

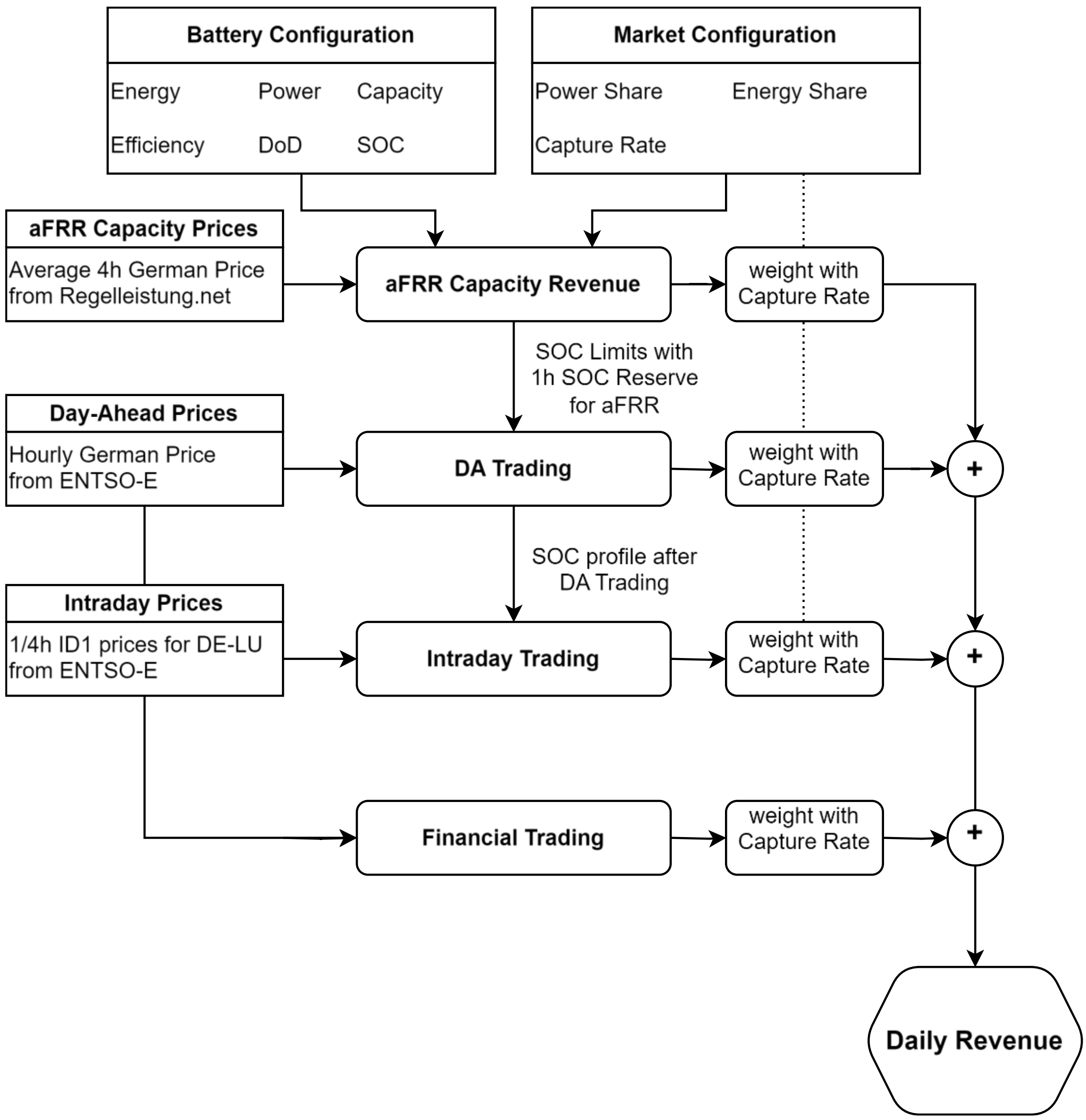

Figure 2: Workflow for the cross-market trading approach.

aFRR Revenues

The market revenues for this market are calculated the same way as described in Section Automatic Frequency Restoration Reserve (aFRR) from the Single-Market results.

Day-Ahead Trading

The Day-Ahead revenues are calculated following the procedure in Figure 1 for the wholesale revenue calculation. However, the power share is limited to 50% in this case as the rest is used for aFRR Capacity. The capacity share for this calculation differs to the single market results due to the 2h power delivery reservation for aFRR. Thus, the SOC limits change for the minimum from 0% to 25% and the maximum value from 100% to 75%. In our results we additionally limit the available capacity for this market to 40% of the available capacity (less than the theoretical 50% as explained above) to leave tradable capacity for the ID1 trading.

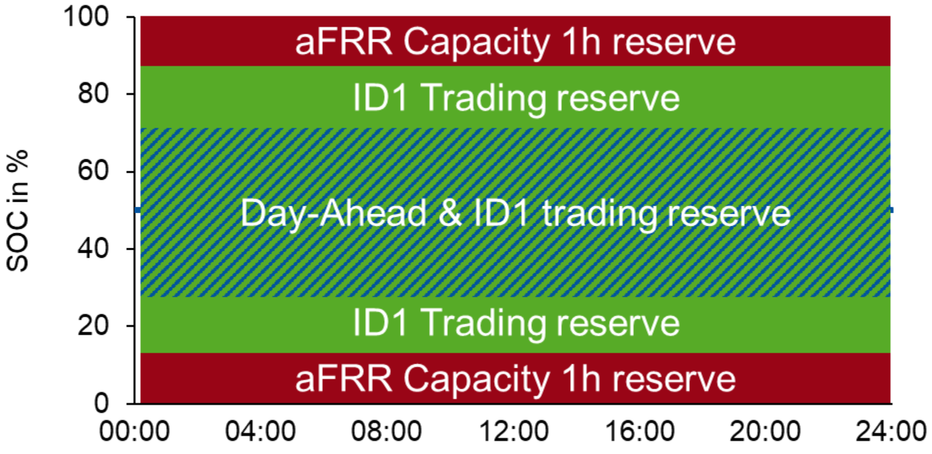

Figure 3: Capacity reservations in the cross-market trading approach.

Intraday Trading

The Intraday market revenues are calculated with the methodology shown in Figure 1 using ID1 prices. There is only one change as this time the calculation has to consider the trading results from the Day-Ahead trading results. To account for this, we take the SOC profile from the Day-Ahead trading and adjust the marketable power in a way that trades are also possible when SOC from DA is already very high or low.

Financial Trading

Additionally, we introduce the so-called Financial Trading revenues from trading multiple wholesale markets at the same time. By opening positions in two markets at the same time but in different directions no physical delivery obligation exists. Figure 4 shows schematically how the price differences between the DA and ID1 prices are used to evaluate the potential of non-physical trading. For every hour the calculate the sum between both prices.

$$r_t^{ft} = p_t^{DA} - \sum_{qh=1}^{4} p_{t,qh}^{ID1} \ \forall t \ in \ [1,24]$$

A positive value means the battery owner could make revenue by selling energy expensive at the DA market and buying it cheaper with ID1 prices. A negative value means that it would buy at the Intraday market and sell at the DA market. To realize these trading opportunities, one would need the DA and Intraday prices the day before delivery. As there are significant time differences of up to 36 hours between DA and Intraday trading it is very hard to predict prices in advance. We use a capture rate of 0.1 for the Financial Trading market to account for this.

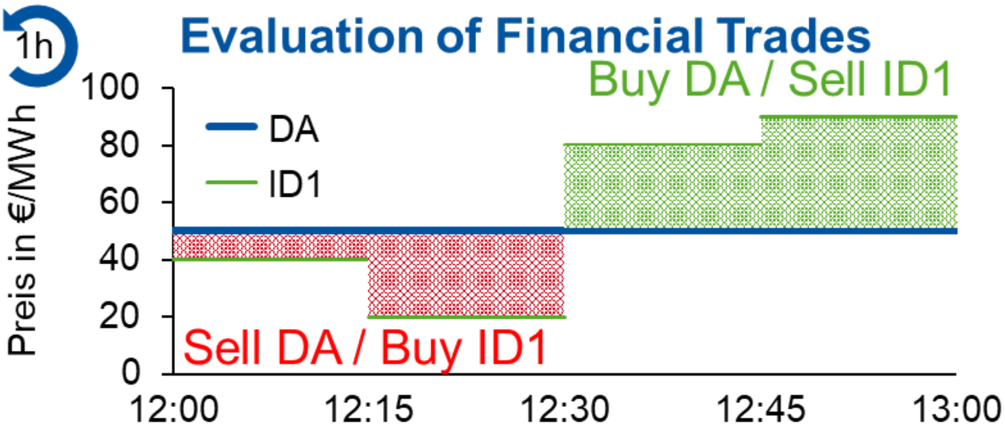

Figure 4: For the Financial Trading the price differences for each hour of one day are aggregated.