INPUT FOR AGNES CONSULTATION

Grid fees for large-scale batteries

Proposal for a battery grid fee in the form of a dynamic energy price to strengthen grid utility

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

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Summary

Role of large batteries. Large 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, they will 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. Investments in large batteries are neither subsidized nor protected against price risks by the government and do not burden public budgets – unlike gas-fired power plants, renewable energies, grids, or home storage systems. In this respect, the great interest of investors in large batteries is extremely welcome, even if the many grid connection requests currently pose challenges for grid operators.

This article. The effect of large batteries on the grid is the subject of controversial debate. The future treatment of batteries in the grid fee system is one of the key issues in the reform of the general grid fee system initiated by the Federal Network Agency (BNetzA). This consultation paper has three objectives: Firstly, we want to structure the discussion on grid serviceability by clarifying terminology and describing the current impact of large batteries on the grid. Second, we evaluate conceivable grid fees in terms of their incentive effect on grid-friendly behavior. Third, we develop a concrete proposal for a special battery grid fee in the form of a dynamic working price. This would allow batteries to take the grid situation into account when optimizing their use, thereby significantly increasing their economic value creation.

Grid impact today. What impact do large batteries have on grid congestion and redispatch costs in today's market design? As battery use and grid congestion are constantly changing, the grid is loaded in some quarters of an hour and unloaded in others. However, a simulation of battery use on the day-ahead market and an analysis of historical redispatch patterns in the transmission grid show that batteries already slightly reduce redispatch costs over the course of a year. This positive effect on the grid is purely coincidental, however, as the German electricity market design does not price grid congestion. With systematic incentives, batteries could therefore be even more beneficial to the grid. This is the purpose of the dynamic energy price we propose.

Grid fees. A static energy or capacity price for batteries generates revenue for grid operators, but does not reduce redispatch costs. A dynamic energy price, which is set daily by the grid operators and reflects the expected congestion situation, can, on the other hand, significantly reduce redispatch costs. In our model, the redispatch cost-reducing effect of such a dynamic energy price is five times greater than that of alternative grid fees. If batteries are to make a further contribution to financing grid costs, a capacity fee or construction cost subsidy can also be levied. A dynamic energy price could be implemented relatively easily as a special grid fee for batteries.

1 Introduction

Grid fees. Large batteries and other electricity storage systems that go into operation before August 4, 2029, are exempt from grid usage fees. At the time of grid connection, storage facilities only have to pay the so-called construction cost subsidy to the grid operator. This grid connection fee varies from region to region. In this article, we discuss grid fees for grid-connected, stand-alone large batteries. This does not include storage facilities that optimize their operation behind the metering point according to producers or consumers.

Investor interest. There is considerable interest in investing in large-scale batteries. This is evident, among other things, in the very high number of grid connection requests, which now total several hundred gigawatts. The reason for this is, on the one hand, the rapid decline in cell prices, driven by massive investments in technology and manufacturing in China. On the other hand, interest is being sparked by the high prices for balancing power and work and by price differences on the German wholesale market, which are in turn driven by the rapid expansion of wind and solar energy. Unlike virtually all other investments in the electricity system – power plants, renewable generators, grids, home storage systems – large batteries are neither directly nor indirectly subsidized or protected by the state against price risks – and yet they are still being expanded. This opens up the opportunity to base the restructuring of the electricity system not solely on state subsidies, but to make targeted use of market dynamics.

This paper. The effect of large batteries on the grid is the subject of controversial debate. Terms such as grid-friendly, grid-effective, and grid-neutral are used in relation to the bottleneck effect of large batteries. However, there is no uniform definition of these concepts. The aim of this consultation paper is to structure the discussion on grid friendliness and grid fees for large batteries. The second objective of the paper is to evaluate conceivable grid fees in terms of their incentive effect on grid-friendly behavior, both qualitatively and quantitatively. Third, we develop a concrete proposal for a special battery grid fee in the form of a dynamic working price. This would allow batteries to take the grid situation into account when optimizing their use, thereby creating considerable economic added value.

2 Role & relevance of large batteries

Role of batteries. Large batteries will play a central role in ensuring an economical, secure, and clean electricity system in the coming years and decades. The energy transition essentially consists of a shift in electricity generation to primarily wind and solar power and the electrification of transport, heating, and industry. As a result of both trends, the residual load will fluctuate by several hundred gigawatts within a single day as early as the 2030s, a multiple of today's levels. At midday, the residual load is likely to be negative on a regular basis, even with moderate solar radiation, and in the evening it will far exceed today's peak load, mainly due to electricity consumption for charging and heating. This, combined with short-term forecasting errors in wind and solar generation, will create a great need for flexibility in the electricity system. At the same time, the addition of approximately 20 GW of wind and solar capacity per year will cause a dramatic decline in market value and threaten to create a surplus of electricity.

Other flexibility. Flexibility resources that mitigate the effects of these trends are being developed too slowly. Household flexibility through smart electric cars and heat pumps suffers from the low availability of smart meters and time-invariant electricity tariffs. Industrial flexibility is hampered by the structure of grid fees for power-metered customers (RLM grid fees) and their discounts. New gas-fired power plants are waiting for the capacity market, which is complex under European law. And home storage systems are being built—but only to optimize self-consumption, which generally does not relieve the grid or the market. Against this backdrop, it is difficult to imagine the energy transition succeeding without the addition of large batteries.

Added value of large batteries. Large batteries already perform important tasks in the power system today, particularly in providing control power (FCR and aFRR) and short-term compensation for wind and solar forecast errors via intraday trading. In just a few years, they will also contribute to security of supply by absorbing generation peaks and providing electricity for peak loads. They reduce overall system costs by eliminating the need for frequent starts of thermal power plants to compensate for forecast errors and reduce peak loads. And large batteries reduce the curtailment of renewable energy plants and subsidy costs by absorbing surplus renewable energy. It is therefore not surprising that the TSOs anticipate a massive demand for large-scale storage facilities: In the NEP scenario framework just approved by the BNetzA, the figure is 68 GW in 2037 (scenario range 41 GW to 94 GW), i.e., an average annual increase of more than 5 GW over the next 12 years. This would require the current pace of expansion to be increased tenfold.

At the expense of the grid. It is sometimes argued that batteries would "optimize themselves on the market at the expense of the grid." It is true that batteries do not take grid congestion into account when optimizing purely for the market – but this also applies to all generation plants and is due to the design of the German electricity market: In the uniform price zone, it is desirable and indeed impossible for market participants to optimize based on wholesale prices that do not take grid congestion into account.

Welfare. Batteries create economic added value in the market and in the grid. The participation of batteries in balancing energy and wholesale markets reduces fuel and start-up costs for power plants. In the grid, they reduce (or increase) redispatch and grid investment costs. The added value in both areas is equally "good" (or "bad") and adds up to the overall economic added value (economic welfare) (Figure1). Unlike the regulated grid or tax-subsidized investments in renewable energies (EEG) or thermal power plants (capacity market) or indirectly subsidized solar systems and home storage (own consumption), large batteries are financed entirely on a competitive basis and thus represent purely private investments.

Welfare effect of a large battery (illustrative)

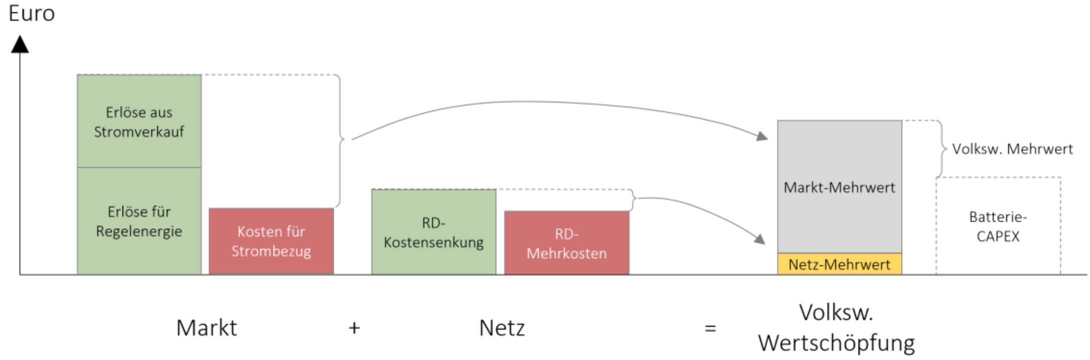

Figure1 : The difference between revenues and costs on the market results in market added value. Cost reductions or increases in the grid result in grid added value (which can also be negative). The sum of these two values results in economic value added. If this exceeds the investment costs of the battery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

Externalities. While market revenues are visible to battery owners and are therefore internalized in business optimization and investment decisions, this is not the case for network effects. The added value of the grid is currently invisible to market participants and is therefore not taken into account in optimization; it thus represents an external effect. This is precisely what the design of instruments to strengthen grid utility should be about: making network effects visible and thus internalizing them in battery optimization.

3 Are large batteries useful for the grid?

Grid impact. Large batteries have different effects on the grid. The most important economic effect is likely to be on load flow in the grid and thus on the need for congestion management measures (redispatch) or long-term investments in grid expansion. Not only the connection grid level is relevant here, but also upstream grids. Other effects concern, for example, the local grid voltage.

1-quarter cycle. The grid impact must necessarily be considered on a quarter-hourly basis because battery use and the grid situation change every quarter hour. Put simply, a storage facility can either charge, discharge, or remain idle. At the same time, there may be a positive or negative redispatch requirement, or no redispatch requirement at all, in the region of the grid connection. Positive redispatch demand exists when additional feed-in is required in part of the grid to alleviate grid bottlenecks. As a rule, power plants are then ramped up. Negative redispatch demand exists when there is too much electricity. Generators are then shut down. If, for example, a storage facility draws electricity from the grid while negative redispatch is necessary in the region at the same time, the storage facility relieves the grid. By reducing the flow of electricity on the congested grid element, less curtailment of generators is necessary. The opposite is true when positive redispatch is necessary in the region – in this case, the storage facility places a load on the grid and ensures that more power plant capacity has to be ramped up. Overall, there are nine different combinations in which the storage facility either relieves the grid in a congestion situation, places a load on it, or has no congestion effect (Figure2). We describe the grid effect as grid-relieving, grid-burdening, or grid-neutral.

Grid effect of a storage facility

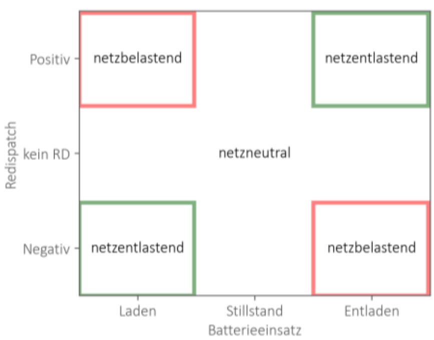

Figure2 : Grid impact of a storage facility in a quarter of an hour depending on battery use and redispatch requirements.

Frequency of states

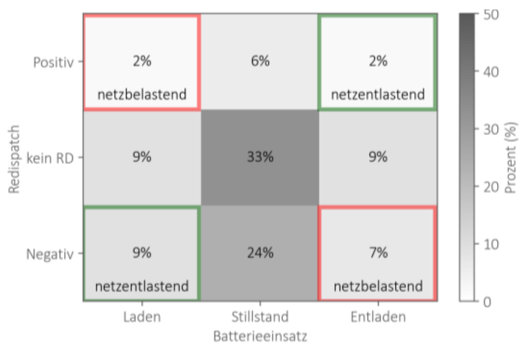

Figure3 : Quantification of the frequency of grid load and relief for a location in northwestern Germany (North Sea coast). For methodology, seeAppendix: Modeling .

Example: North Sea. Figure3 shows the frequency of these states for a simulated 2-hour large battery on the North Sea coast that operates day-ahead arbitrage. Due to typical electricity consumption and solar patterns throughout the day, the battery often runs two cycles per day: night-morning and noon-evening. The redispatch requirement in the transmission grid, on the other hand, depends on wind feed-in, which is not subject to recurring daily fluctuations. The redispatch requirement often lasts for many hours or even several days, after which the transmission grid is largely free of congestion again for several days. During a windy day with curtailment requirements in the North Sea region, the battery relieves the grid when charging at night and at midday because it absorbs excess electricity that would otherwise have to be curtailed. However, it puts strain on the grid when discharging in the morning and evening because it feeds into an already overloaded grid and merely causes additional curtailment. Depending on the quarter hour, the battery therefore relieves the grid in some cases and burdens it in others.

Quantification. Over the course of a year, our calculations show that the battery relieves the grid in about 11% of the quarter hour, burdens it in 9%, and has no bottleneck effect in 80% (for details on the calculation, seeAppendix: Modeling). Although the battery exacerbates grid bottlenecks in individual situations, over the course of a year it tends to be beneficial to the grid, albeit to a limited extent. This means that batteries remain far below their potential in terms of grid serviceability as long as they do not receive any signals regarding the grid situation.

Southern Germany. A battery south of the bottleneck behaves in exactly the opposite way, but also places a load on the grid twice a day and relieves it twice a day. This applies to all regions of Germany: there are no areas in which market-optimized batteries systematically relieve the transmission grid and never place a load on it due to their location.

Other studies. These results also coincide with the studies by TenneT (Quo Vadis Großbatteriespeicher) and 50Hertz (unpublished) on the topics.

Consequences. These findings have two key consequences. On the one hand, a blanket classification of large batteries as a burden on the grid is not empirically justified. Rather, batteries used in day-ahead arbitrage reduce grid bottlenecks over the course of a year. Second, the results clearly show that location control alone does little to improve grid serviceability. Incentives are needed to encourage the use of batteries in a way that benefits the grid. A grid-friendly mode of operation for batteries can be achieved through the sensible design of grid fees.

4 Two objectives of battery grid fees

Two objectives. Grid fees for large batteries generally pursue two objectives. These two objectives are fundamentally different and should be separated analytically:

- Generating revenue (financing function)
- Strengthening grid serviceability (incentive function)

Financing. In economic terms, generating revenue is a form of redistribution: funds are redistributed from one group (battery owners) to another group (grid fee payers, i.e., electricity consumers). The revenue generated by battery grid fees can be used by grid operators to reduce general grid fees. The desire for a financial contribution to the grid infrastructure is legitimate. However, this is limited by the financial viability of the battery business model. To put it bluntly, if too much money is skimmed off, no batteries will be built and there will be no revenue. It must be taken into account that, unlike grids, power plants, and renewables, large batteries cannot fall back on any government investment framework to hedge price risks and therefore naturally have significantly higher capital costs.

Grid serviceability. The second goal, strengthening grid serviceability, is not about redistribution, but about creating economic added value through the smarter use of batteries. If redispatch and grid investment costs are reduced, consumers can be relieved without burdening another group. Financing is therefore about cutting the cake differently, while grid serviceability is about making the cake bigger.

Grid serviceability and the electricity market. Incentives for grid-friendly behavior—i.e., storing regional surplus electricity and releasing it when there is regional scarcity—do not necessarily have to arise from the grid fee system. There is virtually unanimous agreement among scientists that these incentives should actually be better implemented in the form of regional wholesale prices, insofar as bottlenecks in the transmission grid are concerned. However, the new federal government has once again confirmed its rejection of price zone division, meaning that this option will not be available in the foreseeable future. Another conceivable source of incentives for grid-friendly behavior is flexible grid connections. However, these usually only take into account local effects at the level of the connection grid itself and do not seem suitable for reflecting the overall impact on different grid levels and operators.

Grid serviceability first! That is why we believe it is essential to focus on the incentive function when it comes to grid fees for large batteries. Large batteries are necessary for the success of the energy transition, and grid serviceability is necessary for the scalability of batteries. And that requires incentives from grid fees.

5 Grid fee options

Four options. There are essentially four basic types of grid fees that could be applied to large batteries:

- No grid fee
- Working price
- Power or connection price
- Dynamic energy charge

Energy charge. With a (static) energy charge, the battery is charged for the energy it draws or feeds into the grid (ct/kWh). For example, the normal RLM energy charge for consumers could simply be applied to the battery's grid consumption. The grid operator can generate additional revenue via an energy charge (financing effect). However, it has two major disadvantages: on the one hand, it significantly limits the profitability of optimization on the electricity markets and thus destroys welfare (which is also reflected in reduced grid fee revenues). On the other hand, our simulations show that it has virtually no effect on grid serviceability. In economic terms, an energy charge is therefore a highly distorting tax that is not recommended. For the calculations shown below, we have assumed an energy charge for electricity consumption of 5.5 ct/kWh, which is the current energy charge in the transmission grid for less than 2500 hours.

Power price. Another type of charge is power-related, which comes in various forms but has a similar economic effect: measured power prices, contractual capacity prices, connection charges (BKZ). What they have in common is that the charge is levied on peak consumption (or feed-in) (€/kW). Whether they are charged once or annually, or whether the power is agreed ex ante in a contract or measured ex post, is of secondary importance for the economic effect. A power price primarily has a financing effect. In addition, a power price provides an incentive to build more MWh per MW of storage, for example, a 4-hour storage facility instead of a 2-hour storage facility. The German construction cost subsidy, which can be classified economically as a grid connection fee, also has this effect. In addition, capacity prices avoid the distorting effect of energy prices on plant utilization because they are unlikely to influence the decision to use batteries once they have been built. (However, it is true that a capacity price reduces investment and this indirectly influences electricity prices.) For the reasons mentioned above, a moderate capacity price is preferable to a static energy price for the purpose of generating revenue. For our calculations, we assume that a 4-hour storage facility will be built instead of a 2-hour storage facility due to the capacity price. To ensure comparability through similar investment costs, we assume that a battery storage system must sacrifice 40% of its capacity for this purpose. Despite the reduced capacity, the scaling in all figures is based on the original scale in order to ensure the comparability of the €/kW key figures between the instruments.

Regional investment control. Both a working price and a performance price can serve regional investment control if they are differentiated geographically. This is already the case today with the BKZ. However, this hardly serves the grid – simply because there are no "grid-friendly battery regions." For batteries to systematically relieve the grid, there needs to be an incentive for their use. Pure investment control is not enough.

Dynamic energy price. The dynamic energy price varies every quarter of an hour depending on the load flow and congestion situation. It can be an effective means of relieving the grid. For our calculations, we use a dynamic energy price based on the level of redispatch costs. For example, it amounts to 10 ct/kWh, which must be paid for grid withdrawal if positive redispatch is necessary in the region. Withdrawal and feed-in fees have opposite signs at all times, so that in the same situation, feed-in is remunerated at 10 ct/kWh. If negative redispatch is necessary, the fee is 8 ct/kWh. If the grid is free of congestion, no fees are incurred. From an economic perspective, this instrument is efficient and also not susceptible to strategic "gaming" because it is not possible to optimize between two market levels.

Quantification. For a battery in the North Sea region connected to the transmission grid, we estimated battery usage and grid impact based on a quarter-hourly simulation model for the four grid fees (Table1). Details can be found in theAppendix: Modeling .

Table1 . The four modeled cases

Case	Description	Amount
No grid fee	No grid usage or grid connection fee	-
Static working price	Energy charge for consumption from the grid	5.5 ct/kWh
Power charge	Power charge	24.4 €/kW p.a.
Dynamic energy price	Quarter-hourly variable energy price for consumption 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)

Grid costs. This shows that a battery without grid fees – i.e., operating in the status quo – already slightly reduces redispatch costs: Over the course of a year, each kW increases redispatch costs by €58, but reduces them by €70 at other times (Figure4). In total, the battery reduces redispatch costs by €11 (yellow bar inFigure5). This shows once again that batteries are already beneficial to the grid today. In contrast, the introduction of a static energy price leads to an *increase* in (net) redispatch costs . A power price, on the other hand, has a minimally positive effect. The dynamic working price massively reduces redispatch costs: the battery reduces redispatch costs by €110 and increases them elsewhere by €48, resulting in a large net benefit of €62 for the grid. The cost-reducing effect of the battery is thus 500% higher than without grid fees.

Value creation. Economic value creation is the sum of market revenues and grid impact (Figure5) and can be interpreted as added value in the market and in the grid. A static energy price does not significantly reduce welfare compared to no grid fee. A capacity price has only a minor effect on welfare. The dynamic energy price creates the most welfare: Although the revenue from the battery from electricity trading decreases here compared to grid fee exemption, the grid relief is so great that the total economic value added increases by around 30%. This should be the primary focus of a grid fee: to maximize economic welfare, i.e., to get the most out of the battery for society.

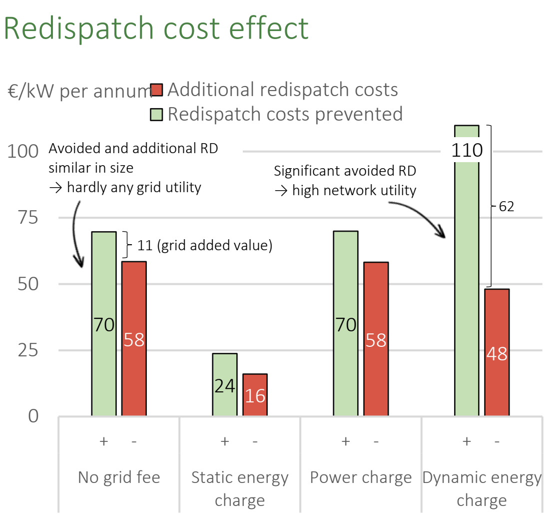

Figure4 : Grid utility of large batteries under four alternative grid fees, measured by their impact on redispatch costs.

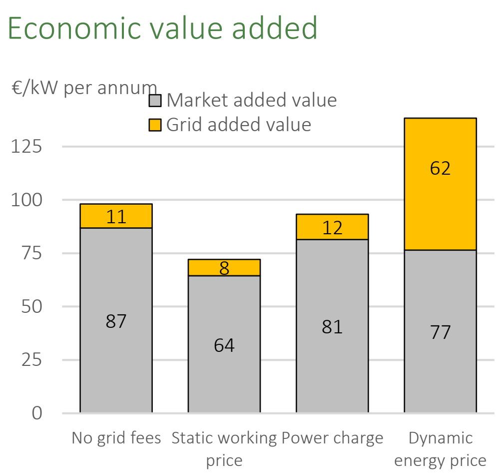

Figure5 : Economic value added of large batteries, calculated as the sum of market revenues and redispatch costs.

Revenues for grid operators. In addition to the question of how much economic added value the battery creates, the question of where this added value accrues is also relevant. Essentially, it can accrue to the battery itself or to the grid operator, who then passes it on to consumers in the form of lower grid fees as part of the regulatory framework. The revenues for the grid operator consist of income from grid fees and the reduction in redispatch costs (Figure6). It is these revenues (additional income and cost reductions) that reduce the general grid fees. Without grid fees, there is only a minimal cost reduction. With static energy and capacity prices, the payments from the grid fees are added. With dynamic energy prices, there is no revenue because the RD cost reduction is paid to the battery through the grid fees.

Battery revenues. The total revenues from the battery are the market revenues minus the grid fee payments (Figure7). Revenues are lowest with static energy prices because, on the one hand, payments are made to the grid operator and, on the other hand, market revenues are greatly reduced by the distorting effect of the fees. The opposite is true for dynamic energy prices, where slightly declining market revenues are more than offset by net income from grid fees.

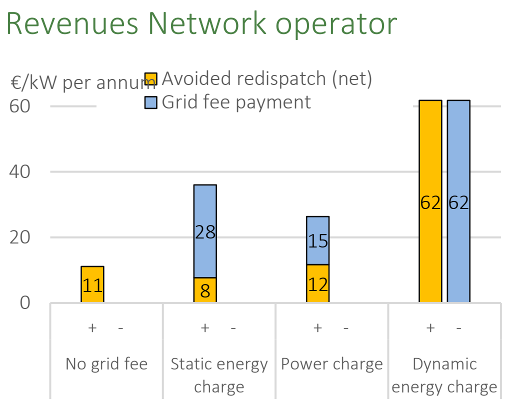

Figure6 : (Net) revenues of grid operators compared to no battery from grid fee payments and reduction in redispatch costs.

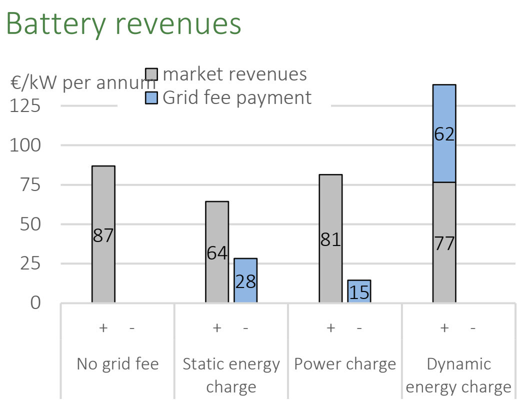

Figure7 : (Net) revenues of the battery from market revenues and grid fee payments.

Distribution of benefits. Put differently, the welfare created is divided between grid operators and batteries (Figure8). The instruments with the greatest benefit for grid operators (static energy price and capacity price) offer the least economic value added. The greatest welfare can be achieved with a dynamic energy price, but its introduction means that grid operators no longer benefit.

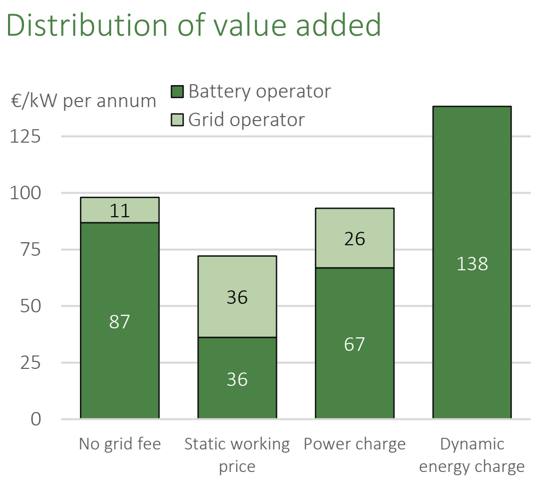

Figure8 : Benefits of value creation broken down by grid operator and battery operator.

6 Possible design of a dynamic energy price

Special grid fee. Specifically, a dynamic energy price for large batteries could be implemented as a special grid fee. In a first step, batteries behind the metering point of producers or consumers (co-location, own consumption) could be exempted. If the dynamic special grid fees prove themselves in practice, they could serve as a model for a reform of the special grid fees under Section 19(2) of the German Electricity Network Access Ordinance (StromNEV) or the general introduction of dynamic grid fees in a few years' time.

Amount. In its simplest form, the amount of the charge can be based on the average redispatch costs and always be symmetrical for withdrawal and feed-in (Figure9). If payments from grid operators to the battery (negative grid charges) are to be avoided, an alternative structure would also be conceivable (Figure10). However, this would be accompanied by a significant reduction in grid utility.

Amount of dynamic grid fees

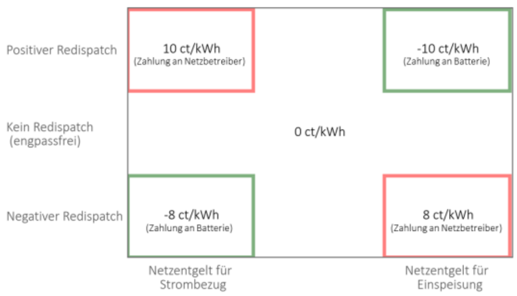

Figure9 : Amount of dynamic grid fees (symmetrical) that result in payments to both grid operators and the battery.

Dynamic grid fees (alternative)

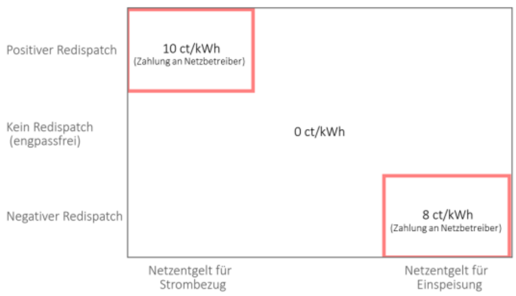

Figure10 : Alternative structure and amount of dynamic grid fees (asymmetric/unilateral) that only lead to payments to grid operators.

Implementation. The dynamic working price should be determined each day by the grid operators on the basis of the redispatch forecast already prepared during the previous day. The ideal time for publishing the price is 6 a.m., before the FCR auction. For batteries connected to the transmission grid, this only requires the invoices from the TSO; for systems with a high-voltage connection, the redispatch forecast from the connecting DSO is also required. In many respects, operational processes could be based on the benefit-instead-of-curtailment instrument (§13k EnWG).

Combinability. A dynamic working price as a special grid fee can be combined with other instruments. In particular, the following is conceivable:

- A combination with a capacity or connection price as a financial contribution for the batteries. If a financial contribution from batteries is desired, such a combination is likely to be the best solution, as it largely avoids harmful distortion ( ). However, it

must be taken into account that although a capacity price has little distorting effect during operation, it will reduce investment in large batteries. An excessive capacity charge would then not only prevent economically sensible battery investments, but would also reduce the financing contribution itself as a result.
- A combination with a flexible grid connection by the grid operator to take local effects into account (control power provision, voltage maintenance, etc.)
- Direct intervention by grid operators on the battery within the scope of redispatch
- General rules for the provision of control power by large batteries, such as limits for provision at a grid connection point
- Technical grid connection conditions such as ramp restrictions.

Two variants. In addition to the dynamic working price shown above, we have modeled two further variants:

- A combination of a symmetrical dynamic working price with a power price of €24.4/kW p.a.
- An asymmetric dynamic energy price, which may or may not result in a payment obligation for the battery depending on the grid load – but never a payment from the grid operator to the battery. This fee therefore represents a financial penalty for behavior that places a load on the grid, without however providing a positive incentive to reduce the load on the grid.

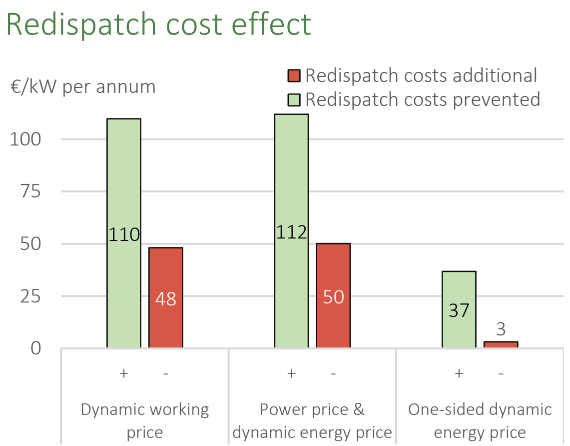

Figure11 : Grid utility of large batteries with dynamic working price measured by their impact on redispatch costs.

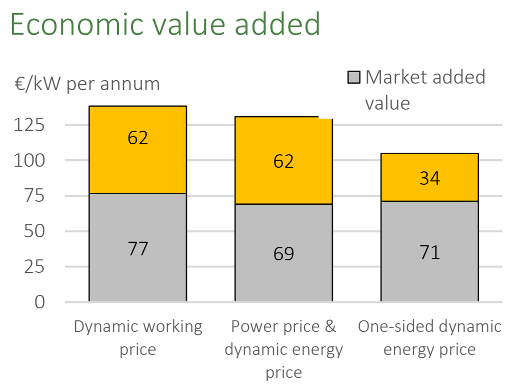

Figure12 : Economic value added by large batteries, calculated as the sum of market revenues and reduced redispatch costs for (combined) instruments with dynamic working prices.

With power price. The introduction of a power price influences the design of battery storage systems and typically leads to longer discharge times – for example, 4 hours instead of 2 hours. This changes the operation and the battery is used more frequently. The incentives of the dynamic working price remain fully effective, so that in our analysis, the grid serviceability remains virtually unchanged compared to a purely dynamic working price (Figure11). On the other hand, the added value on the electricity market decreases slightly, leading to a slightly lower value added (Figure12). In return, the grid operator now benefits not only from lower redispatch costs, but also from the financial proceeds from the capacity price (Figure13).

Unilateral dynamic energy price. With a unilateral (asymmetric) dynamic energy price, the battery operator must pay for behavior that burdens the grid, making it unattractive. However, the grid operator does not provide any remuneration for behavior that relieves the grid, so there is no active incentive to relieve the grid. As a result, the battery only achieves about half of the grid added value compared to the symmetric model. In addition to the avoided redispatch costs, the grid operator benefits from the grid fee revenues. However, the uncompensated decline in market revenues on the part of the battery operator leads to considerable losses – with a correspondingly negative impact on the attractiveness of investment.

Distribution of value added

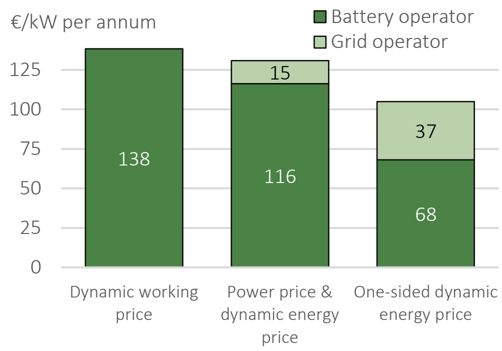

Figure13 : Benefits of value creation broken down by grid operator and battery operator for (combined) instruments with dynamic working prices.

Appendix: Modeling

Basic approach. We use model-based analysis to evaluate the grid utility of large-scale battery storage systems. The analysis procedure can be divided into two steps. First, battery storage operation is determined by means of market optimization. The resulting battery operation is then compared with local redispatch data, and conclusions are drawn about grid serviceability. For the calculation, we use quarter-hourly data based on historical time series.

Data. For market optimization, we use hourly day-ahead prices from 2024. For the same period, we analyzed the redispatch measures published by the transmission system operators on Netztransparenz.de and used them to determine the congestion-related redispatch demand (positive and negative) per region and quarter hour. We use a standard 2-hour battery (2 MWh / 1 MW) with 5% charging and discharging losses, whose operation is limited to an average of two cycles per day.

Battery operation. Optimizing the battery on the day-ahead market leads to location-independent operation that does not take local grid utilization into account. The result is a distinct daily pattern with two cycles (Figure14): charging at night and at noon, and discharging in the morning and evening. Taking the local grid situation into account leads to location-dependent operation.Figure15 shows battery operation in the North Sea region, which results from the day-ahead price and an additional incentive of a dynamic working price. The basic structure of operation with two cycles remains unchanged.

Day-ahead-optimized operation

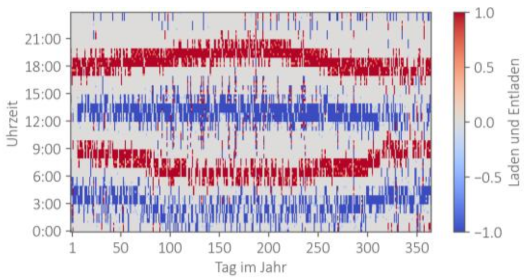

Figure14 : Operation of a 2-hour battery optimized for day-ahead prices from 2024 (location-independent).

Day-ahead & dynamic working price

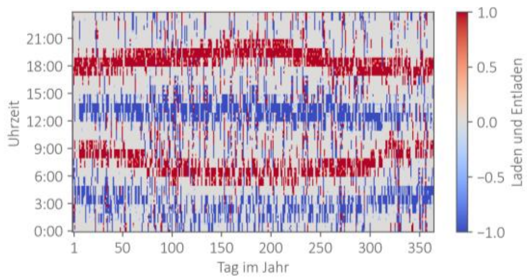

Figure15 : Operation of a 2-hour battery optimized for day-ahead prices from 2024 and taking into account a local dynamic working price (location-dependent).

Redispatch. We use redispatch data as an indicator of grid serviceability, as it provides information about bottlenecks. If redispatch occurs in the battery's region at a given time, battery operation that places a load on the grid increases redispatch, whereas operation that relieves the grid reduces it. We only consider the transmission grid level and do not take into account bottlenecks in the distribution grid or effects on voltage stability. The redispatch measures published by the transmission grid operators are specific to individual plants and are assigned by us to a region, typically a federal state.

Local aggregation. For the location on the North Sea coast considered in this article, we assume that its operation has a direct impact on redispatch in Schleswig-Holstein, Lower Saxony, and offshore wind farms in the North Sea. This applies, for example, to the frequent case of a bottleneck in the middle of Germany. Accordingly, we aggregate all redispatch measures from plants in these regions and assume that 1 MW of storage operation in the event of redispatch also changes it by 1 MW.

Economic evaluation. By comparing the time series of battery operation and redispatch measures at a location, the quarter-hourly local grid impact of the battery can be determined. From this, it can be deduced how often the battery relieves or burdens the grid (seeFigure3). Assuming a marginal influence, we also determine the extent to which battery operation changes redispatch requirements. Based on average costs of €100/MWh for positive redispatch and €80/MWh for negative redispatch, we calculate the absolute redispatch cost savings. These savings represent the added value for the grid and can be offset against market revenues as market added value.

Marketing. In recent years, large batteries have been used primarily to provide system services such as control power and balancing energy. However, the results presented in this article are based on marketing on the day-ahead market, as this has proven to be the most robust option for battery storage in our analyses. Supplementary internal calculations show that the statements on grid utility remain valid both without regulatory changes and with regard to the instruments examined, even in the case of intraday optimization or additional marketing in the control power market (FCR and aFRR). However, one significant limitation is that the necessary capacity reserve for control power reduces the flexibility of the battery for grid-supporting purposes.