SHORT STUDY

Grid utility of large-scale batteries

Grid impact of large-scale batteries today and instruments for grid-friendly behavior

This is a machine-translated version of a study originally published in German. The original is available at www.neon.energy/netzdienlichkeit-großbatterien

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Neon Neue Energieökonomik is an energy consulting firm based in Berlin. As a boutique firm, we have specialized in sophisticated quantitative and economic-theoretical analyses of the electricity market since 2014. Through consulting projects, studies, and training courses, we support decision-makers in addressing the current challenges and future issues of the energy transition. Our clients include governments, regulatory authorities, grid operators, energy suppliers, and electricity traders from Germany and Europe.

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Summary

Grid utility of large-scale batteries. Large-scale batteries will play a key role in electricity systems over the coming decades, particularly balancing electricity generation and consumption in the short term. The high level of interest in battery investments in Germany is therefore extremely encouraging. While the benefits of batteries for system balancing are undisputed, the effect of large-scale batteries on the grid is the subject of heated debate. Recently, intensive energy policy discussions have arisen on various topics related to the regulation of large-scale batteries, such as the allocation of grid connections, flexible connection agreements, technical connection conditions, grid fees, and building law privileges. The discussion often revolves around the question: How useful are large-scale batteries for the grid?

This article. This short study has three objectives. First, based on our definition that "grid utility is what reduces grid costs," we develop a practical methodology for quantifying grid utility by estimating the redispatch caused or avoided by a large-scale battery. Second, we calculate the grid utility of two specific battery projects in the 110kV grids of Schleswig-Holstein and Bavaria. Third, we discuss various approaches and instruments for increasing the grid utility of large-scale batteries.

Determining grid utility. Large-scale batteries create economic value on the electricity market by engaging in arbitrage transactions on the wholesale market and offering power on the balancing energy market. They also have a number of effects on the power grid, particularly on redispatch and grid expansion costs, which are collectively referred to as "grid utility." Depending on the situation, they can increase or reduce grid costs. We quantify these grid costs by comparing battery operation (charging, discharging, idle) for each quarter hour of the year with the regional redispatch demand in the grid to which the battery is connected (positive, negative, none). For example, if a battery feeds electricity into a grid area where there is already a surplus of electricity, the feed-in leads to additional curtailment of generators – in other words, the battery increases the redispatch demand. Conversely, it reduces the amount of redispatch when it draws electricity from the grid in this situation. Since both battery use and grid bottlenecks change dynamically, the grid is loaded in some quarter-hours and unloaded in others. We calculate the impact of a battery on total redispatch costs over the year from the individual quarter-hours. To do this, we use the actual redispatch of the grid operators in 2023 and 2024.

Grid impact today. Our calculations show that a large-scale battery relieves and burdens the grid with approximately equal frequency – around 20% of the quarter-hours in each case (in the remaining 60% of the time, either the battery is idle and/or the grid is free of congestion). From a financial perspective, the battery reduces redispatch costs over the course of the year, even if the contribution is small. This applies to both locations examined, in the south and north of the country: According to our calculations, grid operators save redispatch costs of around €3-6 per year for each kW of battery capacity. In this sense, large-scale batteries should by no means be classified as a burden on the grid, even if this is sometimes suggested in the energy policy debate.

Instruments for strengthening grid utility. There are no regional prices in the German electricity market design. Batteries (like all other systems) are therefore guided by the uniform German price signal on wholesale and balancing energy markets. Grid bottlenecks are not priced and are therefore not visible to batteries. The positive effect on grid congestion is therefore purely coincidental and much smaller than it could be. In order to "get the most out of batteries," we are therefore investigating three regulatory approaches to strengthening grid utility:

- A static grid fee, i.e., a working price for withdrawals from the grid and a fixed annual capacity price
- A dynamic constraint, which we understand to mean a ban on grid-straining operation
- A redispatch price signal, i.e., a variable energy price per quarter hour for withdrawal and feed-in depending on the redispatch situation, which could be implemented, for example, as a special battery grid fee

Results. The picture is clear: although the static grid fee generates revenue for grid operators, it makes the battery *less* useful to the grid because it increases redispatch costs. It also significantly limits the value added by the battery on the electricity market. A dynamic constraint strengthens the grid utility of the battery but causes even greater collateral damage to market operations. The dynamic redispatch price signal is clearly the best of the three instruments examined: it creates both the greatest grid added value and the least loss of market added value. According to our estimates, a battery reduces redispatch costs by around €50 per year per kW of installed capacity.

1 Introduction

Growing investment. In recent years, there has been a remarkable surge in investment in large-scale batteries. This is particularly evident in the large number of grid connection requests, which now total several hundred gigawatts across Germany. This development is primarily driven by the rapid decline in battery cell prices and attractive market opportunities: high revenues on the balancing energy markets and increasing price spreads on the wholesale market as a result of the strong expansion of solar energy in particular. It is noteworthy that, unlike almost all other technologies in the electricity system, large-scale batteries receive neither direct subsidies nor protection against market price risks. This opens up the opportunity to base the restructuring of the electricity system not exclusively on government subsidies, but also on market dynamics.

Systemic role of large-scale batteries. Large-scale batteries already perform key tasks in the electricity system, such as providing balancing power and compensating for short-term forecast errors in wind and solar energy via intraday trading. In the medium term, large-scale batteries will continue to gain in importance and also contribute to security of supply by absorbing generation peaks and providing electricity for peak loads. Their contribution is also crucial because alternative flexibility resources such as bidirectionally charging electric cars or flexible industrial demand are developing more slowly than hoped.

Between the market and the grid. Some critics argue that large-scale batteries optimize themselves on the market "at the expense of the grid." In fact, battery storage systems today are based exclusively on market prices—regardless of local grid bottlenecks. However, this is not due to ignorance on the part of operators, but rather to the design of the German electricity market: in the uniform price zone, there is currently no provision for bottlenecks to be reflected in market prices. This system logic therefore affects all market players, not just storage facilities. Since grid bottlenecks are not priced, all players in the electricity market are blind to the grid.

Grid utility. Against the backdrop of a large backlog of grid connection requests and regulatory and energy policy debates on grid fees and price zones, an intense discussion has arisen about the impact of large-scale batteries on the power grid. The discussion often hinges on the question of whether batteries are "grid-friendly," i.e., whether they have an overall relieving effect on the power grid.

Aim of this short study. We have three objectives with this short study. First, we develop a definition of grid utility and a methodological approach to quantifying the grid impact based on the effect of batteries on redispatch demand. Second, we determine the grid impact of a specific large-scale battery, the 100 MW battery from ECO STOR in Bollingstedt, Schleswig-Holstein, which went into operation this year. We also evaluate a second, hypothetical plant of the same design with a grid connection in Plattling, Bavaria. Third, we discuss three approaches and instruments for relieving the burden on the electricity grids and quantify them in terms of their grid impact: a static grid fee, a dynamic guard rail, and a redispatch price signal.

2 Analytical framework

In this section, we discuss the welfare effects of large-scale batteries in the market and grid, develop a definition of grid utility, and explain our quantitative approach.

2.1 Welfare effects of large-scale batteries

Wholesale. Large-scale batteries create economic value in the electricity market and in the grid. In the day-ahead and intraday markets, batteries create added value through arbitrage. For example, if a battery stores wind power that would otherwise be curtailed at a price of €0/MWh and later releases it at €100/MWh in a situation where a gas-fired power plant is the marginal power plant, it has created added value equal to the difference. This added value consists specifically of lower gas consumption, lower CO2 emissions, and no wear and tear from starting up the gas-fired power plant.

Balancing power. If a large-scale battery provides balancing power, it replaces a thermal power plant that is no longer forced to produce electricity continuously as a must-run plant. Here, too, the economic added value materializes in the form of lower fuel consumption. The added value created on the market accrues to the battery as revenue.

Welfare effect of a large-scale battery (illustrative)

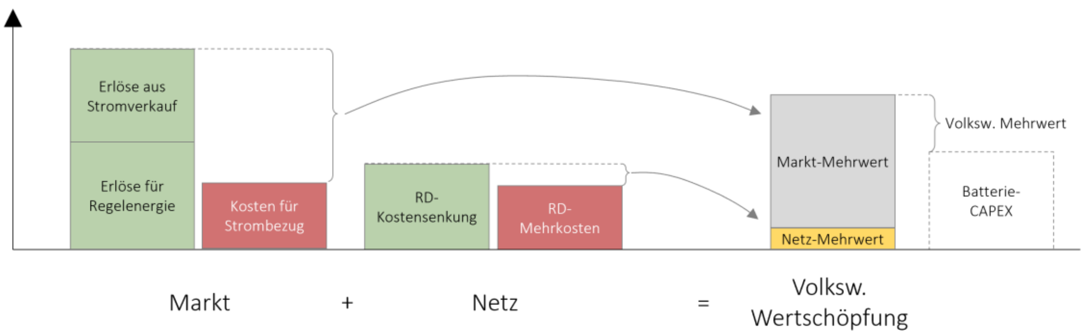

Figure1 : The difference between revenues and costs on the market results in market added value. Cost reductions or increases in the grid result in grid added value (which can also be negative). The sum of these two values results in economic value added. If this exceeds the investment costs of the battery (CAPEX), the project makes economic sense.

Grid. However, a large-scale battery—just like producers or consumers—also has an impact on the grid, i.e., an effect on redispatch and grid expansion requirements. A battery can then increase or decrease the costs of redispatch, so the grid added value can be negative or positive. However, a key difference is that the grid costs are invisible to the battery because grid bottlenecks are not priced in the unified German electricity market. In economic terms, grid costs are therefore externalities. However, this does not make them any less real: both components – market and grid contribution – are equally important components of overall economic welfare (Figure1).

2.2 DEFINITION OF GRID UTILITY

Diversity of terms. There are numerous terms and classifications relating to grid utility. These include, for example, the traffic light system used in the Stromgedacht app from TransnetBW ("super green" for local electricity surpluses, "orange/red" for shortages), the NRV balance traffic light with the colors "green," "orange," "red," and "blue," and the categories "grid-burdening" (formerly "grid-effective"), "grid-neutral," and "grid-friendly" for storage operations. There is no generally accepted definition of "grid utility." We therefore present our understanding of grid utility in this section, consisting of a more abstract qualitative definition followed by a concrete proposal for quantifying the grid impact of large-scale batteries.

Definition. We propose the following abstract definition of grid utility: "A grid user is serviceable for the grid if they reduce grid costs." This definition applies to storage facilities, but also to generators and consumers.

Effects on the grid. Large-scale batteries affect the grid and thus grid costs in various ways, e.g., on local voltage. However, by far the most important effect in financial terms is likely to be their impact on load flow, i.e., on bottlenecks in the power grid. Bottlenecks in the distribution or transmission grid are remedied by redispatch measures.

Operationalization of the definition. To make our abstract definition usable and quantifiable, we therefore reduce it to the influence on redispatch. For this study, we therefore consider a system to be grid-friendly if it reduces redispatch costs. A battery can reduce, increase, or leave the need for redispatch unchanged. For the definition, it is irrelevant whether the grid effect occurs by chance or whether grid-friendly operation was explicitly brought about by appropriate incentives. This effect must be considered separately for each quarter hour because both the grid situation and battery operation change every quarter hour. If a battery reduces the need for redispatch in a quarter hour, we call it "relieving" the grid; if it has the opposite effect, we call it "burdening" the grid; if it has no effect, we call it "neutral."

Redispatch. If no power grid line is operating at its capacity limit, the grid is free of bottlenecks and grid operators do not need to take any redispatch measures. However, this is often not the case and grid bottlenecks occur. Grid operators then activate positive redispatch in regions with electricity shortages, i.e., they start up additional power plants. At the same time, generation plants in regions with electricity surpluses are shut down, e.g., wind farms are curtailed. This is negative redispatch. An increase in electricity consumption has the same effect on the grid as a reduction in electricity generation. The congestion situation changes dynamically, so that positive redispatch may be necessary in a region where generators had been curtailed shortly before.

Battery operation. If a battery draws power from the grid while negative redispatch is required in the region, it reduces the load on the grid. Drawing power from the battery allows local surplus power to be used and avoids curtailment of generation plants. Conversely, drawing power from the battery puts a strain on the grid if positive redispatch is required in the region, as more power plant capacity must then be ramped up. There are a total of nine possible combinations of battery use (charging, discharging, standstill) and redispatch requirements (positive, negative, none) in which battery operation either relieves, burdens, or has no effect on the grid (Figure2).

Grid impact of a storage facility

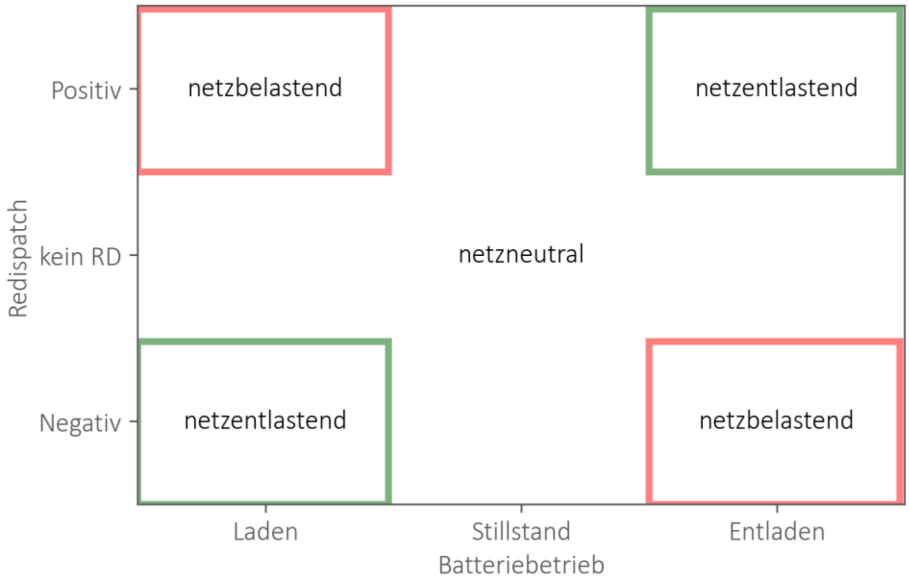

Figure2 : Grid impact of a storage facility depending on battery operation and local redispatch demand.

Average view. The influence of battery use on redispatch demand can change dynamically: a battery that has just relieved the grid may burden it a short time later. This is because both battery operation and grid status change every quarter hour. Most batteries will therefore neither always burden the grid nor always relieve it. We therefore consider how often a battery relieves and burdens the grid over all 35,000 quarter-hour periods in a year. A battery that has a more relieving than burdening effect over the course of a year is also referred to as tending to be grid-friendly.

Redispatch vs. grid expansion. Structural grid bottlenecks can be addressed through redispatch or grid expansion. Expanding the grids, e.g., with more powerful transformers or lines, only makes economic sense if the necessary investment costs are lower than the redispatch costs that would otherwise be incurred. Otherwise, it is cheaper to continue to relieve the grid through redispatch measures. For this reason, a battery that reduces redispatch demand can delay or even completely avoid grid expansion in the long term. With an efficient level of grid expansion, the grid is only expanded if the associated savings from lower redispatch costs exceed the investment costs. In this case, the "saved redispatch costs" we have determined can also be interpreted as "saved grid expansion costs."

Other technologies. The approach we propose for assessing the grid utility of batteries can in principle also be applied to other technologies, e.g., generators and consumers. In this case, the grid impact can often be easily estimated without further calculation: In a scarcity region with predominantly positive redispatch demand (e.g., in southern Germany), conventional power plants almost always relieve the grid or are grid-neutral, while consumers tend to burden the grid. In surplus regions with a lot of curtailment (e.g., in northern Germany), additional consumers such as electrolysers tend to have a grid-friendly effect, whereas additional generators, e.g., wind turbines, usually exacerbate grid bottlenecks. Since batteries both draw and feed in electricity and also provide substantial balancing power, assessing their grid benefits requires more extensive empirical calculations.

Limits of redispatch. Our definition of grid utility focuses on the effect of battery use on redispatch requirements. We assume that every MWh of battery power has a direct impact on redispatch. However, we neglect the fact that not every battery behavior can be remedied by redispatch or prevent redispatch. For example, if the battery only executes a trade shortly before the end of continuous intraday trading, which exacerbates grid congestion, transmission system operators do not have enough time to activate the necessary redispatch measures. Similarly, short-term battery use to reduce congestion has no effect on redispatch requirements, as the corresponding redispatch process was requested several hours in advance and cannot usually be canceled.

Other aspects. Other aspects of battery operation also play a role in ensuring secure grid operation and system stability. In particular, the rapid response and ramping capabilities of batteries can contribute to power quality, but also pose challenges for grid operation. These include, for example, local voltage maintenance, which is made more difficult in some distribution grid areas by frequent switching between feeding into and drawing from the battery. In addition, large-scale batteries already offer valuable system services today, such as balancing energy in particular. However, since batteries are remunerated for this by existing and functioning markets, we do not take the corresponding benefits into account when calculating the grid impact, but instead add them to market revenues.

Generalization. The definition of grid utility proposed and used here is by no means the only conceivable and meaningful definition. Grid utility could also be defined more generally as "the effect on the total costs of German grid operators" – a battery would then be considered serviceable for the grid if it ensures that grid fees are reduced. However, in this study, we understand grid utility to mean the effect on redispatch costs. Our approach is thus compatible with other cost-based definitions, such as that of the FfE, which also focuses on the effect on grid costs.

2.3 Approach to quantifying the grid impact

Procedure. We determine the influence of a large-scale battery on redispatch costs in two steps (Figure3). First, we simulate quarter-hourly battery operation based on optimization, i.e., the marketing of the battery on day-ahead, intraday, and balancing energy markets, as well as the resulting physical use of the battery. In the second step, we compare this battery operation with regional redispatch requirements to determine how storage operation affects them.

Approach to quantifying the grid impact

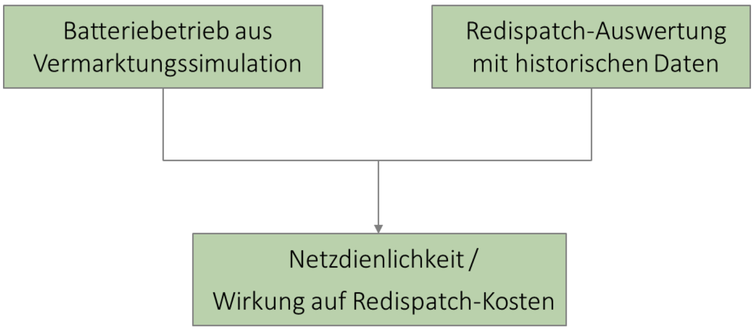

Figure3 : Two-step approach to quantifying the grid impact in this study.

Time resolution. The native time resolution of the European electricity market is 15 minutes. This means that battery use (schedules, balancing group settlement) and redispatch are also determined and settled in 15-minute intervals. We therefore also consider the grid impact of the battery in 15-minute intervals. This simplified approach ignores the fact that battery use and grid utilization also vary within a quarter of an hour.

Frequency. Based on the two 15-minute time series – battery use and regional redispatch – we calculate how often, i.e., in how many 15-minute periods per year, the battery increased redispatch and how often it reduced redispatch.

Financial evaluation. We calculate the grid added value of the battery based on the size and sign of the energy flows and the redispatch costs. In doing so, we take into account the amounts of energy fed in and withdrawn and the asymmetry in redispatch costs: Positive re-dispatch (starting up power plants) is generally more expensive per MWh than negative redispatch (curtailing renewable energy plants). This is how we calculate the influence of the battery on redispatch costs per year. This value allows a comparison with the market added value and thus a weighing up of market-oriented and grid-oriented operation, enabling an economically efficient resolution of the potential conflict of interest between battery operators and grid operators.

3 Grid impact of batteries today

In this chapter, we quantify the grid impact using the example of two large-scale batteries in northern and southern Germany. For both locations, we simulate their use under the current regulatory framework without specific restrictions or flexible connection contracts.

3.1 Simulation of battery operation

Locations. The first location we examined is the ECO STOR battery storage facility in Bollingstedt, which went into regular operation on the 110 kV high-voltage grid in April 2025 and is one of the largest projects implemented in Germany. The location in Schleswig-Holstein is in a region with high wind energy production. For comparison, we also consider a hypothetical project in Plattling (Bavaria), which would be located in a distribution grid with a high feed-in of solar power.

Battery parameters. Regardless of the location under consideration, the large-scale battery in Bollingstedt is used as the basis for simulating battery operation. It has an installed capacity of 103.5 MW and an effective usable capacity of 220 MWh. We assume charging and discharging losses of 5%, and operation is limited to a maximum of 2.2 cycles per day and a maximum of 550 cycles per year. However, we do not consider any restrictions in the form of maximum permitted ramps during operation.

Marketing. The battery operation was provided by ECO STOR for this study. It is based on a quarter-hourly simulation of the marketing of the storage facility using historical market prices for the year 2024. To this end, a step-by-step model-based approach is used to run through the times of the auctions for balancing power and in electricity trading, and the use of the battery is optimized on the basis of forecasts. The battery is marketed simultaneously and optimally across all relevant market segments with limited foresight: day-ahead auctions, intraday auctions, continuous intraday trading, frequency containment reserve (FCR), and automatic frequency restoration reserve (aFRR). This takes into account the fact that the provision of balancing power limits the battery capacity for other markets. The result of the simulation is the marketing per segment, revenues, and the quarter-hourly physical battery operation (charging/discharging in MW). The local grid situation naturally plays no role in the optimization, so that the result of the battery simulation is location-independent – the plants in Bollingstedt and Plattling behave identically.

Result of battery operation. On most days, optimized battery operation has a distinct pattern with two cycles: the battery charges at night, discharges in the morning, then charges again at noon and discharges again in the evening (Figure4). This reflects the typical price trend over the course of the day, which is characterized by the usual fluctuations in demand and solar power generation, which regularly lead to changes in the residual load of 50 GW and more during the course of the day. Wind power and seasonal fluctuations in demand cause different price levels (higher prices in cold, windless weeks), but typically maintain the pattern over the course of the day because they fluctuate less within a single day. The maximum output of the battery of around 100 MW is only called upon relatively rarely, e.g., during individual evening hours. This is because a large part of the output is marketed as balancing power (up to 80%) and is not available for trading.

Location-independent battery operation in 2024

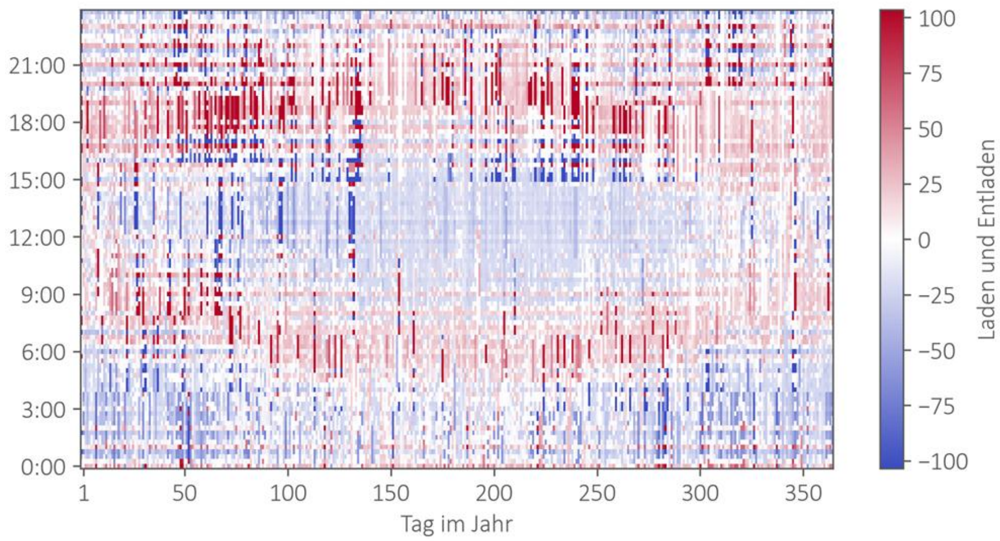

Figure4 : Operation of the battery optimized for trading and control power for the year 2024 (location-independent). Two cycles per day can be seen, with charging at night and at midday, and discharging in the morning and evening.

3.2 REDISPATCH DEMAND

Locations. Battery operation has an impact on local redispatch demand. To illustrate this, we consider two example storage locations: Bollingstedt in Schleswig-Holstein (in the grid area of the distribution system operator Schleswig-Holstein Netz) and Plattling in Bavaria (Bayernwerk Netz). The Bollingstedt location is representative of northwestern Germany, where the distribution and transmission grids are dominated by wind energy and strong winds often lead to electricity surpluses, requiring wind farms to be curtailed. There, the large-scale battery can absorb additional electricity from both the distribution grid and the transmission grid, thereby preventing redispatch. The second location in Plattling represents the southern German perspective and is thus on the other side of the frequent north-south bottleneck in Germany. Redispatch measures in the transmission grid there typically involve ramping up conventional power plants. At the distribution grid level, on the other hand, curtailments also occur regularly during the summer months due to high PV feed-in.

Data basis. We use the publications of the transmission system operators on Netztransparenz.de and the completed congestion management measures of the distribution system operators SH Netz and Bayernwerk Netz as the data basis for redispatch. The published redispatch measures are plant-specific and are further processed by us.

Spatial aggregation. For the impact on the transmission grid, we assume that congestion occurs over a large area and that redispatch measures in the Schleswig-Holstein, Lower Saxony, and North Sea (offshore wind farms) regions are identical in terms of their load flow sensitivity. This applies, for example, to the north-south congestion in Germany. Accordingly, we aggregate all redispatch measures from plants in these regions and assume that 1 MW of battery operation in the event of redispatch also changes it by 1 MW. For the location in the south, we aggregate the redispatch measures in Bavaria and Baden-Württemberg in the same way.

Transmission grid. Figure5 shows the redispatch demand caused by grid congestion in the transmission grid in the regions of the two locations. In northwestern Germany, redispatch occurs in half of all quarter-hours. This is predominantly negative (40%), but sometimes also positive (9%). Redispatch does not follow a daily cycle, but there is a visible seasonal pattern with more redispatch in winter. The individual phases of high redispatch demand often last several days. The seasonality and duration can be explained by the fact that redispatch is strongly influenced by wind conditions. In the south, on the other hand, positive redispatch (41%) is mainly required during these periods. Negative redispatch (6%), which is rarely used, is distributed around midday and occurs more frequently in summer.

Redispatch in the transmission grid in the northwest (left) and south (right)

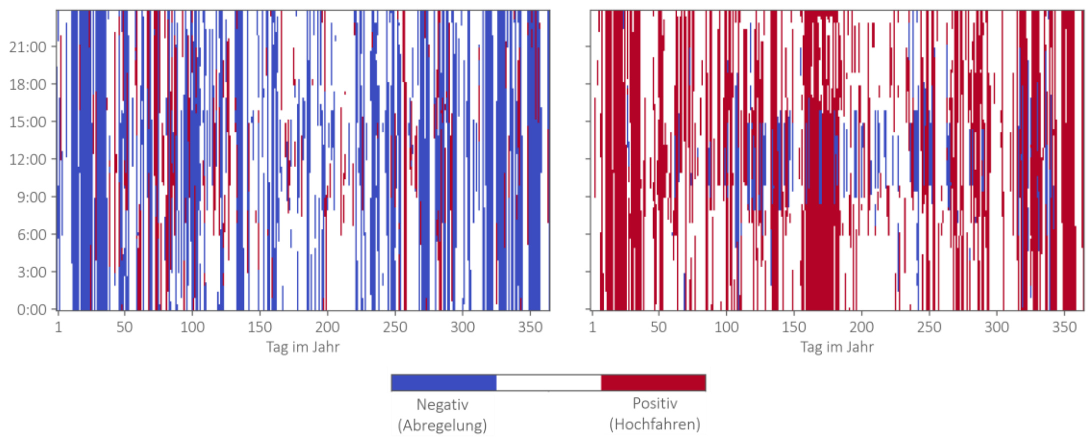

Figure5 : Redispatch demand at the transmission grid level in 2024. In the northwest (left), redispatch occurred in around half of all quarter-hours, the majority of which (around 40% in total) was curtailment. In the south (right), on the other hand, power plants were ramped up in around 41% of all quarter-hours.

Distribution grid. Redispatch is necessary not only because of bottlenecks in the transmission grid, but also in the distribution grid. For this purpose, we aggregate redispatch caused by the distribution grid per substation. Redispatch is necessary time and again at both locations, but to a much lesser extent than in the transmission grid (Figure6). At the Bollingstedt site, curtailment is necessary in approximately 2% of all quarter hours. In Plattling, redispatch is slightly more frequent, accounting for around 5%. This is almost exclusively PV-related curtailment around midday during the summer months. Distribution system operators usually only shut down generation plants, which is why no positive redispatch is reported.

Redispatch in the distribution grid for Bollingstedt (left) and Plattling (right)

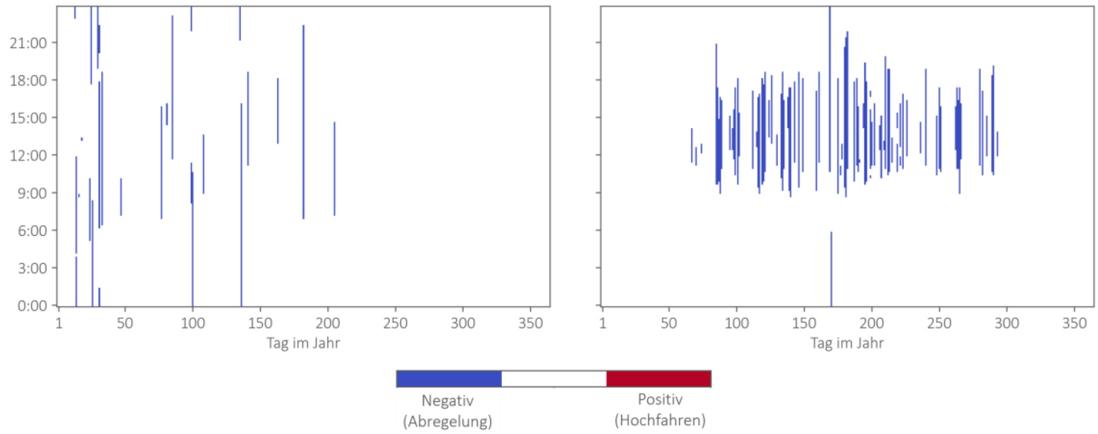

Figure6 : At the Bollingstedt site (left), there were curtailments in around 2% of quarter-hours in 2024, triggered by bottlenecks in the distribution grid. The curtailments mainly occurred in the windy first half of the year. In Plattling (right), there was more curtailment (5%). Curtailment occurred mainly at midday in the summer, when high PV feed-in put strain on the grid. No positive redispatch was activated in either grid area.

3.3 DETERMINING THE GRID IMPACT

Grid impact. Comparing battery operation and redispatch time series makes it possible to determine the periods during which the battery loads or unloads the grid.Figure7 shows the frequency of these states for the two locations considered in northwestern and southern Germany. In the north, the proportion of quarter-hours during which the grid is relieved is around 24%, while the proportion during which it is loaded is around 20%. The battery therefore relieves the grid slightly more often than it loads it. In the south, it is the other way around: here, relief in 21% of quarter-hours is offset by a load in 22%. Batteries in both the north and south therefore place a load on the power grid in individual quarter-hours – but in other quarter-hours they relieve it. Calculated over the year, both situations occur with virtually equal frequency. It is therefore not the case that batteries can generally be described as beneficial or detrimental to the grid. Nor is it the case that batteries in the north (or south) have significant differences in their grid impact over the course of a year. In this sense, there is no such thing as a "grid-friendly battery location."

Periods of grid relief and strain in the northwest (left) and south (right)

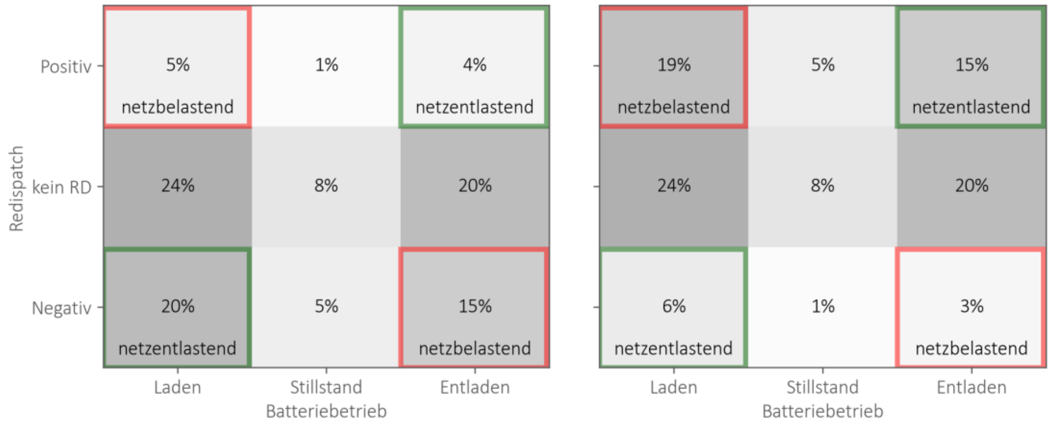

Figure7 : In 2024, a market-operated battery in northwestern Germany relieved the power grid 24% of the time and burdened it 20% of the time. In southern Germany, the relief of 21% is slightly below the burden of 22%. Overall, the periods of grid relief and burden largely balance each other out.

Explanation. This result can be explained by the interaction of battery operation and redispatch patterns. Due to the typical daily patterns of electricity consumption and solar generation, the battery often runs two cycles per day: night-morning and noon-evening. Redispatch demand, on the other hand, often depends on wind feed-in, whose fluctuations are more long-lasting. Redispatch demand often lasts for many hours or even several days, after which the transmission grid is free of congestion again for a longer period of time. During a windy day with curtailment demand in northwestern Germany, the battery relieves the grid when charging at night and at midday because it absorbs excess electricity that would otherwise have to be curtailed. In the morning and evening, the grid feed-in causes additional curtailment in the region. Overall, phases of grid load and relief largely balance each other out.

3.4 Economic assessment

Economic assessment. A benefit for the grid arises when the need for redispatch is reduced by battery operation. To estimate the financial implications, we assume average costs of €100/MWh for positive redispatch and €80/MWh for negative redispatch. From this, we calculate the redispatch costs saved per year. To do this, we assume a marginal influence of battery operation on the congestion. The savings in redispatch represent the added value for the grid and can be offset against the market added value, which consists of market revenues from electricity trading and for control power.

Redispatch change.Figure8 shows the prevented and additional redispatch costs caused by battery operation. In the north, around €44/kW (per year) can be saved in the quarter-hours with grid-relieving battery operation. The additional redispatch requirement due to grid-burdening operation, on the other hand, costs €38/kW, resulting in a grid added value of around

€6/kW. Despite more grid-burdening quarter-hours, large-scale batteries also have a benefit in the south, although at €3/kW this is slightly lower than in the north.

Redispatch change

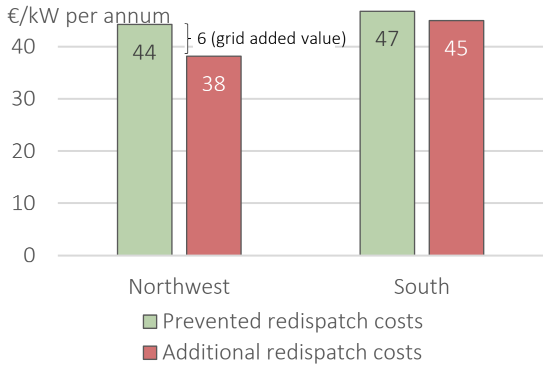

Figure8 : Redispatch change in the operation of large-scale batteries in the north and south. There is a slight decrease in net redispatch costs at both locations. However, prevented and additional redispatch are similarly high.

Economic value added

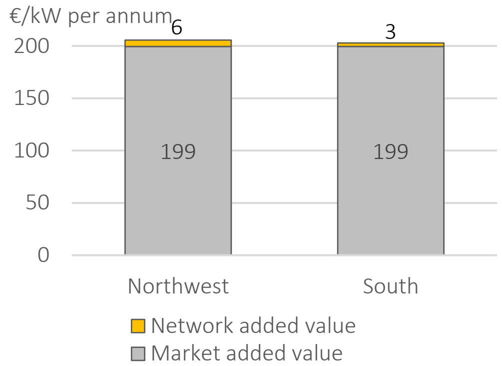

Figure9 : The economic value added by large-scale batteries consists of the added value for the electricity markets (trading and balancing power) and the added value for the grid. The added value for the electricity markets clearly outweighs the added value for the grid.

Economic value added. The positive benefits for the grid arise even though battery operators receive no financial incentive for grid-friendly behavior and respond exclusively to (Germany-wide) market signals. The benefit for the grid is therefore purely coincidental and not systematic. In comparison, the added value achieved on the market, which is remunerated to battery operators in the form of market revenues, is orders of magnitude higher than the added value for the grid at €199/kW (regardless of location) (Figure9). As a pure externality, the latter represents only a very small economic benefit.

3.5 Bottlenecks in the Distribution Grid

Grid levels. Bottlenecks can occur in the transmission or distribution grid. A battery therefore has an independent effect on bottlenecks at both grid levels. The evaluation of the grid effect by grid level (Figure10) shows differences between locations in the north and south. In the north, the grid effects on the transmission grid and distribution grid are similar and simultaneous, as wind energy is primarily curtailed at both levels. Overall, the battery has a slightly beneficial or neutral effect on the grid here. In the south, on the other hand, the levels differ more significantly: additional feed-in is required in the transmission grid, while in the distribution grid, PV systems in particular are curtailed at midday. In the distribution grid in particular, battery storage systems behave in a manner that is beneficial to the grid and can reduce grid bottlenecks, as they store energy at this time due to favorable wholesale prices. In the transmission grid, on the other hand, the effect tends not to be beneficial to the grid. However, since the redispatch requirement in the transmission grid is significantly greater overall at both locations than in the distribution grid, its influence on the overall effect predominates.

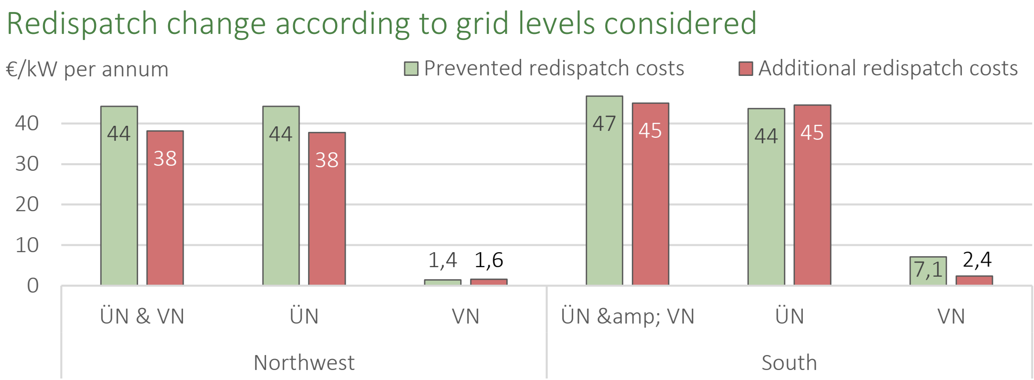

Figure10 : Redispatch change in the operation of the large-scale battery in the north and south in the transmission and distribution grid. Due to the many bottlenecks, the grid effect is significantly higher in the transmission grid. The grid benefit is not the sum of the grid effects at the transmission and distribution grid levels, as the battery can have the opposite effect on grid bottlenecks in the distribution and transmission grid within a quarter of an hour, for example.

Generalization of the results. The analysis shows that the effect of large-scale batteries on bottlenecks in the distribution grid depends on the specific design and load/generation structure of the respective grid. Qualitatively, four typical characteristics can be distinguished:

- Type 1: Classic load grids – e.g., urban grids with congestion during high evening or midday loads. In these grids, batteries are likely to have a relieving effect due to the correlation between load and electricity prices throughout the day.
- Type 2: Solar-dominated grids, in which there is also design-relevant feed-back at midday. Here, batteries are likely to have a relieving effect, as our modeling shows (Plattling location).
- Type 3: Wind-dominated grids with feed-back bottlenecks during strong winds. Because wind generation and daily price profiles are largely uncorrelated, the grid effect here tends to be neutral on average, as our modeling also shows (Bollingstedt location).
- Type 4: Future grids dominated by flexible loads that respond to the electricity price (including large-scale batteries). If batteries already dominate a grid, further investments in batteries are likely to place an additional burden on the grid.

3.6 SENSITIVITIES

Sensitivities. To examine the robustness of the grid impact of large-scale batteries, we also consider two sensitivities. First, we repeat the analysis using market prices and redispatch from 2023. We then test the influence of different marketing strategies for large-scale batteries.

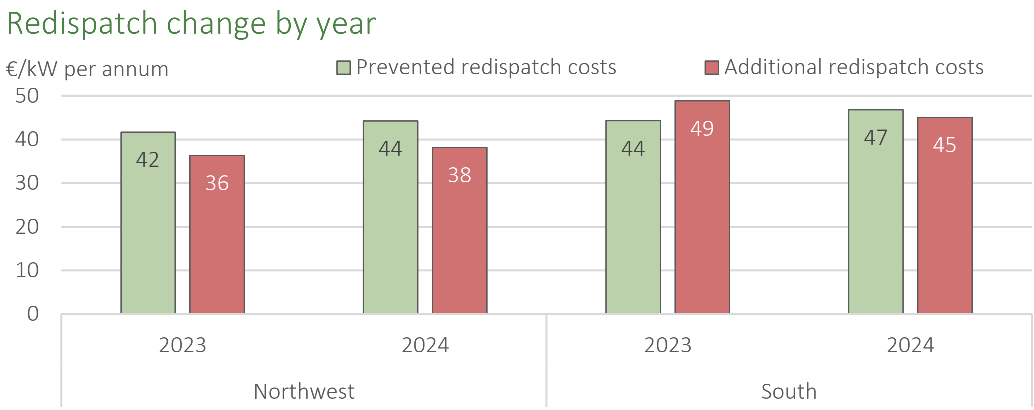

Figure11 : Redispatch change in large-scale battery operation in the northwest and south in 2023 compared to 2024 (reference). In the northwest, the changes in redispatch are similar at a slightly lower level. In the south, however, battery operation leads to a net increase in redispatch.

Redispatch change in 2023. The grid utility of the large-scale battery also appears to be largely robust in 2023 compared to the 2024 reference (Figure11). In the northwest, the redispatch change remains virtually unchanged. Both the prevented and additional redispatch decrease by €2/kW to a slightly lower level. In the south, on the other hand, the balance shifts slightly into negative territory: since significantly fewer redispatch measures were required in the distribution grid in Plattling in 2023, the slight grid-loading effect at the transmission grid level prevails.

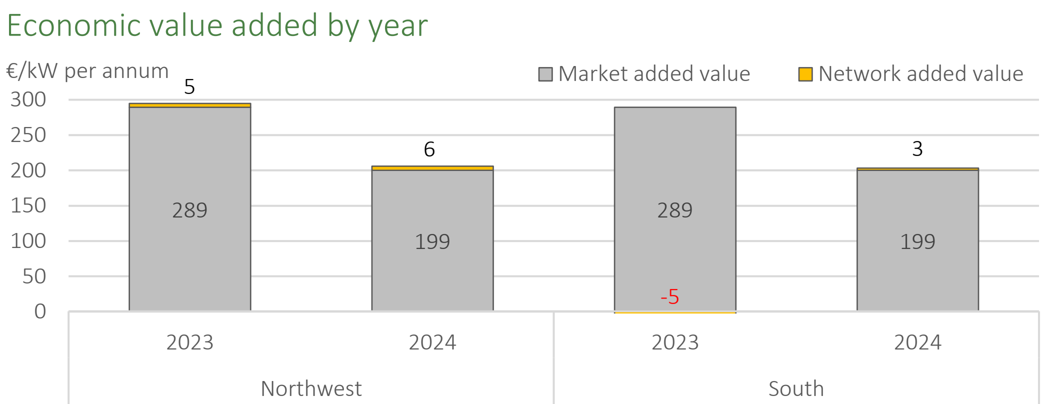

Figure12 : Economic value added from the operation of the large-scale battery in the northwest and south in 2023 compared to 2024 (reference). Value added is almost entirely determined by market revenues. The decline in these revenues in 2024 due to falling balancing power prices outweighs the added value to the grid. The slightly negative added value to the grid in the south is therefore of little economic significance.

Economic value added in 2023. The structure of the economic value added of the large-scale battery will also remain almost entirely determined by the market added value in 2023 (Figure12). Higher balancing power prices will lead to higher market revenues (€289/kW). The grid added value in the northwest is slightly positive and in the south slightly negative. From an economic perspective, however, the grid effect—both positive and negative, regardless of location—remains negligible.

Marketing strategies. All results shown are based on a reference scenario (DA+ID+RL) that reflects the current market practice for marketing battery storage systems – consisting of participation in day-ahead and intraday auctions, continuous intraday trading, and the provision of control power (FCR and aFRR). However, since the control power market is significantly smaller than the energy trading markets and is likely to come under increasing revenue pressure in the future as the number of large-scale batteries increases, the day-ahead market in particular appears to be a robust marketing option in the long term. Against this backdrop, we are investigating how alternative marketing strategies – such as pure day-ahead marketing (DA) or a combination of day-ahead and intraday trading without participation in the balancing power market (DA+ID) – can affect the grid-friendly operation of the battery.

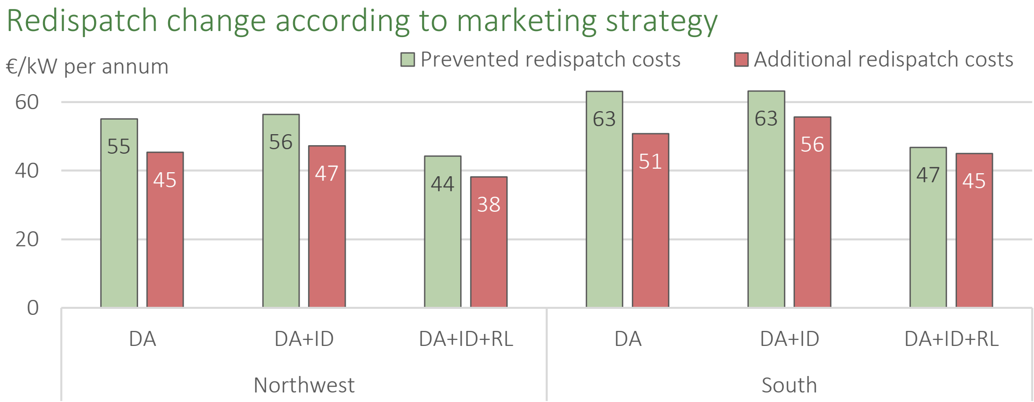

Figure13 : Redispatch change in the operation of the large-scale battery in the northwest and south depending on the marketing strategy. All marketing strategies considered lead to a net cost reduction from redispatch. The provision of balancing power (RL) leads to less energy throughput of the battery, which means that the impact on redispatch is lower compared to pure electricity trading in the day-ahead (DA) and intraday (ID) markets.

Electricity trading. If the battery is not used to provide balancing power but only for electricity trading, the amount of energy physically stored increases. This also means that battery operation occurs more frequently during periods of redispatch demand, causing this demand to rise. This is illustrated by the higher changes in redispatch costs for marketing strategies without balancing power (Figure13).

Conclusion. Although the market revenue of the battery depends on the chosen marketing strategy (as well as on the year), the effect on the grid is remarkably robust (Figure14). With all the marketing strategies considered, there is a slight net redispatch cost saving (grid added value) in both the north and the south. However, measured in terms of market added value, the added value of large-scale batteries in the grid is currently negligible (albeit positive). This applies even in the case of pure day-ahead marketing, in which less than half of the revenues generated by current marketing practices can be achieved.

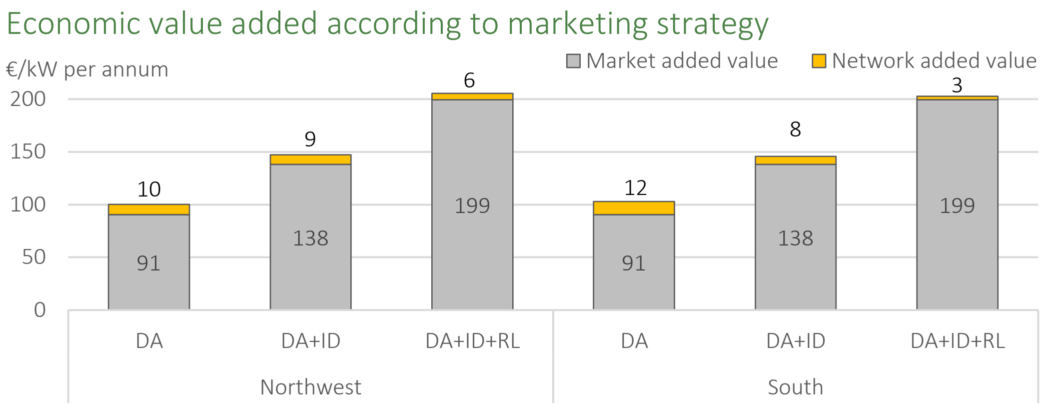

Figure14 : Economic value added from operating the large-scale battery in the northwest and south depending on the marketing strategy. The value added is almost entirely determined by the marketing strategy. If a battery is marketed in balancing power, the market added value is almost twice as high as with pure day-ahead marketing. The grid added value is significantly lower.

4 Instruments for grid-friendly behavior

Instruments. According to our analyses, large-scale batteries already reduce redispatch costs and thus relieve the burden on the power grid, but this contribution is small – and smaller than it could be. The Germany-wide electricity market without local signals offers no systematic incentives for grid-friendly behavior. How can we get the most out of batteries and promote grid-friendly behavior through targeted incentives? In this section, we examine three different approaches and evaluate their potential for improving grid utility compared to the status quo (Table1).

Table1 . The modeled cases with the status quo as a reference and three instruments examined

Case	Description	Amount
Status Quo	-	-
Static grid fee	Working price for withdrawal from the grid and fixed annual capacity price	5.5 ct/kWh €16.2/kW p.a.
Dynamic constraint	Prohibition of grid-loading operation	-
Redispatch price signal	Quarter-hourly variable working price for withdrawal and feed-in depending on the redispatch situation	For grid consumption: -8 ct/kWh (negative redispatch), 0 ct/kWh (no redispatch), 10 ct/kWh (positive redispatch) (Reverse signs for feed-in)

4.1 Instruments examined

Static grid fee. The grid fee model predominantly used today is based on a constant working price and an annual capacity price. Large-scale batteries have been exempt from this model to date. As a first step, we are applying this system to battery operation on a trial basis. This shows that the working price is payable when the battery is charged—i.e., at the point in time when it draws energy from the grid. This arrangement has two major disadvantages. First, it significantly reduces the economic efficiency of the battery and thus lowers the achievable welfare – which is also reflected in lower grid fee revenues in the long term. Second, our simulation shows that the energy price has little influence on the grid-friendly behavior of the battery. From an economic perspective, this is therefore an inefficient and distorting price signal that fails to achieve the desired steering effects and is not recommended from a regulatory point of view. For the analysis, we assume a uniform energy price of 5.5 ct/kWh, based on the current transmission grid price, as the values at the distribution grid level vary greatly from region to region and from year to year. In addition, we take into account an annual power price of €16.2/kW (RLM tariff, SH Netz), which is paid to the grid operator but has no influence on the operational mode of the battery. Adjustments to the dimensioning of the battery due to the power price are not considered in the model.

Dynamic constraint. The dynamic constraint is a regulatory instrument that prohibits the grid-loading operation of large-scale batteries without actively rewarding grid-friendly behavior. Specifically, every quarter of an hour, a check is made to see whether there is a redispatch requirement in the transmission or distribution grid at the planned location. If there is a bottleneck, the battery must not be operated in a way that would exacerbate it. If there are conflicting signals between the grid levels, the signal from the lower-level distribution grid is given priority. In our modeling, this rule means that the battery is restricted in one direction (charging or discharging) for about half of the time. The operator receives information about any restrictions the day before, so that the schedule can be adjusted accordingly, especially in the balancing power market. It is important to note that grid-friendly behavior in the opposite direction is not remunerated. Outside of the restrictions, the battery continues to optimize itself entirely according to market conditions. The dynamic constraint thus primarily acts as a protective instrument for the grid, but not as an active incentive system for grid-friendly behavior.

Redispatch price signal. The redispatch price signal is a dynamic, economically oriented instrument for the targeted promotion of grid-friendly behavior. Unlike the dynamic constraint, it does not rely on restrictions, but on economic incentives: if there is a positive redispatch requirement, the electricity price at the affected location increases by €100/MWh; if there is negative redispatch, it falls by €80/MWh. This creates a financial incentive for storage facilities to act in a targeted manner that benefits the grid in bottleneck situations – for example, by discharging when there is positive redispatch demand or by avoiding storage at these times. The price signal specifically changes the existing market signal in the direction of grid-friendly operating modes without restricting participation in day-ahead, intraday, or balancing power markets. This could be implemented technically via a dynamic special grid fee that reflects the incentives in the form of a variable working price. This generates additional revenue for grid-friendly operation – and thus a direct economic benefit.

4.2 Battery operation

Battery operation. The application of the three regulatory instruments examined changes the operation of the large-scale battery (Figure15). The constant working price with the static grid fee (left) reduces the attractiveness of arbitrage transactions, which leads to a lower number of storage cycles and tends to shift the focus to the provision of balancing power. The dynamic constraint (center) generally allows for market-based optimization behavior, but regularly interrupts it in the event of local congestion, which manifests itself in sometimes longer interruptions in operation. The redispatch price signal (right), on the other hand, influences market valuation through targeted price signals in the event of grid congestion, thus leading to more grid-friendly operation without fundamentally impairing economic operation (seeFigure4).

Battery operation with instruments (Bollingstedt)

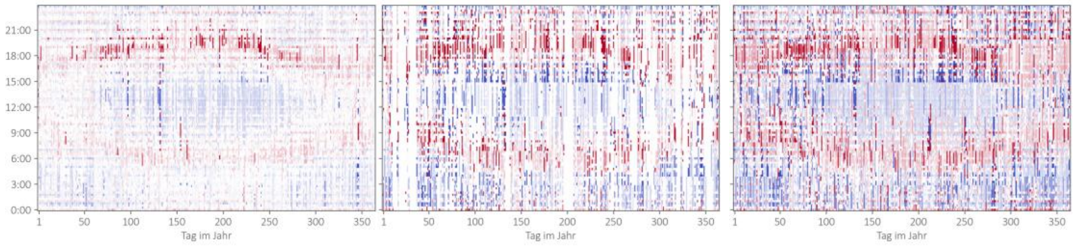

Figure15 : Battery operation optimized for 2024 for electricity trading and balancing power, taking into account the instruments at the Bollingstedt site. Two cycles per day are visible for all instruments. However, operation is severely restricted with the static grid fee (left). With the dynamic constraint (center), the battery is idle during certain periods. Operation with a redispatch price signal (right) most closely resembles pure market operation.

Grid utility. The frequency distribution of battery operation and redispatch (Figure16) already shows clear differences between the instruments under consideration. While the static grid fee visibly restricts storage operation, it only leads to a limited proportion of grid-relieving applications – at the same time, grid-loading situations continue to occur despite reduced operation. The dynamic constraint, on the other hand, is effective against grid-burdening behavior, preventing it completely, but it is associated with a very high downtime rate and leads to hardly any active grid relief overall. The redispatch price signal, on the other hand, ensures a noticeable improvement in grid utility: the proportion of grid-relieving operations significantly exceeds that of grid-burdening ones, meaning that the battery increasingly "works" in the interests of the overall system.

Periods of grid relief and strain with instruments

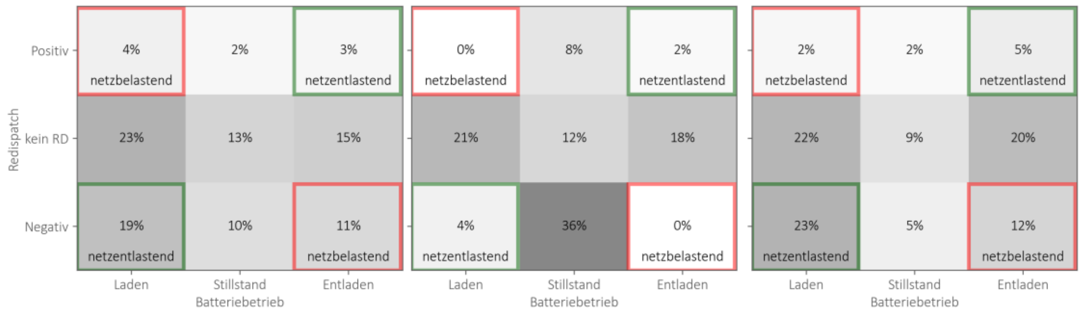

Figure16 : Frequency distribution of battery operation and redispatch for the Bollingstedt site and the instruments considered: static grid fee (left), dynamic constraint (center), and redispatch price signal (right).

4.3 Redispatch and welfare

Redispatch change. As the previous section shows, the three instruments change battery operation. This also leads to a significantly changed grid effect and the required redispatch (Figure17).

Redispatch change by instrument

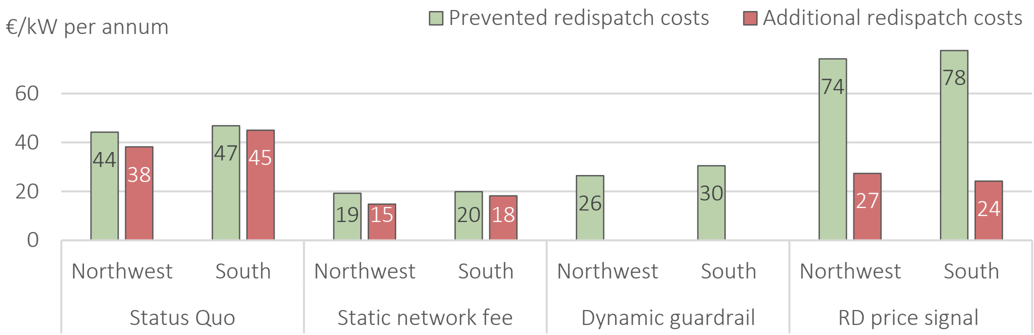

Figure17 : Redispatch change of the instruments for the locations in the north and south. All instruments considered lead to a reduction in the additional redispatch costs incurred. However, only the redispatch price signal also prevents the redispatch of existing bottlenecks.

Static grid fee. Due to the strong market-distorting effect of the static grid fee, fewer operating hours also reduce energy flows in congestion situations. The impact of battery operation on redispatch falls to less than half of what it is under status quo conditions. In addition, the contribution to grid relief remains low with static grid fees – saved and additional redispatch costs are almost balanced in both the northwest and the south, so that the net redispatch savings actually decrease slightly compared to the status quo. A static grid fee is therefore not a systematic instrument for increasing grid utility.

Dynamic constraint. On the other hand, a clearly positive grid effect can be achieved with dynamic instruments that take the current grid situation into account. These include the dynamic constraint, which effectively prevents grid-burdening behavior and excludes additional redispatch measures. However, due to the sometimes prolonged congestion situations in the transmission grid, the battery has to cease operation for a longer period of time, which also reduces the phases of grid-relieving operation. A battery that is not allowed to store energy on an evening when there are strong winds in the north, for example, cannot absorb any surplus during the night either. Compared to the status quo, the redispatch costs prevented are also reduced by more than a third.

Redispatch price signal. Another instrument that dynamically takes the grid situation into account is the redispatch price signal. In contrast to the guard rail, however, a bottleneck situation does not result in a restriction on operation, but rather a monetary incentive. This leads to the targeted mobilization of grid-friendly flexibility. While the battery still causes additional redispatch, this is significantly lower than in the status quo. At the same time, however, more redispatch measures are prevented, so that the net redispatch savings compared to the dynamic constraint almost double.

Economic value creation. The three instruments differ not only in their effectiveness in providing incentives for grid-friendly operation, but also in the extent to which they restrict the battery in market operation. This becomes apparent when comparing the economic value added of the battery under the three instruments, i.e., the sum of market revenues and grid impact (Figure18).

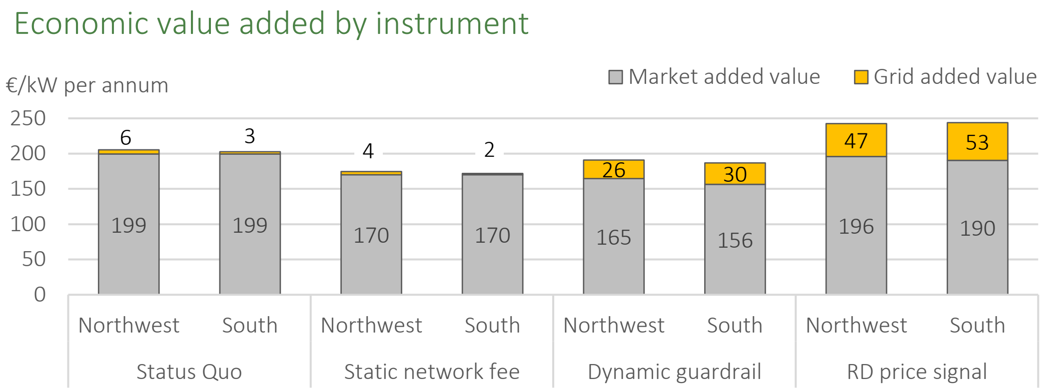

Figure18 : Economic value added through market and grid added value of the instruments considered in the north and south. Static grid fees and dynamic guard rails reduce value added by restricting battery marketing, whereas the passed-on redispatch price signal leads to an increase.

Static grid fee. Because the static grid fee increases the cost of charging, batteries reduce their operation, creating less added value on the market. Because such grid fees also do not strengthen grid utility, the added value provided by batteries *decreases* by about 15% compared to the status quo, both in the north and in the south. From an efficiency perspective, a static grid fee is therefore clearly negative.

Dynamic constraint. Although the dynamic constraint strengthens grid utility, this comes at a high price for market operations: the added value created here falls by around 20%, which is even more than with the static grid fee. Although the grid added value can be increased, the overall economic value added is lower than in the status quo. This result is also robust with regard to the location of the battery.

Redispatch price signal. The redispatch price signal enables higher grid added value without significantly impairing market added value. Total value creation is 20% higher than in the status quo, meaning that each kW of battery capacity creates a fifth more wealth than in the current market design. This instrument therefore manages to "get the most out of the batteries." It also shows that there is no hard conflict of interest between market operation and grid utility: the positive effect on the grid is about 10 times higher than in the status quo, while the positive effect on the market is only minimally reduced.

4.4 Grid Level

Grid signal. The grid impact of regulatory instruments depends on the grid level at which the underlying signal is applied. While no grid signal is taken into account in the static grid fee, both the dynamic constraint and the redispatch price signal control operation via congestion information – usually at the transmission grid level. Their demand is forecast centrally, whereas the integration of distribution grids would be significantly more complex: it would require all of the numerous distribution grid operators to provide their own reliable forecasts for their local redispatch demand. In the following, we therefore examine how the grid impact changes depending on whether the signal is based exclusively on information from the transmission grid or also on information from the distribution grid.

Differences in the south. Since there are only minor differences between the grid levels in the north, the analysis focuses on the location in the south, where the effect of the underlying grid signal varies more (Figure19). The results show that if the dynamic constraint is defined solely on the basis of bottlenecks in the transmission grid, the grid added value is reduced from €30/kW to €24/kW (around -20%) compared to a comprehensive signal that also takes distribution grid bottlenecks into account. In the case of the redispatch price signal, the decline is slightly lower at around 14%, but remains noticeable. For locations with differing redispatch requirements depending on the grid level, the following therefore applies: In order to maximize the grid-beneficial potential of large-scale batteries, the grid signal should ideally also reflect the local redispatch requirements in the distribution grid.

Redispatch change with grid signal by grid level (south)

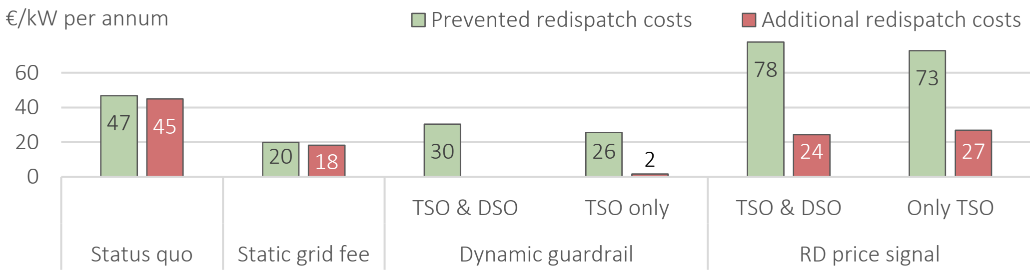

Figure19 : Redispatch change of the instruments with and without consideration of the distribution grid level in the grid signal for the location in the south. Even without considering the distribution grid level, the instruments have a positive grid effect. However, this is up to 20% lower.

4.5 Distribution effect and grid operator revenues

Distribution of benefits. The added value created from market and grid added value is distributed very differently between battery and grid operators, depending on the instrument (and associated payments) (Figure20). In the current discussion about the financing of grid infrastructure, it is often emphasized that additional grid operator revenues—such as from battery grid fees—can contribute to reducing general grid fees. Against this background, it is particularly significant that although the redispatch price signal achieves the highest added value, it does not generate any direct financial benefit for grid operators. Instead, they benefit primarily from instruments such as the static grid fee or the dynamic constraint – even though both significantly reduce economic welfare compared to the status quo. This is particularly evident in the case of the static grid fee, which, at up to €49/kW, generates the highest benefit for grid operators but provides the least welfare overall. For battery operators, the situation is reversed: while the redispatch price signal increases economic benefits by over 20%, the static grid fee reduces the result by a third, thereby jeopardizing economic operation. This does not even take into account the fact that market revenues from the static grid fee increasingly come from the prospect of declining control power marketing.

Distribution of value added by instrument

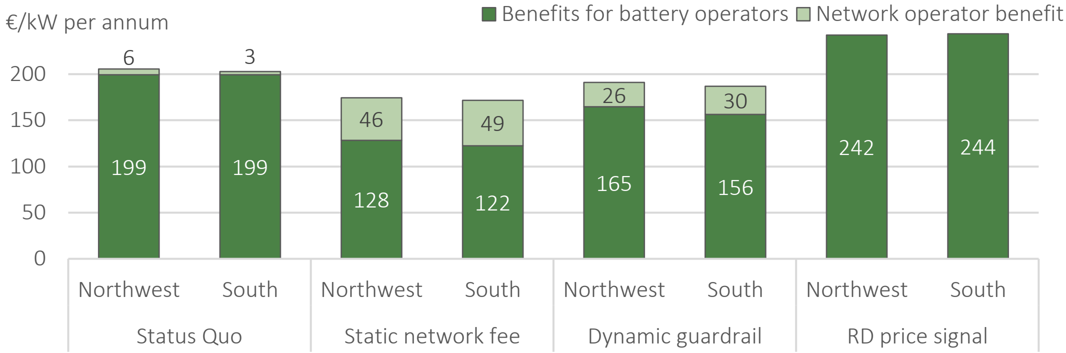

Figure20 : Benefits of value creation broken down by grid operator and battery operator. The redispatch price signal increases welfare, but in our example design, it does so unilaterally to the benefit of battery operators. Grid operators benefit from the static grid fee and dynamic constraint, which, on the other hand, reduce economic value creation and fundamentally jeopardize the willingness to invest in large-scale batteries.

Compromise. The analysis thus reveals a conflict of objectives: instruments such as the redispatch price signal create the highest economic welfare, but largely exclude grid operators. Conversely, static grid fees or dynamic guard rails secure additional revenue for grid operators, but reduce overall welfare and inhibit investment in large-scale batteries. In view of the increasing demand for flexible storage, the expansion of large-scale batteries is desirable from an economic perspective. If restrictive instruments significantly reduce the benefits for battery operators, investments – and thus value creation in the market and in the grid – will not materialize. A possible compromise could therefore be a combination of market-based incentives (redispatch price signal) and moderate participation of storage facilities in grid costs (e.g., via a location-dependent capacity price).

5 Conclusion

Grid utility today. Large-scale batteries can help relieve the burden on the power grid – but today they only do so to a limited extent. Current market-driven operation leads to roughly equal amounts of relief and strain on the grids, with a slightly positive net effect. In the north, both the transmission and distribution grids benefit, while in the south, it is primarily the distribution grid that is relieved of solar surpluses at midday. Overall, however, the contribution to grid utility falls well short of its potential. The associated grid added value is low compared to the market benefit. Locations that are systematically beneficial to the grid cannot be identified without targeted incentives.

Instruments for improvement. Regulatory instruments offer the possibility of specifically increasing grid utility – but with considerable differences in their effect. The greatest effect is achieved by a dynamic price signal that prices in the redispatch requirement locally. It increases the grid added value many times over without fundamentally distorting market signals – and can thus combine both grid- and market-friendly behavior. A static grid fee, on the other hand, provides no incentives for grid-friendly operation and at the same time significantly reduces the economic attractiveness for operators. The dynamic constraint also falls short of its potential: although it effectively prevents grid-straining operating modes, it severely restricts storage operation and achieves only limited grid added value.

Recommendation. The incentives provided by the redispatch price signal, which offers the greatest economic value among all the instruments examined, are suitable for increasing the grid utility of large-scale batteries. This could be introduced in the form of a special grid fee, which would be determined daily by the grid operators and would reflect the expected local congestion situation. This would allow battery operators to take the current grid situation into account in their deployment optimization and significantly reduce redispatch requirements. To reduce general grid fees, it would be conceivable to pay part of the additional revenue for the battery to the grid operators as a performance-related levy, without fundamentally jeopardizing investments due to reduced profitability.