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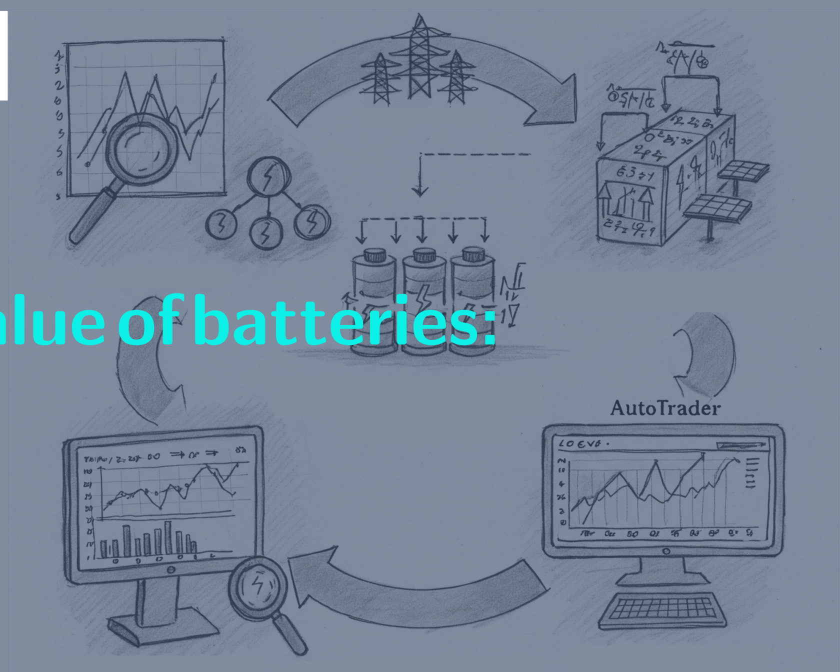
Maximizing the value of batteries: A hands-on guide



In this hands-on guide we give an overview on the main commercial building blocks of a successful battery project. We start by outlining their economics and introduce the **main use cases and relevant markets** that provide the foundation of their business case. Central European power markets serve us as an example.

Trading strategy: We develop a benchmark trading strategy, which we describe up to a level of detail, which we believe may serve as a starting point for building up own operations or to challenge service providers. We believe that such a baseline process is needed as a simple and solid basis for continuous improvement – and to identify levers to improve the strategy and to increase returns.

Benchmarking, hedging and project valuation: In order to set up a battery business case or to procure trading services, an investor will need to understand the main drivers of the value, a battery can unfold in the market. We outline the main considerations across different time frames: short-term benchmarks for trading services, mid-term market risks & hedging possibilities as well as long-term and investment valuation for investment decisions.

About RIVACON – RIVACON is a consulting company focused on technology-driven projects in Energy, Financial Engineering, Risk Management & Machine Learning. In Energy, we bring along extensive experience in valuating, monetizing or hedging renewable or conventional assets, flexibility or complex contracts such as green PPAs.

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Contents

1 Introduction

This white paper aims to be an introduction to how large-scale batteries are used in the market or in local use cases and how their flexibility is actually monetized. Our target audience are investors interested in project valuation, operators building up their battery trading activities or analysts working on the topic. We have been working on various related topics such as on how to set up the trading organization strategically and how to set up the IT architecture, on how to actually design the trading strategy as well as on specific analyses to challenge trading results. It was therefore a difficult decision, where to go into depth and where to stick to outlining principles. We decided to go for an outline of the main value drivers in the monetization of a battery and the description of how to combine them in a basic trading strategy.
We believe that the paper may be well suited as a recipe to identify the main tasks and building blocks of a project to launch or improve commercial battery operation. Please feel free to get in touch with us if you would like to discuss.

The paper is structured into the following sections:

Value drivers and markets: In the first sections we give an overview across all relevant use cases and introduce available market channels and value drivers from central power markets such as reserve markets and intraday markets to local use cases such as the maximization of own supply.

Trading strategy: In a next step (section 4) we go into the details of how the optimization of a battery is actually done. We start with a typical daily market schedule in Central Europe, describing how a real-life trading strategy can be implemented. Our strategy is designed as a robust starting point and benchmark for more sophisticated strategies in a real-life implementation. We believe it provides a recipe, how battery owners can build up their capabilities – defining main tasks, systems and outlining improvement potential.

Benchmarking, hedging, and valuation: A trading strategy provides the detailed recipe how a battery can be monetized in the market on a daily basis and how returns can be maximized. In section 5, we take a step back and discuss how the value of a battery can be assessed and hedged in the short, mid- and long-term. For short-term, we describe how benchmarks can help to challenge the performance of a trading service provider or the own trading desk's performance and, for mid-term, we describe market risks and challenges in hedging. For investment decisions, we describe the main tasks and challenges of such a valuation and how an investor can build up the capability to judge the main drivers of the business case.

Modelling assumptions: Throughout the paper we show several analyses and illustrative optimization results. We have based those on a battery with the following specifications: capacity 1 MW, size 2 MWh, cycle efficiency 90%, maximum one cycle per day. For day ahead prices as well as generation forecasts we use transparency.entsoe.eu as data source. For prices on ancillary services and intraday markets we referred to netztransparenz.de. For our illustrations we utilize the ID AEP index[1]. For optimization we have extensively utilized our "Energy Asset Optimization" (EAO) library. The library is based on linear and mixed integer programming, helping us to flexibly combine markets, positions and assets into portfolios to be optimized [6].

[1] Note that for our illustrations we have deliberately chosen to optimize the battery against an index for sake of simplicity. This is widely done, but in real-life it is required to resort to a specific trading strategy as in section 4. The ID AEP index represents trades shortly before delivery.

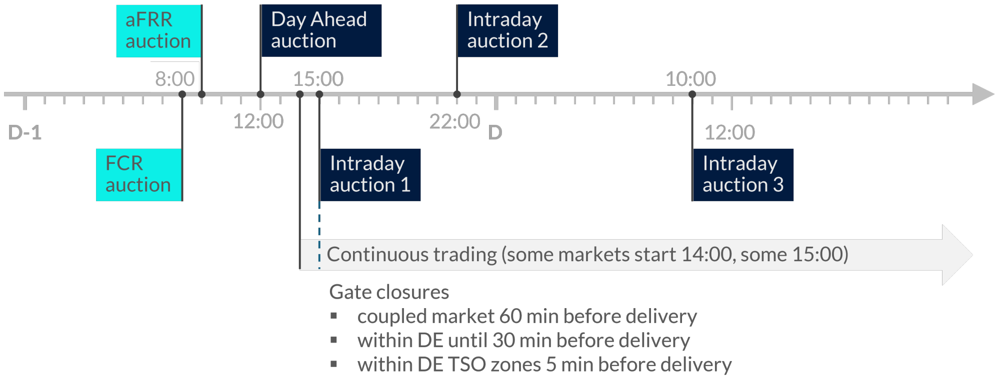

Figure 1: Spot markets at EPEX spot for Central Europe and ancillary services for Germany with their daily timing. Simplified view.

2 Use cases and markets for batteries

Flexible fossil power plants are already being pushed out of the market by the growing share of variable wind and solar PV generation. Their role is expected to diminish further in the coming years, eventually serving primarily as backup reserve during periods of "Dunkelflaute"—times with little or no wind and solar generation.

Batteries are increasingly recognized as a critical source of system flexibility, enabling the delivery of electricity when it is needed, rather than being solely dependent on variable weather conditions for power generation. No doubt: macro-economical considerations indicate an important role of batteries in a renewable and decentral power market. However, let us leave macro-economic considerations aside in this paper to concentrate on concrete ways to successfully monetize a battery.

Section 2.1 covers central power wholesale markets. These central markets allow grid-connected batteries to compete with other assets on a technology-neutral basis, irrespective of their specific geographic location. This use case for batteries is often referred to as "in front of the meter". The design of the market will be the foundation for our benchmark trading strategy, which we develop in section 4.

In section 2.2 we describe "behind the meter" use cases that rely on the localization of a battery. They may, by nature, be widely different and we restrict ourselves to a high-level overview.

2.1 Central power markets

Although different power markets vary by their designs, most of the arguments here hold in principle for many of these markets. Therefore, we concentrate on the Central European power markets as prototypes for markets in which batteries are operated to generate revenues. Where needed, we use the German market (more precisely the market area DE/LU) as to drill down (e.g. for ancillary services).

Central markets and bidding zones: A "central" power market is typically given by regulatory market design. Grids provide a network, that connects producers and consumers of electricity and the exact location of an asset can be ignored to a certain extent. Electricity may be delivered to or from predefined virtual market areas, grid operators taking care that physics works out. Interventions by grid operators are often required, e.g. redispatching assets. But let us leave this out for now, since these measures are designed to minimize monetary effects on assets[2].

Effectively this means, that trading takes place within market areas and prices refer to these. Market areas or bidding zones are, for example, five Norwegian, four Swedish and two Danish zones, but only one zone for Germany and Luxembourg (DE/LU). According to EU Regulation, bidding zones should be defined in such a manner as to ensure efficient congestion management and overall market efficiency. On the one hand they should be as large as possible to increase liquidity in trading and on the other hand they should take into account existing grid bottlenecks. The design of market areas is highly disputed – as in ongoing discussions about the potential split of Germany into several zones. See ENTSO-E's current review for details [2]. A potential split would have a significant impact on the economics of a battery and should be considered in the choice of a location.

[2]The effect of redispatch on battery assets may, effectively, not be negligible and details need to be taken into account in investment decisions as well as operations or contracts.

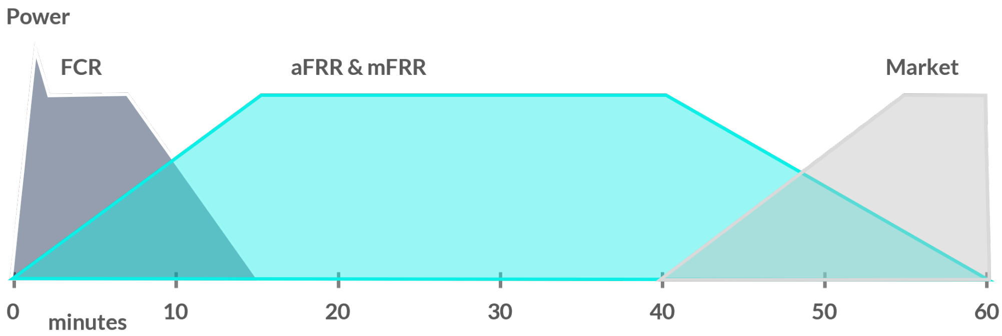

Figure 2: Ancillary service products. Illustration adapted from [7]

Markets and timeline: There are several trading platforms and products in central power markets. For simplicity, we give an overview on the EPEX Spot trading platform as the largest spot exchange [4] together with ancillary services procured by German TSOs [7]. Figure 1 illustrates the main market channels and decision points in the Central European power markets:

- **Ancillary services:** Grid operators require flexible capacity to balance demand and supply in the grid. In Germany and most of Central Europe, its procurement is organized in central auctions. For batteries, most relevant are Frequency Containment Reserve (FCR) and Automatic Frequency Restoration Reserve (aFRR). Figure 2 illustrates how different reserves (FCR, aFRR & mFRR) and the intraday market cover imbalances across time.

  Assets that bid into ancillary services must be prequalified to ensure they meet TSOs' criteria e.g. in terms of response times, maximal duration and availability. Requirements for FCR and aFRR are mostly easily met by batteries. However, minimum storage size and the need for a backup may be a bottleneck that needs to be kept in mind and may lead to significant extra costs.

  In principle, ancillary services are required to come with 100% "N-1" availability in Germany, meaning that the failure of one unit must not lead to reduced service. What *one* unit is, needs to be discussed in detail with TSOs and may, depending on design, represent a significant capacity share. Backup can be provided by keeping a unit in standby or by securing backup from a third party. It is clear, that this comes at a significant cost if the biggest unit is large compared to the portfolio.

  Ancillary services and particularly FCR used to be the market of choice for batteries in the past years, constituting the fastest and most valuable capacity in the system. However, the market is very limited (in Germany 570 MW for FCR and 1.923 MW positive / 1.842 MW negative aFRR on average in 2024 [1]. Even if growing in the future, it is clear that these markets cannot support the huge capacity of batteries that is expected to enter the market.

  Auctions for FCR in Central Europe are performed jointly for several countries within certain capacity limits (e.g. delivery of FCR from France to Germany up to grid limits). This means that order books are aggregated, providing a deeper market – effectively leading to more competition and lower prices in some areas, but also the chance for assets to deliver services across the border.

- **Other system services:** Besides the above ancillary services, batteries can deliver other system services to system operators or TSOs. We chose no to consider those in detail in the following, but in some markets they may constitute significant revenue streams. Such services include: *capacity payments* to remunerate batteries' capacity to secure coverage of system peak load such as in the UK Capacity Market, *black start capability*, helping to restart the system after a black out, *reactive power* to stabilize voltage or *instantaneous reserve* to replace the stabilizing effect of spinning reserve from heavy turbines.

- **Day-ahead auctions:** Day-ahead (DAH) auctions represent the central cornerstone in Central European markets. They mark the point in time when most generators, consumers, traders, and retailers consolidate their forward trades and forecasts. At this stage, they align their expected physical positions with the market on an hourly, 30 or 15 min basis to ensure balance. Accordingly, it represents the short-term trading platform with by far the highest liquidity: On EPEX Spot alone (all regions) 654 TWh have been traded in day-ahead auctions as compared to 215 TWh in the intraday market in 2024 [3]. In addition, market coupling performed by exchanges ensures that interconnectors are used optimally and assets effectively bid cross-border into other markets.

The main driver of DAH auctions is the fundamental interplay of demand and supply – the merit order. Particularly operators of dispatchable generation assets use DAH auctions to offer various alternative capacity slices at different variable costs. Since auctions takes place day-ahead, their basis are day-ahead forecasts of asset availabilities and wind & PV generation – and corrections of forecast errors need to be traded in the intraday market.

For the above reasons, also battery monetization cannot fully ignore DAH markets as a potential trading platform. However, as we shall see in section 4, they cannot leverage their full potential here: First of all, currently many DAH auctions operate on an hourly level[3], so that battery flex will not be fully utilized. In addition, price variation is typically much higher in intraday markets.

- **Intraday auctions:** As shown in figure 1, there are several intraday auctions that follow DAH auctions. Their main purpose is to allow market participants to react to forecast changes or outages. In addition, they act on a 15 min time grid, allowing bidders to refine hourly schedules, e.g. incorporating ramps. Since 2024, market coupling is also applied in intraday auctions, effectively generating pan-European order books.

  Intraday auctions provide additional trading opportunities with the opportunity to design structured bids (e.g. coupling charging and discharging). However, continuous trading still provides the bulk of liquidity over the course of the day (for DE/LU 291 TWh were traded in the DAH auction, 91 TWh in intraday continuous as compared to 11 TWh in the intraday auction on EPEX Spot [3]).

- **Intraday continuous trading:** As we have seen above, the bulk of intraday trading in Central Europe takes place in continuous trading. This means bids and offers are not collected at specific points in time for a central auction. Instead, market participants continuously place them in an order book and/or accept existing orders. Thus, there is no clearing price as in auctions – instead, all intraday trades on 15 min or hourly products come with their own quantity and price. Price indices, such as EPEX Spot ID average, ID1 or ID3, reflect aggregated price curves generated from single trades. They are often used to approximately valuate batteries, but do not reflect prices that could have been directly achieved in the market. We will come back to this in section 4.

  Continuous trading starts well before delivery (see figure 1) and (example Germany) is open until 5 min before delivery. This means, that a battery operator can sell the flex of his asset until very shortly before the battery actually delivers the power into the grid. Counterparties would, for example, be operators of wind or PV assets that refine their forecasts and aim to balance their portfolios.

  Note that in Germany the market splits into the four TSO areas 30 min before delivery. This means that also order books will depend on the TSO area and batteries may have different values depending on where in Germany they are located.

- **Portfolio balancing:** Market participants with a portfolio of (particularly renewable) generation assets and consumers face the challenge to balance their portfolio at all times. This means, they need to have access to good forecasts and continuously trade differences in generation or consumption on the intraday market. For remaining imbalances, grid operators charge imbalance prices that reflect their costs for ancillary services and intraday prices – resulting in partly very extreme positive or negative price spikes. Batteries can be used within a portfolio to physically avoid imbalances and reduce related costs.

Revenue Stacking: A term often used when battery business cases are discussed. It means that batteries are used in several of the above market segments. Revenue stacks often suggest that parts of an asset are used for one, others for another revenue stream. Although this is true for the usage of the overall battery capacity in the market, this typically does not apply for a single asset. In reality (see section 4) one will look at expected revenues across revenue streams for the next day and pick the most promising. Which one that is, will depend on forecasts and the technical characteristics of the battery.
Since markets are typically quite liquid, assets switching to the best market channel, revenue streams will – up to technical requirements – be similarly attractive: More capacity is drawn towards the revenue stream that is temporarily more attractive, flattening differences. This should usually leave only systematic differences stemming from differences in technical requirements (e.g.

[3]It is planned to change the auction to 15 min products and at the time of writing, it has been announced for end of September 2025. For DE/LU, EXAA provides a DAH auction on 15 min level.

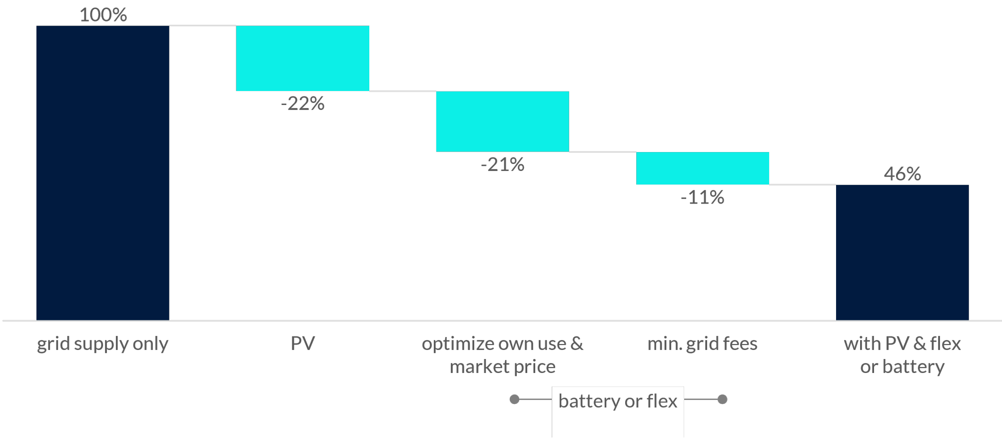

Figure 3: Battery used locally to maximize own consumption and to minimize grid fees.

prequalification for ancillary services or storage size in arbitrage). However – beware to be ready technically to switch markets as you will want to be able to profit from price spikes in a market segment. As we will show, a good forecast which market to use on a daily basis will be decisive for a successful trading strategy.

2.2 Local use cases

There are various local use cases for batteries. Since they are often highly specific to local circumstances and considerations, we chose not to include them in our detailed monetization strategy in section 4. However, they may well provide a solid business case, where circumstances are favorable. Particularly where there are generation units or demand located at the same meter as a battery, we recommend to include the local specifics into the considerations of a monetization strategy.
Main local use cases are the following:

- **Maximizing own use:** Consumers' power bills are to a large extent driven by additional costs such as grid fees. Where consumers have local generation assets like PV, they can greatly benefit from a local battery to minimize the amount of electricity procured from the grid. At the same time, they may utilize a battery to shift demand to periods of lower power prices or lower grid fees.

  Figure 3 shows an illustration for a commercial user[4]. The analysis shows that in this setup, a battery can significantly drive down costs. By nature, the business case highly depends on grid fees as well other local side conditions. And, naturally, investment and operational costs of a battery need to be considered to analyze the business case. In this case, all value drivers are included in the optimization to come to an overall minimum of electricity costs. In particular, the battery helps to reduce peak load to reduce grid connection cost, to maximize own usage of PV production and to shift procurement from the grid to cheap hours.

- **Co-location with wind or PV:** A battery that is located at the same location as wind or PV assets, can be utilized to reduce the required capacity of the grid connection or to shift feed-in into times of higher power prices.

- **Steady green power supply:** As some consumers commit to very high shares of physical green power consumption, they have the need to bridge times where not enough wind or PV is available. For those cases, batteries can be used to shift surplus green power to those times. Particularly for the production of green hydrogen, a local battery may prove to be critical to meet regulatory requirements.

- **Grid asset:** Batteries may be used as grid assets instead of other investments in grid enforcement. To give an example, instead of enforcing the connection of two locations in the grid, a battery may be used to limit peak load in a region that is weakly connected[5]

[4]Illustration for a commercial consumer in Germany: demand 500 MWh, own rooftop PV with 0.25 MW, 0.25 MW battery storage (2h, 90% efficiency), grid fees fix 166 EUR/kW and 1.3 ct/kWh variable. 2024 DAH prices, commercial standard load profile

[5]For a sample project, a so-called "grid booster" see www.amprion.net/Netzausbau/Aktuelle-Projekte/Dezentraler-Netzbooster

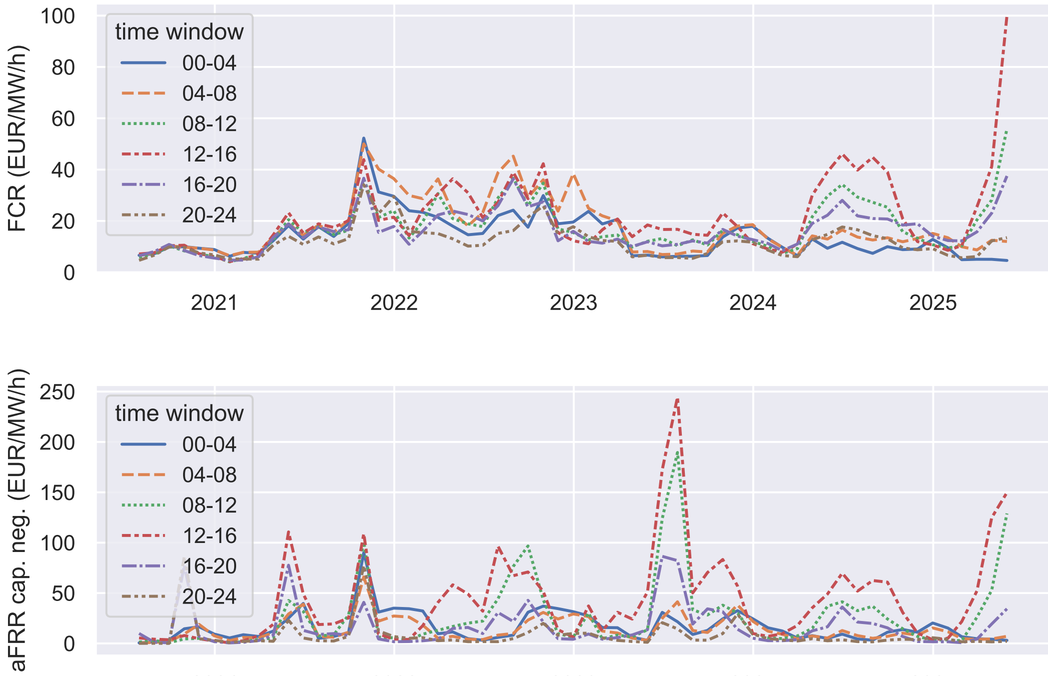

Figure 4: FCR (top) and aFRR capacity (bottom) prices against for available time windows. Note that particularly in summer, reserve capacity is expensive during PV production.

- **Island power supply or emergency backup:** On grid islands, i.e. areas not connected to the overall grid, batteries can be used to ensure a stable supply. Particularly in combination with wind or PV, they can help to reduce utilization of expensive diesel engines. Batteries also serve consumers with high requirements on power availability (e.g. hospitals or data centers) as a temporary backup power supply.

3 Markets and value drivers

In this section we give an overview of the main value drivers of a battery applied across central power markets. Our aim is to provide a view on the value drivers, not to give a thorough valuation. The latter requires a specific analysis that takes into account the technical characteristics of the battery as well as local side conditions. In the following we go through the main markets and value drivers:

Local use cases: We leave local use cases aside, since they highly depend on local side conditions. The previous section should give a good overview.

Ancillary services: Figure 4 shows monthly averages of prices for FCR and aFRR for Germany. Prices are formed in daily auctions for six time windows of four hours, separately for negative and positive reserve in the case of aFRR. While reserve markets are highly regulated, prices are driven by the market and show high fluctuation. On a daily level, fluctuations are much higher (see figure 6). Besides overall fluctuation, we observe that time windows come with distinctively different prices. Reserve for 12:00-16:00 for example, has become significantly more expensive, particularly in summer. The reason is to be found in growing PV penetration, saturating the market. Other (flexible) sources leave the grid and are not available to provide reserve or can only do so at high opportunity costs.

Price arbitrage In principle, price arbitrage is simple: Charge when power is cheap, discharge when it is expensive. A closer look at power markets shows, however, that this not as straight forward as it may seem. Once we have decided to go for arbitrage, the first market available are DAH auctions. In order to participate, we need to leverage forecasts to generate suitable bids on when to charge or discharge at what minimum return. More details are covered in the following section. Similarly, participation in intraday auctions and the continuous market require a stable trading process and a suitable quantitative tool set. See section 4.

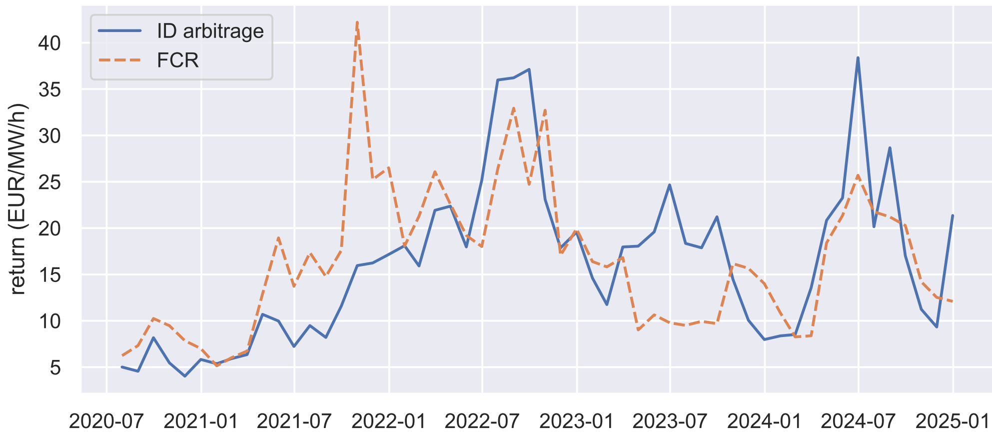

Figure 5: Monthly returns FCR vs. arbitrage (simplified view: FCR without backup; arbitrage intraday only, 2h battery).

Comparing returns from utilizing batteries in intraday arbitrage to those obtained in reserve markets, we find that on a monthly level relative attractiveness may change, even if markets are clearly linked on a longer time scale. Figure 5 compares returns from FCR to those from intraday arbitrage. Note that, while for FCR only capacity matters, battery size (in MWh) is highly relevant for arbitrage – the larger the battery in terms of MWh, the better arbitrage will perform against FCR.

Choosing the right market: One of the main tasks of a trading strategy for batteries is to choose the right market. Ancillary market or arbitrage and subsequently where and when to do arbitrage. This will be covered in detail in section 4. Here we provide an initial analysis to show the importance of the right choice (i.e. good analytics and forecasts that enable this choice).
Figure 6 shows revenues from FCR versus a strategy that combines DAH and ID. On a daily level we observe a very high volatility: In many instances, ID arbitrage possibilities and FCR prices prove to be very far from each other.

To add to this, doing such analysis *ex-post* with perfect foresight is too simple, since the battery must be placed in the ancillary auction the day before (see process in figure 1). A good forecast on which market will be most attractive, is therefore required as a basis for the decision on market channel. See the following section, where we describe the process along the benchmark trading strategy (section 4). The maximum potential value add of such a forecast is very high – increasing return by up to 26% in the analyzed time frame and setup.

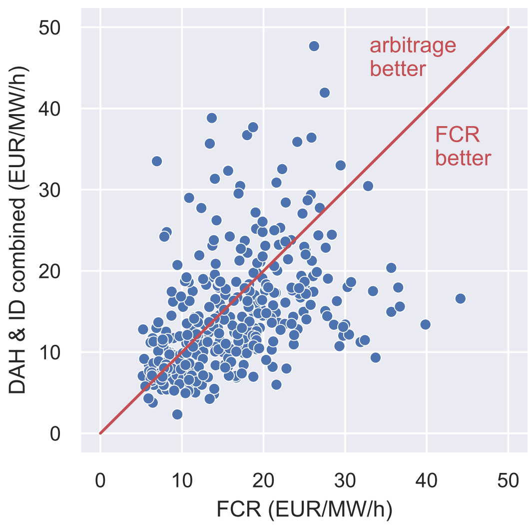

Figure 6: Daily revenues from FCR and arbitrage for a 2h battery in 2024 show great volatility – the right forecast on which market to place the battery is a significant value driver. Values above 50 EUR/MW/h have been cut off for greater clarity, but note that extreme days have a significant effect.

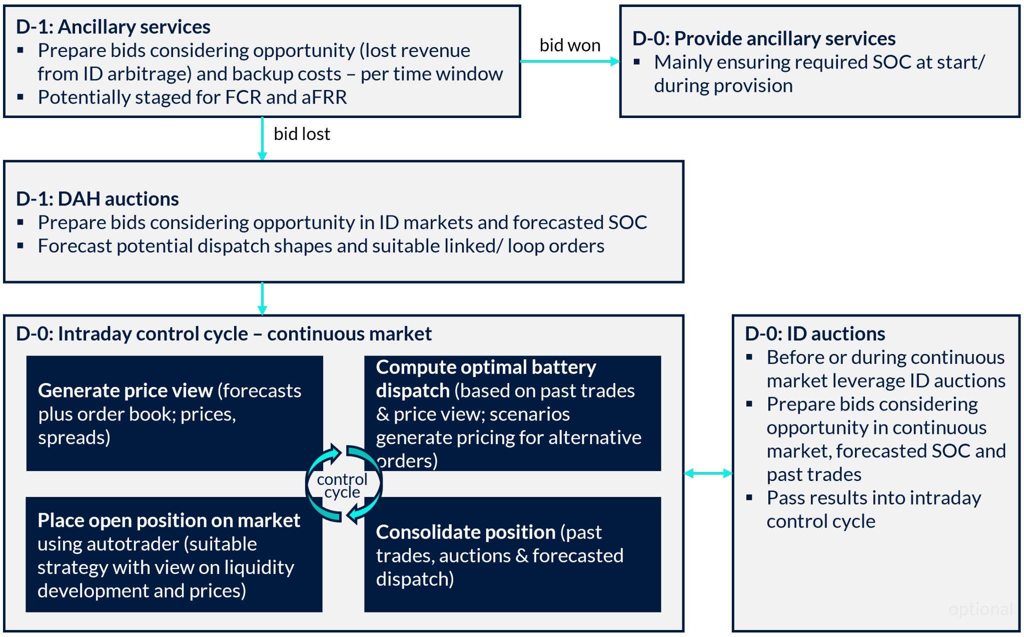

Figure 7: High-level process for the baseline trading strategy.

4 Hands-on strategy to monetize a battery

In this section we present the main steps and challenges of a trading strategy for a battery. In the first part we present the base strategy with all main steps and requirements. In the second part we discuss improvement potential for more elaborate strategies.

4.1 Baseline process and benchmark strategy

The control cycle: Power markets and the basic steps to optimize and control a battery give rise to an idealized control cycle as sketched out in figure 7, which already defines a baseline strategy. In an implementation, it provides the foundation for designing how systems, software packages and forecast models interact.
The four center pieces of the trading strategy are shown as dark blue boxes in the process sketch. Each one of them is an important task by itself, which must be solved efficiently to maximize revenues. The same holds for the preparation of bids for ancillary service, DAH or ID auctions. Fortunately, those steps can to great extent be tackled and back-tested independently. Let us go through each step in detail:

Preparing bids for ancillary services: The marginal costs for having a battery provide ancillary services are relatively small (wear and SOC management). Therefore, the opportunity costs of not having the capacity available for intraday arbitrage are leading and must be determined.

As a starting point, a market analysis as in the previous section (see figure 4) can consist in simply choosing the preferred market on the basis of historical prices in the current market phase, taking into account product, weekday and season. We discuss ways to improve the decision later on.

DAH and ID auctions: Similarly, good forecasts are required to generate bids for DAH and ID auctions. As a starting point, we need a view on the battery dispatch to generate a block or loop order[6], defining when the battery would be charged and discharged. In the simplest setup, we can enter a DAH auction at the battery's marginal costs and let the auction determine prices – or alternatively decide not to leverage DAH auctions at all.
Figure 8 shows average returns for those edge cases (going into the ID market only or always going into the DAH auction first and re-optimize in the ID market). Going into the DAH auction alone clearly leads to significantly lower returns. In the case of 2024 prices with extreme cases removed, we observe, that the combination of both markets with re-optimization in the intraday market leads to better results. However, there may be days in which, for example, intraday prices show extreme spikes, which we cannot profit of if we have already sold the battery dispatch in the DAH auction.
As we shall see later on, there lies much value in more elaborate strategies that leverage a suitable forecast on whether to go into the DAH auction. See section 4.2.

[6] EPEX terminology used. Please refer to specific exchange information on how to generate suitable orders for batteries.

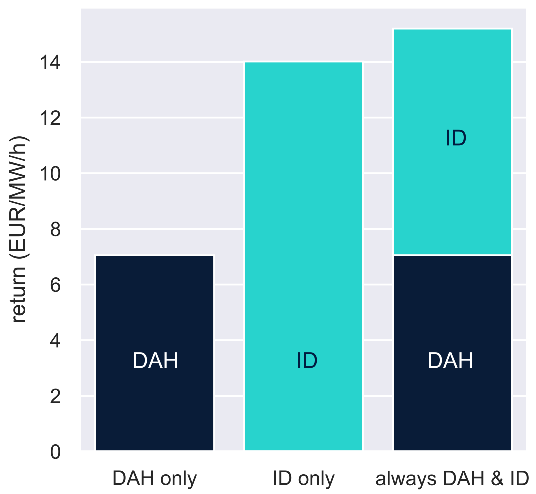

Figure 8: Comparison of the simple strategies "always go into DAH auction" and "ID only". Shown are average returns for 2024 in EUR/MW/h, excluding extreme days beyond 100 EUR/MW/h.

Control cycle: The control cycle which we have sketched here corresponds to the concept of a "rolling intrinsic" marketing of the battery's capacity (see e.g. [5] for a technical description of an implementation in the continuous ID market). In each step we generate an optimal dispatch and trade the overall position to zero. A similar mechanism is often applied to hedge power plants in forward markets. The idea is, simply speaking, to adjust battery dispatch every time prices change and then close the position by buying back power where prices decreased and selling where they increased. Every time we change the dispatch, we should increase overall return.

Generating a price view: As discussed above, it is key to have a good view on intraday prices for the upcoming 1-2 days, as they provide the basis for bids in most steps in the trading strategy. Such price view needs to comprise the following elements:

- prices in a 15 min time grid
- bid/ask spreads and their development against time to delivery
- estimated liquidity to ensure the position can actually be closed

The data input for such price view is typically the current order book along with performed trades. Additionally, we will need to add past experience, weather information and forecasts on the development of spreads and liquidity as we get closer to delivery. For example, uncertainty in weather is a major driver for volatility in intraday prices as compared to DAH prices.

A good aggregation of current market data and forecasts is a central piece of information for our trading strategy and must be made available continuously in an automated manner. Utilizing external price forecasts without continuously challenging and improving them in the view of battery optimization will significantly reduce our returns.
Technically, it is possible to directly run an optimization framework on order books as shown in figure 9[7]. The advantage is that we skip any translation from trades and order books into price curves and spreads – directly taking into account available quantities and prices. The main disadvantage, in our view, is that liquidity in Central Europe typically increases as we come close to delivery. This means that at 10:45, for example, we see many orders for 11:00-13:00, but less for the time after. Thus, there would not be many orders in the order book that allow us to sell back power in the evening, which we could charge during sunny hours. It is therefore key to amend the order book with an assumption on the development of spreads and liquidity to successfully trade in the continuous market.
It should be noted that in the continuous intraday market, it is only possible to submit independent orders for independent 15 min or hour products. As a result, there is a risk of exposure to open positions if only a subset of the submitted orders is executed. This is a significant difference to auctions, where specific bids can be made, linking charging and discharging. Particularly when assuming increasing liquidity at a later point in time, risks associated with entering open intraday positions need to be evaluated carefully. While such strategies may offer higher average profitability, they may not be suitable for all investors.
In our experience, the most practical and flexible solution is to separate price (and liquidity) analysis from optimization – mainly to define price analysis as a clearly defined and separate analytical task that can be back-tested regularly. It generates one or several bid and ask price curves with estimated depth.
Market uncertainty is also a highly relevant result of forecasts. The more uncertain prices are, e.g. due to uncertain weather forecasts, the more extrinsic value lies in the battery. The level of uncertainty is an important ingredient for the strategy used in the autotrader (see below).

Optimal battery dispatch: Our trading strategy requires a battery dispatch that is continuously updated on the basis of the current price view, SOC and trading position. Good solutions are available and the main challenge is to seamlessly integrate the optimizer into the system landscape. The main output is the current view on the optimal battery dispatch. Working on an improved

[7] We have used the Energy Asset Optimization (EAO) framework, that already implements order books.

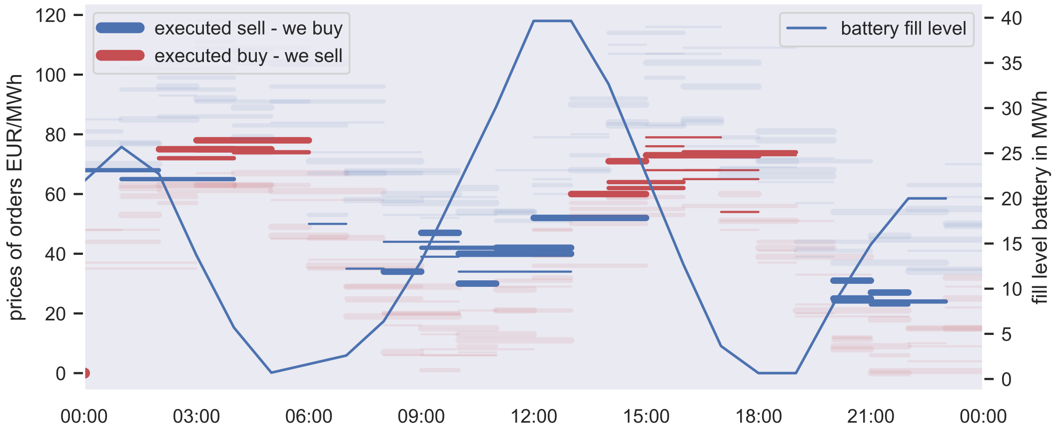

Figure 9: Illustration: Direct optimization of a battery against a given order book. Technically it is no problem to directly execute bids and offers with their prices and sizes according to battery capabilities.

strategy, we can add dispatches based on price scenarios to price alternative orders to be placed in the market.
In our sample cases we utilize the Energy Asset Optimization framework (EAO package, see [6]). EAO easily lets us include spreads, liquidity and existing positions in the optimization using a Mixed Integer Program approach. A fast alternative for the optimization of batteries are Dynamical Programs and can be applied for many use cases.
Local use cases can be covered in the optimization step. Once we have settled on an optimization target – mostly maximization of revenue or minimization of costs – it is straight forward to consistently combine all use cases into a joint optimization problem without the need to change the trading strategy.

Consolidation of positions: We must always keep track of past trades and auction results to be able to monitor and balance the power position. This task is typically performed by an existing dispatch system. In addition to tracking the position, a dispatching system performs all logistics on the physical market, such as communicating with TSOs and exchanges and providing an interface to market data.

Autotrader – placing positions in the market: Once the current view of the optimal battery dispatch is available, the open position is closed against the market within the range of prices assumed in the dispatch. Since battery flexibility unfolds much of its potential in the last hours before delivery, manual trading is prohibitive slow and error prone. Therefore, investors implementing the intraday continuous trading component of the proposed strategy should employ an automated trading system to efficiently place and execute orders in the market. Autotraders often come with predefined strategies, that help in performing trades in an optimal manner and with a suitable safety net to catch data mismatch or other errors.

4.2 Strategy improvements

Once we have the baseline strategy in place, we can work on improving each building block. In our view, **continuous improvement** is the key word. Successful trading strategies are less about one great idea or the fact of "applying AI", but an effective continuous process of improving in small steps. For this, we believe that a clear view on the main ingredients and a solid baseline are essential. The good news is that once a dispatching system and an autotrader are in place, implementing a basic battery trading strategy as the starting point does not come with great hurdles.

Combination of DAH auction and ID markets: A question that directly arises from figure 7, is whether battery flex should be placed into a DAH auction, and if so, at which price. It is clear from figure 8, that utilizing DAH auctions alone reduces the battery's value, since it omits much of the price variation. However, what remains to be answered is whether ID optimization *plus* initial DAH auction will improve the overall result.
Figure 10 shows daily returns for (1) going into the DAH auction plus ID[8] reoptimization vs. (2) an ID optimization only. The red line separates days where one or the other would have turned out to be of higher value. We observe several outcomes:

- On most days, the combined strategy leads to higher returns (points below the red line).
- Still, there are many days in which going only into the ID market would have been better than the combined strategy.

[8]Our illustration optimizes the battery against an ID price index; utilizing a full strategy including the continuous market will lead to different results in detail.

- Outliers significantly influence the average return (for readability we had to cut off extreme outliers). This reflects situations, where there are extreme prices, e.g. in ID markets, but not DAH markets

In a first simple strategy we therefore recommend to leverage DAH auctions in combination with ID markets. However, a forecast that can predict (even only to some precision), which version is better for a specific day, can add much value to our battery. In this example up to 19%. This represents a promising opportunity worthy of further exploration.

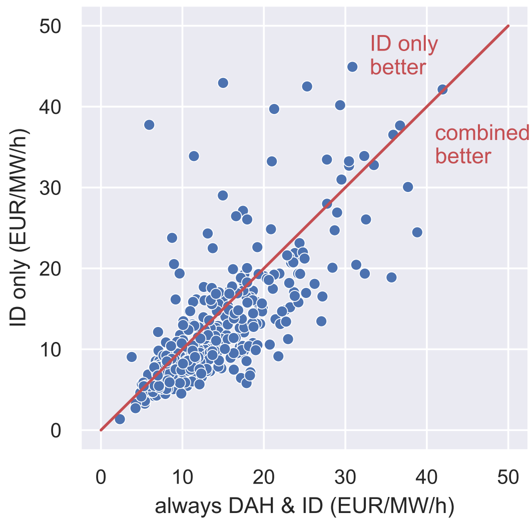

Figure 10: Daily returns for 2024 doing arbitrage in ID markets only vs. DAH plus ID reoptimization. Values above 50 EUR/MW/h have been cut off for graphical clarity, but note that extreme days have have a big effect overall.

Such forecast can be designed to trigger a decision on whether to go into the DAH auction or to compute a suitable bidding price for the DAH auction. Weather uncertainty, which directly translates into intraday forecast errors in PV and wind generation, is a relevant trigger and can be a good input for such a forecast based on machine learning models ("AI") or regression analysis. The same holds for classification into day types such as "a sunny holiday". Make sure to add meaningful information step by step to keep it understandable – human interpretation is often key for successful trading.

Forecasts and timing in continuous trading: Continuous trading in intraday markets leads to similar questions as the above. Besides the choice of the right autotrading strategy of how to place and execute orders, it is highly relevant to obtain a good view on how the value of the battery capacity will develop over the course of the day. This includes forecasts on spreads and liquidity. As for other forecasts, it is critical to continuously improve and back-test.

In some market phases, waiting until shortly before delivery is a good choice. In others, side movements and high volatility provide opportunities for repeated re-optimization. In the DE/LU zone, the decoupling of TSO zones in last 30 min constitutes an additional process step that should be considered, as order books become more restricted.

Ancillary services or arbitrage: As shown in figure 6, a similar argument holds for the question whether to sell the capacity into ancillary services or to keep it for arbitrage. The drivers for a successful forecast on the best market channel will be somewhat different from the above case – particularly FCR is fundamentally driven by alternative assets such as thermal power stations and their opportunity costs.

In Central Europe, FCR is procured for six windows of four hours, which may differ widely in prices (see figure 4). This means we may further improve our strategy by taking more granular decisions on the level of those time windows.

Typically, ancillary services are served out of a portfolio, that is able to provide the backup required by TSOs. In that case, the marginal costs within the portfolio are relevant. Those are given by the change of the *portfolio's* expected return change if x MW FCR or aFRR are delivered.

5 Benchmarks, hedging and valuation

Value drivers of a battery asset are significantly different from those of other assets, as we have described in the previous sections. This translates into specific requirements for a successful asset lifecycle. In the following we outline, what that means for benchmarking trading service contracts, market risks and hedging, as well as long-term and investment valuation.

5.1 Short-term benchmarks

Monetizing a battery requires both: Capabilities for intraday trading and quantitative modeling (e.g. for forecasting) – as well as an efficient setup of trading systems to be able to automate and capture the battery's value in short-term flex. In addition, participation in reserve markets requires a portfolio of a certain size for cheap backup. The combination with other assets in the portfolio (e.g. wind or PV) can help to tab additional value.

Therefore, many battery operators choose to leverage third party trading services. A main problem that arises, is that adequate revenues for a battery are not easily read from the market and there is the need to define benchmarks in the contract. Ideally, a contract defines a benchmark return on the basis of a suitable index, potentially plus a suitable share in profit on returns that exceed the index.

It is beyond the scope of this paper to define and implement such a benchmark. However, we believe it should be based on a benchmark trading strategy such as the one we have presented above. By clearly defining simple forecasting and decision mechanisms, the baseline trading strategy can then be used to compute a fair and reproducible benchmark. As we have seen, a simple reference e.g. to FCR prices or some intraday price index we optimize against, may underestimate the value.

5.2 Market risk and hedging

As we have seen above, battery revenue streams are to great extent market driven. An exception may be local use cases that rely, for example, on avoiding grid fees. In central power markets batteries rely on ancillary service markets as well as on short-term arbitrage in DAH and intraday markets. As shown in figure 5, both are tightly related, as assets can relatively freely choose the most attractive market. Variation of returns across years can be enormous.

Battery revenues therefore, directly or indirectly, depend on the variance in the hourly or 15 min shape of DAH and intraday prices. This, in turn is influenced by wind and PV production, forecast errors and commodity prices via competing flexibility from fossil generation.

In forward and futures markets, unfortunately, only base and peak standard products are liquidly traded for the next 1-3 years and it is hardly possible to effectively perform a hedging framework for batteries similar to delta hedging performed for fossil generation. By far, most of the battery value is not hedgeable via standard procedures and products.

First players have reacted and created lease contracts for battery capacity for various time frames, effectively taking market risks from a battery owner. This enables investors to secure cash flows and off takers to obtain battery flex without the need to operate a battery. Such agreements are mentioned increasingly in press[9] – and are considered an important tool to open the battery market to financial investors, not willing to take high market risks (as it is the case for wind and PV assets). Other products are defined via spreads between the highest and lowest prices of the day, for example, serving as proxies for battery value.

Since there is not yet a liquid market for such contracts, there is also no reliable market price for battery capacity. This means that battery owners need to be able to challenge offers up to a certain degree, having own models in place or at least being able to understand models and indices provided by third parties. While many operators will shy away from building up a team of analysts, we believe that a minimal expertise is both feasible at low cost and worth the invest.

5.3 Long-term & investment valuation

Fundamental drivers: As we have seen, market risks in short- and mid-term are significant and difficult to hedge. Accordingly, the uncertainty of cash flows in the long-term is even higher. Weather risks will average out in the course of several years, but changes in the merit order of competing generation assets will have a great effect. We see one of the most significant risk in an increasing battery capacity in the market, since it is developing fast and will cannibalize on the value of flexibility. Rapid additions in wind and PV capacity, on the other hand will increase the value of flex.

Figure 11 illustrates for spike prices in Germany, how strong the effect of additional flexibility may be: We observe that spike prices mainly occur below a wind & PV generation below approx. 10 GW – indicating that with battery capacity around that size, we will quickly see those diminish.

Since the battery investment case comes with market risks, investors need to actively challenge long-term price forecasts and forecasts of battery revenues if they have no long-term capacity lease in place. It is key to understand the main drivers of such forecasts and to be able to perform sensible stress tests on the investment case.

Asset specific cash flows: For an overview on market developments, third party revenue forecasts are valuable as a first step. However, for investment models, a more specific view is needed. We suggest to perform a specific analysis for the own setup in terms of technical battery specification and potential additional local use cases. Effectively, this entails performing a granular optimization on historic prices and forecasts.

Doing this, we can also analyze the impact of technical parameters on return, for example, choosing a 4h instead of a 2h battery or of a restricting the maximum number of cycles. Having a battery optimization model in place, this is absolutely feasible and significantly increases transparency on the investment case.

[9] See, for example the Power Storage Agreement (PSA) between Steag Iqony and Deutsche Bahn: https://www.pv-magazine.de/2024/11/14/deutsche-bahn-schliesst-psa-fuer-200-megawattstunden-speicher-von-iqony or a similar agreement done by Vatterfall: https://group.vattenfall.com/press-and-media/pressreleases/2025/vattenfall-signs-agreement-to-optimise-large-scale-battery-park-in-the-netherlands

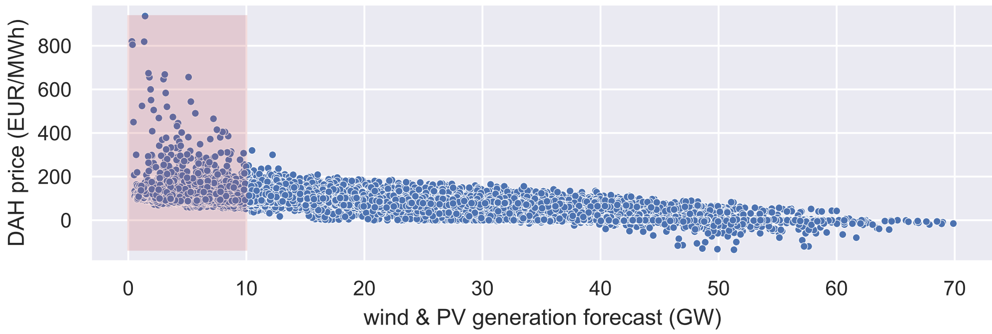

Figure 11: DAH prices against wind & PV generation forecast. Besides a trend of increasing prices at low wind & PV generation, we observe that spike prices mainly occur below approx. 10 GW. Hourly view for DE/LU, 1/2024-5/2025.

6 Building up capabilities – a journey, no magic

The main target of our paper is to show that capabilities required for a successful battery project need to be built up step-by-step. They are based on a solid understanding of battery economics and available markets as well as the process of how their value is actually generated.

The process in its full scope is complex – but it neatly breaks into building blocks that can be tackled one-by-one. We believe it is absolutely possible to develop valuation capabilities as part of the project development phase and to set up operations (if desired) within the time between investment decision and commissioning.

The important part is to get started and improve step-by-step. Where to start and where to focus on, naturally depends on the point of view: An investor will be more interested in understanding and developing a suitable business case and business model. An operator will face the challenge of benchmarking a trading service provider or to build up an own optimization team. By outlining all ingredients of the whole process and defining a benchmark monetization or trading strategy, we hope to have provided a solid starting point.

References

[1] Bundesnetzagentur. Monitoringbericht 2024. https://www.bundesnetzagentur.de, 2025.

[2] ENTSO-E. Bidding zone review of the 2025 target year. https://www.entsoe.eu, 2025.

[3] EPEX Spot SE. Annual trading results of 2024. https://www.epexspot.com, 2025.

[4] EPEX Spot SE. Company information. https://www.epexspot.com, 2025.

[5] L. S. et al. An algorithm for modelling rolling intrinsic battery trading on the continuous intraday market. *ACM SIGENERGY Energy Informatics Review*, 4(2), 2024.

[6] T. Pfingsten and D. Oeltz. EAO – a framework for optimizing decentralized portfolios and green supply. https://ssrn.com/abstract=3842822, 2021.

[7] regelleistung.net. German TSO portal on ancillary services. https://www.regelleistung.net, 2025.