SHORT STUDY

System utility of large batteries

Analysis of the impact of large batteries on the electricity market and grid, and evaluation of instruments for strengthening grid utility

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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

Impact on the market. Large batteries are currently operated primarily on a market basis in Germany. On the wholesale market, batteries store cheap electricity and release it again during expensive hours. Because this allows cheaper generation to come into play, it reduces the cost of electricity generation. It also lowers CO_2 emissions, reduces price volatility, and reduces the curtailment of renewable energies. In the balancing energy market, batteries replace expensive thermal power plants, which also reduces system costs.

Impact on the grid. However, the potential of large batteries to reduce the costs of the electricity grid has remained largely untapped to date. The greatest leverage here lies in reducing grid bottlenecks, which could lower redispatch costs and avoid grid expansion. The fact that large batteries do not make a systematic contribution here is due to the lack of suitable incentives in the uniform price zone. Recently, a number of proposals have been made on how to improve the grid serviceability of batteries, including differentiated construction cost subsidies, flexible grid connections, dynamic grid fees, and restrictions on battery use. However, this smorgasbord of regulatory measures carries the risk of generating little benefit while stifling the expansion of storage that makes economic sense.

This study. In this study, we present the effects of batteries on the electricity market and grid, discuss where regulatory action is needed, and evaluate instruments for strengthening their grid serviceability.

External effects. Action is needed where batteries have a significant impact without being "visible." This applies in particular to their effect on grid bottlenecks, which are neither foreseeable nor priced in for battery operators. Economically, this is an external effect that should be internalized through appropriate incentives. Overall, we identify five key external effects of large batteries:

1) Effect of battery use on redispatch
2) Effect of *short-term* changes in use on grid congestion
3) Misguided incentives within the 15-minute balancing period
4) Schedule jumps between balancing periods
5) Impact on voltage maintenance

Instruments. The most relevant problem is likely to be the effect of batteries on grid congestion: behavior that causes congestion can result in high redispatch or grid expansion costs, while behavior that prevents congestion saves costs. Three groups of solutions are discussed for this problem: geographical signals in the electricity market, a restriction on the grid connection of batteries, and a restriction on short-term flexibility marketing.

Evaluation. We show that most proposals address certain problems, while others do not. When evaluating the instruments, it is important to note that some proposals cause greater collateral damage than others. The grid utility of storage systems is not the only criterion:

ultimately, instruments must be measured by whether or not they generate economic added value. And this is generated in the market just as much as in the grid. In particular, instruments designed to solve grid bottlenecks, apart from price zone division, are likely to entail relatively large restrictions on the economically sensible short-term flexibility of batteries. The economic damage caused by this threatens to outweigh the benefits for the power grid.

1 Background

Background. Large battery storage systems are currently used in Germany primarily for market purposes, i.e., they are marketed on wholesale and balancing energy markets. This reduces the cost of electricity generation, thereby creating economic prosperity. From a societal perspective, it would make sense to also make the flexibility of electricity storage available to the power grid, for example to systematically reduce bottlenecks in transmission and distribution grids. However, this is currently failing due to a lack of (price) signals for the system- or grid-oriented use of large-scale battery storage.

Political focus: grid serviceability. In recent months, the question of the impact of large batteries on the power grid has become increasingly important in the energy policy discourse. The discussion often hinges on the question of whether batteries are "grid-friendly." The main drivers of these discussions are the large backlog of grid connection requests for large batteries, the grid fee reform of the Federal Network Agency (AgNes process), and the preferential treatment of grid-friendly installations under building law.

Political initiatives. There are a number of political and regulatory efforts to make large-scale battery storage in Germany more "grid-friendly." These include:

- Emphasis on the system-friendly integration of storage facilities in the coalition agreement
- Design of the construction cost subsidy (a "low" grid connection fee) for storage facilities with regional differentiation
- Grid fee reform (AgNes), with an intensive discussion on grid fees for storage
- Allocation of flexible grid connections by grid operators in return for (variously defined) grid-friendly operation
- Introduction of new ramp restrictions within the framework of technical connection conditions of grid operators
- Various proposals from the industry to restrict the operation of batteries ("envelopes" and "funnels")

Risks. These simultaneous and uncoordinated processes pose four risks:

- The development of poor instruments that inadequately address problems in the grid but at the same time cause unnecessary costs for battery operators (e.g., passing on the full costs of integrating batteries into the system to battery operators without taking into account their grid cost-reducing effect)
- A cacophony of competing approaches, with each grid operator pursuing their own concepts
- An inconsistent set of instruments in which different instruments overlap in a redundant or contradictory manner
- A high degree of discretionary decision-making power for grid operators, which they could use to avoid batteries in their own grid area as much as possible

As a result, there is a real danger that investment conditions for large-scale battery storage in Germany will deteriorate significantly. In the worst case, this could stifle the market ramp-up of the only asset class in the energy system in which investments are currently being made without subsidies. In addition, the dynamic expansion of large-scale battery storage systems is causing an overload of the responsible departments at grid operators, leading to a defensive attitude toward large-scale battery storage systems.

This study examines the impact of large batteries on the electricity market and grid. To this end, we define the frequently used but also contradictory terms and concepts of "grid-friendly" and "system-friendly." We highlight where large batteries create economic added value in the electricity system and how this is achieved in concrete terms. A key focus is on the effects (both positive and negative) of large batteries on the electricity grid, which battery operators do not currently take into account in their deployment decisions due to the lack of price signals, and which therefore represent external effects. We then structure regulatory instruments to internalize these external effects. These include, for example, price signals, incentives, restrictions, and requirements. We show which of these approaches can address which grid problems and which problems they cannot. Finally, we present the most important criteria for evaluating the instruments, discuss the limitations of the individual approaches, and provide basic design recommendations. However, a final evaluation of individual instruments is not the aim of this study.

2 System and network utility

Objective. The terms "system utility" and "grid utility" are firmly established in the energy policy debate. But what do these terms actually mean? How can they be meaningfully defined, delineated, and used? We address these questions in this section.

System utility of batteries. Large batteries can add value to the electricity market and the power grid. The added value to the electricity market arises primarily from shifting electricity from hours with low electricity prices to hours with high electricity prices. Added value for the power grid arises when batteries reduce grid bottlenecks or contribute in other ways to lowering grid costs. The system utility of a battery is therefore the sum of its market and grid benefits (Figure1). For such an overall economic assessment, it is irrelevant in which area the benefits accrue.

Welfare effect of a large battery (illustrative)

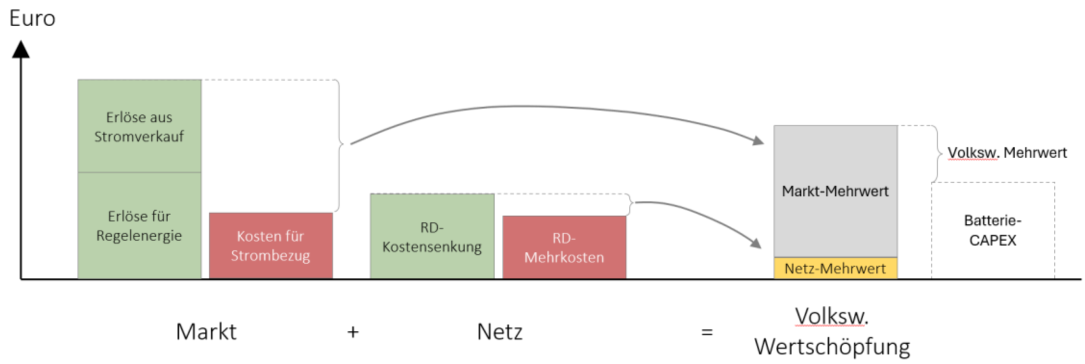

Figure1 : The difference between revenues and costs on the market results in market added value. Cost reductions or increases in the grid result in grid added value (which can also be negative). The sum of these two values results in the economic value added. If this exceeds the investment costs of the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

Practice. In practice, numerous different classifications are used for grid utility. These include, for example, the traffic light system of the Stromgedacht app from TransnetBW ("super green" for local electricity surplus, "orange/red" for shortage), the NRV balance traffic light with the colors "green," "orange," "red," and "blue," and the categories "grid-burdening," "grid-neutral," and "grid-beneficial" used by Bayernwerk Netz for storage operations.

Our proposal. We propose two definitions of grid serviceability, which are broadly defined in different ways: grid serviceability in the broader sense and in the narrower sense.

Network utility in the broader sense. Network utility in the broader sense takes into account all costs of the electricity grid incurred by grid operators. It considers the influence of the battery on grid expansion or redispatch requirements, voltage maintenance, but also the contribution of the battery to providing system services such as control power more cheaply and quickly. This definition covers the costs of all grid levels and not just the effect on the connection grid level. In this sense, a battery is grid-friendly if it ensures that grid fees are reduced. This definition can be measured as the sum of the revenue caps of all German grid operators.

Network utility in the narrow sense. Network utility in the narrow sense exclusively comprises network congestion costs. This definition only takes into account redispatch and network expansion costs, but not, for example, the costs of balancing reserves.

Classification. There is no scientifically clear and objective definition of grid serviceability. This is particularly due to the fact that the distinction between market benefit and grid benefit is ambiguous because there is a large gray area between the two. For example, grid operators procure balancing power on markets, but the costs for this are collected via grid fees. If a battery reduces the costs of providing control power, this could therefore be interpreted as either grid-useful or market-useful (Figure2).

System utility and grid utility of batteries

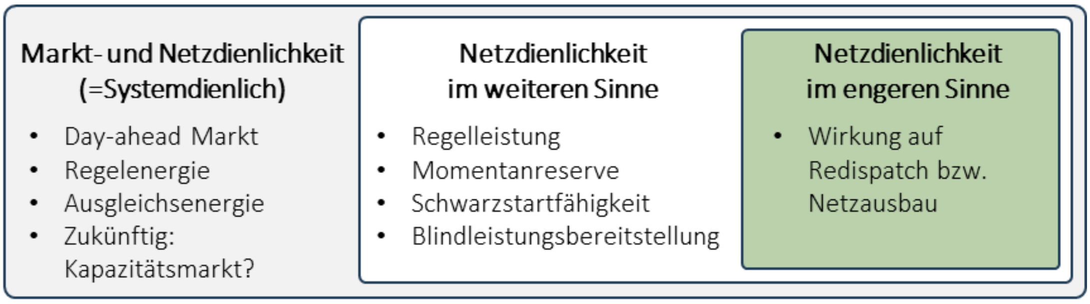

Figure2 : The added value of batteries in the electricity system is realized in electricity markets and in the grid. In order to determine the grid serviceability of batteries, a distinction must be made between market and grid serviceability. This is not possible in a clear-cut manner.

Characteristics of grid utility. Such definitions of grid utility are not only applicable to batteries. They also apply to electricity producers and consumers, as they also have an impact on electricity markets and grid bottlenecks.

Temporal aggregation. Virtually all assets can be beneficial to the grid at certain times and increase grid costs at others. An assessment of grid benefits can therefore only be made over a longer period of time and should take both aspects into account. For example, an aggregate value can be determined from the various temporary grid effects. Focusing exclusively on periods that place a strain on the grid, on the other hand, provides a distorted picture and does not seem sensible to us.

Continuous variable. An asset is therefore not simply either useful to the grid or not. Rather, its usefulness to the grid can vary, corresponding more to a gradation of gray tones than to a simple difference between black and white. The usefulness of batteries to the grid, for example, can be quantified in EUR/kW.

Limits of the definition. Strictly speaking, the definition of grid serviceability has no deeper analytical value. In the electricity system, the costs of the overall system should be minimized, not just the costs of grid operation. It would therefore be more appropriate to evaluate the system utility of plants and not just their grid utility. Grid utility is not even desirable per se: even a battery with negative grid utility can make economic sense if it reduces overall system costs, i.e., if its system utility is positive. The economic added value of this battery in electricity markets would then more than compensate for its grid load.

3 Internal vs. external effects

Need for regulatory action. Whether there is a need for regulatory and political action in the electricity system does not depend on the distinction between market and grid benefits. Rather, the decisive factor is whether a battery also "feels" its impact on the electricity system, i.e., whether it is financially rewarded for the benefits it generates and penalized for the costs it incurs. Regulatory action is appropriate if this is not the case and if the impact on the electricity system is significant.

External effects. When the actions of a market participant cause costs or benefits for third parties that are not compensated for by the price mechanism, economists refer to this as external effects. One example of an external effect is the impact of batteries on grid congestion. In the unified German electricity price zone, batteries, like all other market participants, are "blind" to grid congestion. They have no incentive to take the redispatch costs they cause into account in their investment and dispatch decisions. This is because it is not the battery operator who bears these costs, but the general public via grid fees. Such external effects prevent the full potential of batteries from being exploited. If the impact of external effects becomes too great, regulatory adjustments are necessary. The external effects of batteries occur primarily on the grid side, but not exclusively.

Internalized effects. Internalized effects occur when the impact of an action is fully reflected in the economic decision of the actor because it is reflected in prices or payments. For example, if a battery buys electricity cheaply and sells it at a higher price, the price fluctuations are an internalized effect—they directly influence the battery's revenues and costs. The sale of balancing reserves is also internalized, as the battery is paid for this system service.

Relevance. More important than the distinction between market and grid utility is therefore the distinction between internalized and external effects of battery operation (Table1).

Table1 : Internalized and external effects of large batteries in the electricity system

	Internalized ("sees the battery")	External effect ("does not see the battery")
Market	• Day-ahead auction • Intraday (auctions and continuous trading) • Future: Capacity market (?)	
Grid (in the broader sense)	• balancing reserves • imbalance energy • Instantaneous reserve (from 2026) • Black start capability • Reactive power (market procurement is currently being introduced)	• Fluctuations within the billing period • Power jumps between billing periods • Voltage
Grid (in the narrow sense)		• Grid bottlenecks / redispatch

4 Internalized effects on electricity markets

Internalized effects. When trading in electricity markets, batteries feel the costs and benefits they cause in the form of market prices. The effects of batteries on electricity markets are thus internalized. Therefore, in functioning markets, the revenues that batteries generate in these markets correspond to the welfare effects. In this section, we discuss the internalized effects of batteries in wholesale markets, in balance energy and in other system services.

4.1 Wholesale markets

Day-ahead market. In the day-ahead market, batteries generate welfare gains by shifting electricity from times of low prices to times of high prices. This allows more electricity to be sourced from low-cost generation sources and reduces the need to use expensive power plants. This lowers the overall economic costs of electricity generation. The principle is easy to explain: if the battery is charged at an electricity price of €10/MWh, additional low-cost generators are activated. If it is later discharged at €100/MWh, the necessary production from expensive peak load power plants, such as gas-fired power plants, decreases. The economic added value created in this way results from the amount of the price difference. Specifically, this added value consists of lower gas consumption, lower CO2 emissions, and no wear and tear from starting up the gas-fired power plant. Overall, the economic added value of batteries on the day-ahead market is significant, as we estimated in a study for ECO STOR. For example, a 100 MW battery would have generated added value of around €9.1 million on the electricity market in 2024 solely through its participation in day-ahead trading.

Intraday market. On the intraday market, batteries can generate welfare gains similar to those on the day-ahead market. Their particular strength lies in their high flexibility, which allows them to supply or absorb electricity at very short notice. If, for example, a power plant unexpectedly fails and intraday electricity prices rise sharply, a gas-fired power plant with high start-up and standby costs would have to step in without a battery. The use of the battery can avoid this expensive power plant deployment, as it supplies electricity at a lower cost. This results in real savings in electricity supply costs and an overall economic benefit.

Additional effects. In addition to these welfare effects, the participation of batteries in wholesale markets has additional desirable effects.

- Average electricity exchange prices may fall
- Less volatile electricity prices
- Improved integration of renewable energies
- Less electricity generation from gas-fired power plants
- Reduction in CO_2 emissions

Average electricity exchange prices. Batteries can lower average electricity exchange prices, especially when the merit order curve is convex, i.e., when it rises more sharply at high prices than at low prices. Batteries then have a strong price-reducing effect when they discharge during periods of high prices, while they only cause a slight increase in price when charging during periods of low prices. This reduces the average electricity price level. A study by Frontier Economics estimates that battery storage will reduce the average wholesale price by around €/MWh between 2030 and 2050.

Less price volatility. The use of battery storage leads to smoother electricity prices. By charging when prices are low and discharging when prices are high, batteries dampen price spikes and reduce the number of hours with negative prices. This reduces price volatility in the electricity market and thus also lowers the price risks for energy suppliers, businesses, and households with dynamic electricity tariffs. This reduces the need and, where applicable, the costs of hedging against price fluctuations.

Integration of renewable energies. Batteries can temporarily store electricity from wind and solar power plants that cannot be consumed at the time of generation. This reduces market-driven curtailment of renewable generation. As a result, their subsidy costs are reduced. According to a study by GEEC, battery storage could generate savings in renewable energy subsidies of between EUR 0.7 and 1.7 billion per year by 2030.

Less electricity generation from gas-fired power plants. Battery storage can partially replace expensive gas-fired power plants that would otherwise be used to cover short-term peak loads. Since gas-fired power plants are among the more cost-intensive generators, their reduced use leads to lower electricity generation costs. At the same time, gas imports are reduced, albeit to a limited extent.

Reduction in CO_2 emissions. Battery storage reduces CO_2 emissions from electricity generation by reducing electricity generation from gas-fired power plants. At the same time, the more stable price level also increases the utilization of coal-fired power plants, which partially offsets the reduction in emissions from gas-fired power plants, but overall the positive effect prevails. According to studies, battery storage could save several million tons of CO_2 in 2030, although the magnitude of the effect is subject to considerable uncertainty: Frontier Economics estimates CO_2 savings at around 6.2 million tons per year, while GEEC estimates only 1.3 and 2 million tons per year.

4.2 Control power and balancing reserves

Currently, the provision of balancing power and balancing reserves is a significant source of income for large batteries. This is because batteries are particularly well suited to offering these services due to their high flexibility.

No minimum generation. Thanks to their high flexibility, large batteries have a decisive advantage over conventional power plants when it comes to providing balancing energy: they can be flexibly ramped up and down. Conventional power plants, on the other hand, must run continuously to provide balancing power. This results in additional costs: for negative balancing power, conventional power plants must continue to run even when wholesale prices are low or negative in order to be able to reduce their output when necessary. For positive balancing power, they must reserve capacity, which incurs opportunity costs. If a battery replaces such a power plant in the provision of balancing power, these costs are eliminated. This reduces system costs, leading to real welfare gains.

Fewer emissions. In addition, fuel consumption and CO_2 emissions are reduced when a large battery replaces a thermal power plant in providing balancing power.

Faster responsiveness. Batteries can increase or decrease their output almost instantaneously to respond to deviations in the system balance or to follow a control signal. In the fastest form of balancing power, PRL, the supply power must be fully available within 30 seconds. With slower secondary control power, a response must only be noticeable 30 seconds after activation; the entire supply power must even be fully activated after five minutes. Batteries usually respond much faster without receiving additional compensation for this ("positive external effect").

Competition. By participating in these market segments, large batteries increase competition for control power provision and control energy supply, reduce excessive profits for existing providers, and contribute to more efficient pricing.

4.3 IMBALANCE ENERGY

In addition to participating in wholesale markets and providing balancing reserves and balancing power, batteries can also provide imbalance energy. This can be done either to compensate for schedule deviations in their own balance group or to compensate for foreseeable system imbalances ("co-regulation").

Balancing the company's own balance group. If a generation plant fails at short notice, it is no longer possible to purchase additional energy on the intraday market within the same accounting period . Instead, a battery belonging to the same company can step in. It provides energy immediately and bridges the gap until additional electricity can be purchased or generation is restored. For the electricity system, this use can mean real cost savings: if the battery steps in immediately after the failure, the control zone imbalance increases less sharply and less balancing reserves have to be activated by the transmission system operator. This reduces the total costs of balancing reserves activation.

Co-regulation. Co-regulation does not balance imbalances in one's own balancing group, but rather the expected imbalances in the entire control area. For example, in the event of a shortfall in the power system, a battery would feed out more energy than it has marketed. If the system imbalance can be reliably anticipated and co-regulation also coincides with the system imbalance within the quarter hour, co-regulation reduces the use of balancing reserves. This lowers the costs of the electricity system, as the battery would only co-regulate if it could provide electricity more cheaply than balancing reserves. The excess energy supplied is compensated for by the imbalance price, so schedule deviations are internalized on a quarter-hourly average. This behavior is not officially permitted in Germany – unlike in most neighboring countries. However, co-regulation is demonstrably taking place and is already reducing the costs of control energy activation, presumably to a significant extent.

4.4 Other system services

System services. In addition to providing balancing reserves and trading on wholesale markets, batteries can also provide other system services. These include, in particular, reactive power, instantaneous reserve, and black start capability. However, these currently play only a minor role in terms of battery revenues.

Reactive power. Reactive power is required for voltage maintenance and is indispensable for the operation of three-phase AC grids. Until now, conventional power plants have been the main source of reactive power via their generators, alongside special grid operating equipment. A minimum supply is stipulated in the grid connection conditions, but plants could also supply higher amounts of reactive power (at additional cost, e.g., for losses). However, batteries must also provide reactive power in accordance with grid connection conditions. If grid operators do not receive sufficient reactive power from connected plants from the mandatory contributions, they must procure the additional demand on the market. This means that the provision of reactive power exceeding the minimum requirements is internalized. This gives batteries an incentive to provide more than the mandatory amount of reactive power.

Instantaneous reserve. Instantaneous reserve is the automatic, immediate release or absorption of energy by plants in response to power imbalances. It is necessary to stabilize the frequency in the power grid and limit the rate of change in frequency in the event of a fault . Until now, instantaneous reserve has also been provided primarily by the rotating masses of conventional power plants due to conceptual and system-related reasons. However, as generation plants based on rotating synchronous generators are increasingly being replaced by converter-controlled plants, other sources are becoming necessary. From 2026, German transmission system operators will pay for the provision of instantaneous reserve. Remuneration will be based on fixed prices, the amount of which will depend on the availability and direction of the power offered. Batteries can in principle provide instantaneous reserve, but must be equipped with grid-forming inverters for this purpose. This may become worthwhile with the introduction of remuneration.

Black start capability. Large batteries could be used as black start-capable systems, i.e., to restore power supply after a large-scale grid failure. This capability is particularly important for grid stability in regions without suitable conventional power plants.

5 External effects in the grid

External effects. Batteries have a real impact on the power system without this having any financial consequences for the battery operator. As with generators and consumers, this particularly affects the power grid: batteries have no incentive to consider the impact of their operation on the power grid or even to behave in a way that specifically benefits the grid. These external effects mean that the economic potential of the battery is not fully exploited.

Aspects. We see five key external effects of batteries in the power grid and market:

1) Effect of battery use on redispatch (plannable)
2) Effect of short-term changes in use on grid bottlenecks (unpredictable)
3) Misguided incentives within the 15-minute balancing period
4) Schedule jumps between balancing periods
5) Influence on voltage maintenance

5.1 Effect of battery use on redispatch

Redispatch demand. Batteries are currently operated without consideration of grid congestion. In the unified German bidding zone, electricity prices offer no incentive for purely market-driven batteries to take the current grid situation into account. The effect of battery storage on grid congestion is therefore purely random: their operation can both reduce and exacerbate foreseeable grid congestion, depending on how battery use and grid congestion coincide in terms of time and location. In a study for ECO STOR, we showed that batteries at many locations in Germany currently relieve the grid on average: according to our calculations, each kW of battery capacity reduces redispatch costs by around €3-6 per year. However, this is a purely empirical finding for the status quo and not a systematic effect.

5.2 Effect of short-term changes in usage on bottlenecks

Short-term grid bottlenecks. Unlike many other technologies, large batteries can provide the flexibility required by the electricity market or within the scope of system services even at very short notice. This is fundamentally a major advantage for the electricity system, but it also brings with it new operational challenges. Short-term changes in battery deployment must be reported to the transmission system operator, but often cannot be taken into account in the planned redispatch, as this usually requires several hours' lead time – for example, for load flow calculations to detect congestion, determining countermeasures, notifying plant operators, and balancing the books.

Example. An example illustrates this: If clouds move over southern Germany at short notice, PV generation there drops and intraday prices across Germany rise sharply. Batteries in northern Germany then discharge almost simultaneously to take advantage of the higher prices.

This causes additional electricity to flow from north to south, exacerbating existing grid bottlenecks because the electricity is not generated where it is needed. A bottleneck can occur even more quickly if PV generation and batteries are part of a balancing group. This is because within a balancing group, balancing may take place up to the point of delivery.

Impact. Such short-term deployments cannot be "remedied" by redispatch processes because these are already planned and can no longer be flexibly adjusted. As a result, other plants have to be curtailed at short notice, which usually has to be compensated for by expensive balancing reserves. Similarly, spontaneous battery use does not prevent redispatch that has already been activated and the associated costs, as the processes cannot be reversed.

5.3 Misguided incentives within the balancing period

Within the balancing period. The balancing period in the European electricity market is 15 minutes. All balancing groups must be balanced on average over the balancing period. The electricity system, on the other hand, must be balanced at all times. For highly flexible plants, this very different time resolution is problematic because they can change their operating mode significantly within the balancing period.

Example. A battery, for example, can discharge at high power shortly before the end of the balancing period to compensate for an otherwise foreseeable shortfall in its own balancing group. As a result, the balancing group is balanced on average, but within the quarter hour it is first under-covered and then possibly heavily long. Both can lead to the need to activate balancing reserves, even though the balancing group is balanced on average. Thus, batteries can reduce or increase the demand for balancing reserves, depending on whether they compensate for imbalances simultaneously or with a time delay.

5.4 Schedule jumps between balancing periods

Between balancing periods. Batteries can perform very rapid load changes at the boundaries of billing periods. Most other market participants, however, especially conventional power plants and consumers, change their output with flatter gradients and over longer time intervals. The interaction of highly flexible batteries with abrupt power jumps and slower other market participants leads to temporary imbalances in the system balance at the transitions between two balancing periods. These must be compensated for by using balancing reserves and thus cause additional system costs.

5.5 Influence on voltage stability

Voltage maintenance. In distribution grids in particular, the behavior of large grid users, such as large batteries, can have a significant impact on the grid voltage. The grid voltage rises when additional power is fed into the grid and falls when additional power is withdrawn. At the same time, grid operators must comply with specified limits for safe grid operation and provide connected consumers with adequate voltage quality. They achieve this, for example, by specifically changing the transmission ratio of control transformers in substations or by supplying or withdrawing reactive power in grid operating equipment or customer installations. In many distribution grids, the voltage is regulated to a specified value by a regulating transformer at the lower voltage level. If the voltage deviates from the setpoint, the regulation triggers a step change in the transformer's tap changer.

Effect of batteries. With slow changes in the connected load and feed-in, typically only a few changes in the tap position are required per day. Batteries that frequently switch back and forth between grid consumption and grid feed-in cause additional voltage fluctuations and thus require additional readjustment of the transformer tap setting, especially if the battery does not compensate for the voltage changes caused by its active power with corresponding reactive power feed-in or withdrawal. Depending on how the batteries are operated, this can lead to a multiplication of tap changes. Since these are fundamentally wear-inducing, premature wear of regulating transformers in substations with batteries connected on the undervoltage side is at least conceivable.

6 Instruments for strengthening grid serviceability

Solution space. The challenges discussed in the previous section can be addressed on the one hand by measures taken by grid operators and on the other hand by adapting battery use.

Measures taken by grid operators. A long-term solution to grid congestion is grid expansion. Predictable grid congestion caused by batteries can be resolved through redispatch, as is the case with all other market participants. In theory, grid operators could also reserve grid capacity to address short-term grid congestion, e.g., through activation of balancing power.

Battery use. However, the current debate focuses on instruments that restrict or change battery use in order to strengthen the grid utility of batteries. This study structures the very different approaches and ideas on this topic. In particular, we work out which of the approaches mentioned address which problems and which do not – in other words, how the problems and solutions fit together.

Two categories. We group the instruments into two areas: those that address grid congestion (effects 1 and 2) and those that address the other effects (3, 4, 5). This makes sense because there is no overlap between these instruments: instruments that address grid congestion do not solve any of the other problems, and vice versa.

6.1 Instruments for avoiding grid congestion

Grid bottlenecks. To prevent batteries from causing or exacerbating grid bottlenecks, there are three basic approaches:

- Introduce a geographical component in the electricity market (possibly only for batteries)
- Restricting the use of grid connections for batteries
- Restricting short-term flexibility marketing (i.e., shortly before delivery)

Geographical component. In the unified German bidding zone, all market participants are blind to the grid, i.e., they do not take grid congestion into account in their deployment decisions. This also applies to batteries. The introduction of local signals could change this. Four different approaches to local incentives are being discussed:

- Price zone division
- Separate regional electricity market for large batteries
- Dynamic regional grid fees (for large batteries)
- Regional restriction of short-term electricity trading

A price zone division would only allow all market participants, both with lead time and at short notice, to engage in trading transactions that do not cause bottlenecks between the different price zones. A separate regional electricity market for large batteries, on the other hand, would only impose these restrictions on batteries. Dynamic, regionally differentiated grid fees, as proposed by us in a BNetzA consultation, would approximate the missing local signals from the wholesale market. Unlike market prices, these would have to be set in advance and would generally not adequately reflect short-term regional price differences. Regional grid fees would therefore not be able to prevent short-term grid bottlenecks. This could be achieved, however, by imposing regional restrictions on short-term electricity trading. From that point on, only trading transactions that do not cause grid bottlenecks between regions would be permitted.

Restriction of grid connection. Targeted restrictions on grid connection could also reduce the redispatch requirement caused by the battery and limit short-term grid congestion. Such restrictions are often discussed under the heading "Flexible Connection Agreement" (FCA), although this name is easily misunderstood because it actually refers to a restriction on battery flexibility. FCAs are usually imposed as conditions when granting grid connection. One variant is that unlimited grid access is therefore not guaranteed at all times. In this case, the grid operator would be allowed to switch off the battery in the event of imminent grid overload ("n-0 connection"). Alternatively, grid operators could define restrictions on battery operation in redispatch situations. For example, battery discharge could be prohibited if curtailment is taking place in the region. Such approaches are also discussed under the heading "guidelines for battery operation." Overloading the grid connection can have a similar effect in generation-dominated regions: a battery that shares a connection line with limited capacity with a PV park might not be able to feed into the power grid at full capacity at the same time as the PV park. However, the plant operator would be able to curtail the PV park in order to offer control power with the battery instead.

Slowing down batteries. A third, frequently discussed solution is to restrict the flexibility marketing of batteries in the final hours before delivery. This prevents batteries from causing short-term grid bottlenecks (but does not prevent them from causing grid bottlenecks at all). Such "shackles" prevent batteries from causing grid bottlenecks through short-term trading transactions that can no longer be remedied by proactive redispatch. This could be achieved, for example, by bringing forward the gate closure time of the intraday market by several hours. Electricity trading would then no longer be possible until five minutes before the delivery quarter-hour, as is currently the case, but would end much earlier. However, this would entail considerable welfare losses: batteries used on the wholesale market would then no longer be able to compensate for short-term forecast errors, e.g., in wind and PV generation. Alternatively, there are discussions about limiting the maximum control power or intraday marketing. This would make the use of batteries more predictable, as only a small part of their power could be adjusted at short notice. However, these approaches do not prevent batteries from exacerbating grid congestion through their day-ahead marketing ( ).

Overview. All three approaches discussed here for reducing grid congestion limit the need for redispatch or reduce short-term grid congestion. Some of the instruments help with both, in particular regional wholesale prices (Table2).

Table2 : Approaches to avoiding or compensating for grid congestion using batteries

Approach	Implementation	Limited redispatch (1)	Limited *short-term* grid congestion (2)	Reduces jumps within the MTU (3)	Reduces jumps between MTUs (4)	Reduces local voltage fluctuations (5)
Introduce geographical component	Regionalized wholesale market (price zone division)	Yes	Yes	-	-	-
	Separate regional electricity market for large batteries	Yes	Yes	-	-	-
	Dynamic regional grid fee for large batteries	Yes	-	-	-	-
	Regional restriction of short-term electricity trading	-	Yes	-	-	-
Restriction of grid connection	Guard rails in redispatch situations	Yes	Yes	-	-	-
	Connection by network operator ("n-0" connection)	Yes	Yes	-	-	-
	Overbuilding of the grid connection, e.g., with a PV park	Yes	Yes	-	-	-
Batteries slow down shortly before delivery	Earlier gate closure	-	Yes	-	-	-
	Limitation of balancing power marketing per plant	-	Yes	-	-	-
	Limitation of intraday marketing ("feasibility range")	-	Yes	-	-	-

6.2 E INSTRUMENTS FOR PROBLEMS OTHER THAN GRID CONGESTION

Other instruments. Other instruments are needed to address the other three external effects of large batteries: misguided incentives within the 15-minute balancing period, schedule jumps between balancing periods, and impact on voltage maintenance. These include shortening the balancing period or specifying certain operating modes, in particular limiting ramps.

Shortening the balancing period. Reducing the balancing period (market time unit, MTU) from 15 minutes to a significantly shorter period, e.g., one minute, would mitigate effects that occur within a balancing period in particular. One problem here is that the quarter-hourly average value relevant for billing can differ significantly from the instantaneous value of battery feed-in/withdrawal relevant for various system issues, in particular the current power balance. Although such differences cannot be ruled out in theory even with a shortened billing period, but the feasibility of, for example, co-control strategies that rely on observing the control zone balance over longer periods and deliberately deflecting the own balancing group with very high power over short periods at the end of the billing interval would be significantly more difficult, simply because the necessary information is not available without delay and with the necessary synchronicity. Shortening the balancing period would also improve the ability to use batteries to precisely compensate for rapid changes in the feed-in/withdrawal of other grid customers, such as the morning/evening PV ramp. However, such a reform would affect all players in the electricity market and such diverse aspects as exchange trading and the imbalance price calculation, with relatively far-reaching European policy reform requirements. Shortening the balancing period is therefore more of a long-term option.

Ramp limitation. Batteries can change their feed-in/withdrawal practically without delay across the entire achievable power range and thus significantly faster than other relevant resources in the electricity system. However, to ensure that no significant power balancing imbalances occur when operating points change at the system level, e.g., when schedules change, the power change rates of the resources involved should be coordinated with each other. Limiting the ramps of storage operation could help to better coordinate the behavior of batteries and other resources. With appropriate design, in particular consideration in balancing group billing, this does not have to result in any disadvantages for batteries. Ramps in storage operation could also be considered within billing intervals because they allow, for example, other grid operating resources or control power plants to perform coordinated "readjustment."

Limiting operating point changes. The potential problems caused by batteries with regard to voltage maintenance result primarily from increased wear on the tap changers of the regulating transformers, which is due to frequent changes in the operating mode of the batteries and the resulting voltage changes. If the possibility of changing the operating points were limited, the need to adjust the transformer tap settings would also be reduced. However, such a measure would entail considerable restrictions on battery operation and associated welfare losses, which would not necessarily be more than offset by the savings in transformer wear costs.

Reactive power control using batteries. If batteries were required to contribute to voltage reactive power control beyond the technical connection rules in order to balance the effects of their active power feed-in/withdrawal on the grid voltage as far as possible, the need to reclassify transformers and thus reduce their wear and tear would be reduced . However, it should be noted that this does not provide a complete solution to the problem, as the voltage control of the batteries would refer to their connection point, which is usually not identical to the point in the grid to which the voltage control refers. Even with appropriate specifications, it is therefore not possible to completely avoid readjusting the transformers.

Implementation	Limited redispatch (1)	Limited *short-term* grid bottlenecks (2)	Reduces jumps within the MTU (3)	Reduces jumps between MTUs (4)	Reduces local voltage fluctuations (5)
Shortening of the balancing period (MTU)	-	-	Yes	Yes	-
Limitation of storage operation ramps	-	-	Yes	Yes	Yes
Limitation of reversal within the accounting period	-	-	Yes	-	-
Specifications for reactive power control using batteries	-	-	-	-	Yes

7 Evaluation criteria for instruments

Wide range of instruments. In the previous chapter, we explained that there are very different approaches to solving even the same problem. Most instruments address one specific problem, but do not help with others. Due to the different problems, a coordinated set of instruments seems to be a sensible goal. However, the introduction of several uncoordinated instruments for the same problem should be avoided.

Design. Below, we make eight recommendations that should be taken into account when designing instruments:

1) The network benefits should be balanced against the restrictions on market operations.
2) Instruments should not only prevent network-damaging behavior, but also promote network-friendly behavior.
3) Restrictions on battery operation should be as targeted as possible.
4) Pure location control is not sufficient; above all, suitable dispatch incentives are needed.
5) Rule-based instruments that apply on the basis of objectifiable data
6) Incentives should take all grid levels into account
7) Instruments should be as predictable and assessable as possible
8) Green electricity storage facilities are not a suitable instrument

Weighing up welfare effects. Every regulatory instrument must be weighed up in terms of its network benefits and the resulting restrictions on market operations. The overall welfare effect is the sum of market and network benefits. A measure that reduces redispatch requirements but at the same time severely restricts the flexibility of batteries on the wholesale market is not desirable from an economic perspective. The measure is only economically justified if the additional network benefits more than compensate for the reduced added value on electricity markets.

Promote grid-friendly behavior. Regulatory instruments must not be limited to preventing behavior that is harmful to the grid. They should also create positive incentives for batteries to actively contribute to grid stability. Prohibitions and restrictions prevent misguided incentives, but they do not promote optimization in terms of overall welfare. Only when instruments include economic incentives in addition to restrictions will operators adjust their operating behavior in a way that benefits both the market and the grid. One example of this is dynamic, time- and location-variable grid fees that reflect local bottlenecks. They enable operators to reduce grid costs and maximize their revenues at the same time through the targeted use of their batteries. A pure prohibition system, on the other hand, would leave the potential for grid relief untapped.

Targeted restrictions. Restrictions on battery use should be as targeted as possible to avoid collateral damage in the market. Blanket restrictions , such as bringing forward gate closure by several hours, may reduce short-term grid bottlenecks, but they lead to significant welfare losses because batteries can no longer contribute to the short-term smoothing of forecast errors. Signals that are differentiated in terms of time and location and only take effect in actual bottleneck situations are more effective in addressing this problem. For example, a temporary restriction on grid feed-in in PV-dominated regions during hours of high solar production may be appropriate, whereas a general ban during all midday hours throughout the year would be inefficient. The more precise the regulation, the lower the economic damage.

Location control. Location control of battery storage systems is not sufficient to systematically reduce bottlenecks in the transmission grid. In a study for ECO STOR, we showed that a battery in northern Germany has a similar impact on redispatch requirements as a battery in southern Germany. The decisive factor is therefore not *where* a battery is located, but *how* it is operated. Instruments that are limited exclusively to location control, such as regionally differentiated construction cost subsidies, are therefore insufficient to reduce redispatch costs. However, a high spatial concentration of batteries, for example when connecting very large capacities to a substation, is risky, especially if there is a high regional concentration of control power. For this reason, location control appears to be useful to a limited extent. In any case, however, it should be combined with incentives for grid-friendly operation.

Regulation-based instruments. Restrictions on battery use can be sensible and efficient in certain situations, but they pose significant governance risks if their application is left to the discretion of individual grid operators. Currently, there is a structurally unfavorable incentive for grid operators: connecting batteries in the grid area usually incurs local costs, while the resulting benefits—such as a grid- or system-friendly effect—often accrue not locally, but at higher grid levels. Since these supraregional benefits are not reflected in the grid fees of the respective distribution grid operator, connecting a large battery can increase local grid fees in the short term without directly benefiting the connected consumers. This creates an incentive to delay or even avoid battery projects. To prevent such misguided incentives, grid operators should not be free to decide on restrictions on battery operation or grid access. Instead, restrictions should be based on transparent indicators that are uniform and comprehensible for all market participants. Such rule-based parameterization minimizes arbitrary interventions, strengthens investment security, and ensures that battery storage facilities can be built where their contribution to system stability and economic welfare is greatest.

All grid levels. Since large batteries affect not only the connection grid level but also all higher grid levels, incentives and control instruments should always take the entire grid structure into account. Focusing on the connection grid level alone is insufficient, as the following example shows. In the grid area of Stromnetz Berlin, the highest loads in the medium voltage range typically occur on winter evenings. The highest electricity consumption from the transmission grid, on the other hand, occurs at noon in summer because the CHP plants widespread in the city are not running at this time. If a large battery in Berlin's medium-voltage grid absorbs additional electricity during the summer midday hours, it can relieve its own grid level. At the same time, however, this increases the load on the transformer to the transmission grid. This example illustrates that the same operating mode of a battery can have opposite effects at different grid levels.

Predictability of grid restrictions. Predictability of regulatory conditions is crucial for investors and operators. Uncertain instruments or those that can be changed at short notice increase risk and thus capital costs, which makes investment in storage technologies more difficult. Restrictions on grid access should therefore not be based on unpredictable decisions by individual grid operators, but should follow clearly defined rules with known upper limits. For example, in the case of flexible grid connection, it may make sense to guarantee free grid access for a minimum number of hours per year, as is the case in the Dutch system. This keeps the risk quantifiable and allows it to be factored into investment decisions.

Green electricity storage. Green electricity storage facilities are only charged with electricity from a directly connected wind or PV park, but not from the power grid. Grid operators often assume that such operation is more "grid-friendly" than battery storage facilities, which are also charged from the power grid. However, this restriction on charging severely limits the storage facility's options and reduces its ability to create added value on the electricity market. Instead of responding flexibly to price and grid signals, the storage facilities are tied to a single power source. This means that although the storage facility is not expected to have a negative impact on the grid when storing energy, it also does not relieve the grid. There is also no reason why discharging from a green electricity storage facility should be more beneficial to the grid. There are therefore better instruments for operating storage facilities in a way that benefits the grid while at the same time less hindering the provision of flexibility for the electricity market.

8 Conclusion

Need for action. Large batteries can balance out fluctuations in renewable energy generation and provide important system services. In doing so, they add significant economic value to the electricity system. At the same time, the impact of large batteries on the electricity system is only partially internalized. The external effects of large batteries occur primarily in the electricity grid; the most relevant effect is that of batteries on grid congestion. There is therefore a need for political and regulatory action in this area.

Instruments. However, the current cacophony of largely uncoordinated instruments poses risks for the further ramp-up of this technology class, which is important for the energy transition. Often, it is not entirely clear from the proposals which problems the proposed solutions are actually intended to address. Furthermore, the debate often overlooks the fact that the grid utility of storage systems is not an end in itself: ultimately, instruments should be evaluated on whether or not they achieve economic benefits. Many of the instruments currently under discussion appear unsuitable, as their grid benefits, depending on their specific design, are significantly outweighed by considerable economic damage.