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# To site or not to site

## A framework development for battery energy storage system siting using data-driven insights

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Civilingenjörsprogrammet i system i teknik och samhälle

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## Abstract

The objective of this study was to develop a structured framework for identifying suitable locations for battery energy storage systems (BESS) in Germany. The framework was constructed using insights from literature, German grid information and expert dialogs. The framework combines technical, economic and spatial factors relevant for BESS siting. To test the practical use of the framework, a case study was conducted based on the 110 kV grid in northeast Germany. A simplified power grid model was constructed in Python using PandaPower and included wind power injection, regional demand and three potential BESS locations.

The framework focused on evaluating how relevant each identified siting factor is and how the factor could be applied using publicly available open data. By mapping the importance of each factor against its data availability, a four-field analysis was performed to determine which factors are most suitable for inclusion in an initial screening tool. The result of the framework shows that residual energy, proximity to substations and land suitability was the factors with the highest relevance and most available data. The case study shows that Lubmin and Greifswald perform similarly well as BESS sites, while Wolgast shows significantly lower total usage and is less suitable for BESS placement.

The study concludes that the framework enables initial BESS siting selection based on the identified factors and open data. Further development could integrate economic factors, larger regional data set of Germany and automated decision making.

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# Populärvetenskaplig sammanfattning

Elektrifieringen av samhället pågår i allt snabbare takt, vilket ställer nya krav på att elsystemet ska kunna leverera el på ett tillförlitligt och hållbart sätt. När fossila bränslen fasas ut och ersätts av förnybara energikällor som vind- och solkraft förändras förutsättningarna för elproduktion. Dessa förändringar innebär att elsystemet behöver hantera större variationer i både produktion och konsumtion, samtidigt som behovet av att nå klimatmålen är mer brådskande än någonsin. Tyskland har satt upp ambitiösa mål, med en fossilfri energisektor till år 2045 och en betydande andel el från variabla energikällor som vind och sol. Detta ställer stora krav på deras elnätet, som måste kunna hantera och transportera stora mängder el på ett effektivt sätt utan att äventyra stabilitet och leveranssäkerhet. En central utmaning är att elsystemet måste bli mer flexibelt för att kunna anpassa sig till dessa förändrade förhållanden. Variabla energikällor innebär att överskott och underskott på el kan uppstå vid olika tider på dygnet och året. För att möta dessa variationer krävs lösningar som kan lagra el när det finns ett överskott och leverera tillbaka när efterfrågan är högre. Batterienergilagringssystem (BESS) lyfts fram som en sådan lösning och har en viktig roll i framtidens energilandskap.

I denna studie har ett ramverk tagits fram för att identifiera de mest lämpliga platserna för att bygga storskaliga batterilager i Tyskland. Ramverket bygger på en kombination av faktorer, där bland annat närhet till elnätsinfrastruktur, lokal produktion av förnybar el och markens användbarhet ingår. Syftet är att skapa ett praktiskt verktyg som kan ge beslutsfattare och planerare ett stöd i det fortsatta arbetet med att implementera batterilager. För att undersöka ramverkets praktiska tillämpning genomfördes en fallstudie i norra Tyskland, där området kring Lubmin valdes ut. Området bedöms som särskilt intressant eftersom det både har starka elnätsförbindelser och stor potential för att ta emot el från havsbaserad vindkraft. Tre tänkbara platser för batterilager analyserades och deras förmåga att bidra till en mer flexibel och pålitlig elförsörjning jämfördes. Genom att simulera olika scenarier visades att vissa platser erbjuder bättre förutsättningar än andra, exempelvis när det gäller att lagra överskottsel från förnybara källor eller minska belastningen på redan ansträngda elnät.

Resultaten från studien indikerar att en strukturerad metod för val av plats för batterilager kan ge ett viktigt bidrag till energiomställningen. Genom att väga in flera olika faktorer i ett tidigt skede kan fokus läggas på de platser som har störst potential att stödja en långsiktigt hållbar elförsörjning. Samtidigt framkommer det att det finns frågor som behöver undersökas vidare. Däremot finns det fortfarande barriärer för denna typ av studie då tillgången till publika data är begränsad. Sammanfattningsvis bedöms detta arbete kunna bidra till att påskynda identifieringen av nya platser för batterilager och därigenom stärka Tysklands möjligheter att nå sina klimatmål. Ramverket kan även användas som grund i andra länder som står inför liknande utmaningar i sina energisystem. Genom att göra en noggrann bedömning av var batterilager kan göra störst nytta kan en viktig pusselbit läggas i omställningen till ett elsystem som klarar både framtidens behov och klimatets krav.

# Acknowledgements

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# 1. Introduction

In response to the pressing climate changes, an international treaty called the Paris Agreement was introduced in 2015 [1]. A total of 196 parties signed the legally binding agreement where the overall goal is to reduce greenhouse gas emissions to limit the rising global temperature and thereby prevent further global warming. In 2019, the European Union (EU) launched its growth strategy called the European Green Deal [2]. The goal is to be the first climate-neutral continent 2050 and to reduce net greenhouse gas emissions by 55% 2030, compared to 1990 levels.

Germany, as a signatory of the Paris Agreement and a core part of the European Green Deal, has long been at the forefront of energy transition efforts. The roots of Germany's Energiewende trace back to the 1970, when public opposition to nuclear power sparked a search for alternative energy sources [3]. The term Energiewende, officially introduced in 1980 by the Öko-Institut, has since evolved into a widely recognised concept describing the transformation of energy systems towards sustainability through renewable energy, energy efficiency and reduced reliance on fossil fuels.

Based on the European Green deal, Germany set a national energy plan in 2023, later updated this year [4]. The so called *Netzentwicklungplan* (network development plan) declares a 65% reduction in greenhouse gas emissions by 2030 compared to 1990 emissions level and full climate neutrality by 2045. To enable this transition, Germany will phase out the burning of coal by 2038 after the completed nuclear decommissioning in 2023. The country will at the same time increase its installed capacity of variable renewable energy (VRE). Unlike conventional generation, which can be dispatched on demand, VRE is weather dependent and introduces both variability and uncertainty into the grid. Therefore, as the German energy system becomes increasingly reliant on variable renewable sources like wind and solar, the 2025 plan emphasises major investments in grid expansion, offshore integration and energy storage to ensure stability and flexibility in the future power system.

One such solution constantly gaining increased attention is the deployment of Battery Energy Storage Systems (BESS). These systems can play a vital role in storing surplus energy, balancing supply and demand and enhancing grid stability in a system dominated by renewables. As Germany progresses toward climate neutrality by 2045, determining how and where to best integrate BESS becomes a crucial planning task. This study addresses that challenge by developing and testing a structured framework to support the screening of potential BESS sites.

## 1.1 Aim

The aim of this study is to develop a framework for identifying suitable locations for BESS, using data-driven insights to support future implementation of BESS in Germany.

The objectives for this study are:

- How would a structured framework for BESS siting look like to support scalable data-driven location analysis?
- How can the identified siting criteria be evaluated and ranked?
- What does the application of the framework reveal when tested on a case study of a simplified, real-world-inspired grid model?
- Delimitations

This study is limited to the German electricity system and assumes a future-oriented perspective targeting the year 2045. The study assumes that Germany will reach its goal of climate neutrality 2045. The study does not analyse current operational conditions but instead focuses on the anticipated grid development and integration challenges associated with Germany's transition to a fully renewable power system, including large shares of VRE.

# 2. Theoretical background

This chapter begins by introducing the ongoing energy transition and the role of BESS in supporting grid stability and flexibility. It then focuses on the German power system, outlining its structure, challenges and relevance for BESS deployment. This contextual foundation is essential for understanding the chosen case study area. The chapter continues by exploring technical applications and market opportunities for BESS, which contribute to a broader framework for optimal placement. Finally, previous research on BESS siting is reviewed and potential research gaps are identified to motivate the methodological approach of this study.

## 2.1 The energy transition and role of flexibility

Flexibility in the power grid is defined as the power system's ability to handle variations and uncertainties in production, demand and grid capacity [5]. As the power system evolves towards only renewable energy production, a broader range of actors must adapt how they consume and produce electricity. Flexibility is essential for integrating higher shares of VRE sources, such as wind and solar, which are key in achieving climate targets [6]. Their intermittent nature introduces challenges such as power fluctuations, grid instability and reduced system inertia, meaning the natural ability of large rotating generators to stabilise frequency by resisting sudden changes is reduced. This is because, as conventional power plants are phased out, the variability of electricity supply increases. Unlike conventional plants that can adjust their output to match demand, wind and solar generation are weather-dependent, leading to fluctuating production [7].

Flexibility in the grid can contribute in different ways, at different hours [5]. It helps balance energy availability over time by addressing seasonal and year-to-year variations as well as fluctuations in residual loads. It also supports frequency regulation by managing short-term deviations and maintaining system stability. In addition, flexibility can relieve transmission constraints, tackle limited grid capacity and reduce the risk of overloads. As electricity consumption increases and new activities connect to the grid, the availability of resources that can provide flexibility will also grow. However, unlocking this potential will require new approaches and collaboration among all involved stakeholders.

In the EU context, the flexibility need is according to the European Energy Agency projected to double by 2030, driven by the rapid increase in renewable electricity generation [8]. The need is thereafter projected to increase even more. To maintain system stability, the energy system must balance positive and negative residual demand using non-fossil flexibility options such as energy storage, demand response and cross-border electricity exchange, see Figure 1.

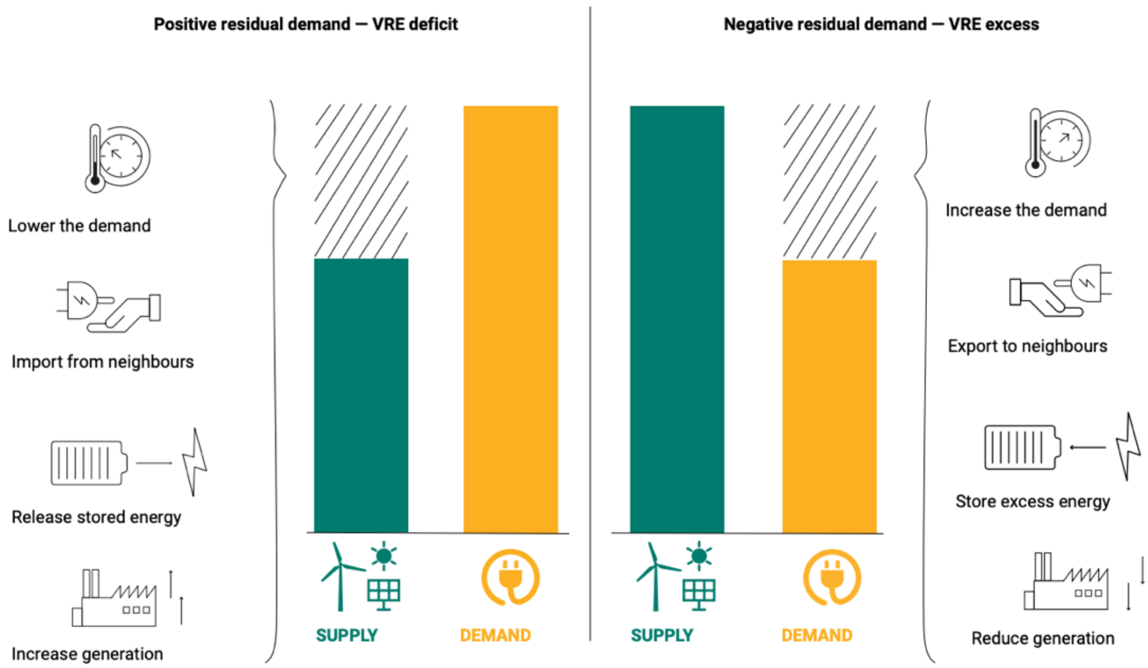


*Figure 1. Different ways to handle positive and negative residual demand when there is a VRE deficit or excess [8].*

Moreover, while the total need for non-VRE generation is expected to decline by nearly 50%, some rare but critical hours will still require high-capacity flexibility as weather conditions might be unfavourable [8]. These events, known as Dunkelflaute, occur when there is very little wind or solar generation available, making backup resources essential, even if only used occasionally. Among the various flexibility options, BESS is highlighted as a key enabler [6]. It allows surplus renewable energy to be stored during times of excess production and discharged when there is a deficit, making it central to balancing short-term fluctuations and reducing curtailment. As illustrated in Figure 1, storage can be applied in both variable VRE deficit and surplus situations, which strengthens its role as a cornerstone in future flexibility strategies [8].

Germany stands out as a leading case in the energy transition, with ambitious targets for decarbonisation and a high share of VRE sources [3]. This makes the German power system relevant for analysing the role of flexibility and the potential contribution of BESS. The following section introduces the German electricity system to provide a foundation for understanding the conditions and challenges relevant to BESS deployment in the selected case study area.

## 2.2 The German power system

The German grid is part of the interconnected European power system. The European grid operates at three main voltage levels [9]. The high-voltage transmission network usually uses 400 kV for long-distance and cross-border transmission, the second level is 220 kV and the third 110 kV. Regional distribution networks use medium voltage, typically starting at 110 kV and going down to lower levels. While the 400 kV level is standard for transmission across most of the EU, Germany uses 380 kV.

As shown in Figure 2, the European grid is divided into four major synchronous areas; the Continental synchronous grid, the Nordic synchronous, the British grid and the Irish synchronous grid [10]. These grids are often linked via high voltage direct current (HVDC) interconnections, enabling power exchange between asynchronous systems. Despite some variations, the EU power grid is designed to facilitate cross-border electricity trade and secure energy supply while maintaining grid stability and efficiency [5] [6].

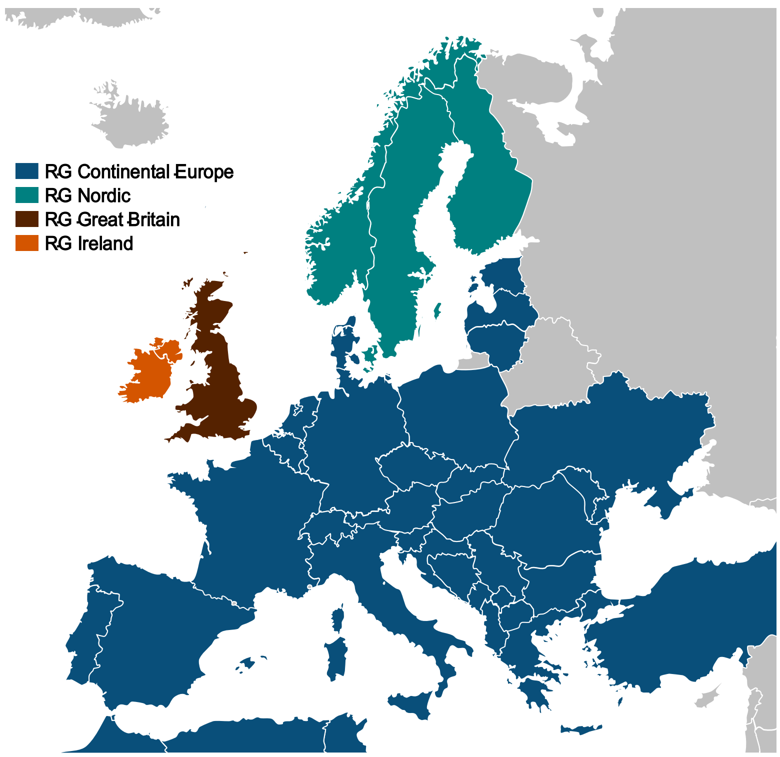


*Figure 2. Synchronous areas of Europe [11].*

There has been a shift in recent decade, EU is moving from a few centralised traditional production sites toward many decentralised smaller productions [12]. In 2010, did the German government presented its energy and climate policy framework for the energy transition, outlining targets and strategies for achieving a sustainable energy system by 2050 [13]. The framework established climate goals focused on reducing greenhouse gas emissions, targeting a 40% reduction by 2020, 55% by 2030 and 80–95% by 2045, all compared to 1990 emission levels. This transition relies on expansion of renewable electricity generation, with targets of achieving 50% of gross electricity consumption from renewables by 2030 and 80% by 2050. Achieving these targets requires not only the deployment of renewable generation but also substantial changes to the electricity grid and markets. This goal has since been updated to 100 % renewable and climate neutral by 2045 across all of Germany [14].

### 2.2.1 Grid structure and market design

Germany's electricity grid is divided into four transmission system operators (TSOs), each responsible for maintaining, operating and developing the high-voltage transmission infrastructure within their region [9]. The four companies in charge of the German grid are Tennet, 50Hertz Transmission, Amprion and TransnetBW. These four TSOs manage grid expansion and maintain stability, ensuring the system frequency remains at 50 Hz and that voltages stay within technical limits to prevent equipment damage or consumer disruption [15]. The German transmission grid operates at 380 kV and 220 kV, while regional distribution system operators (DSOs) handle sub-transmission and distribution at lower voltages, from around 110 kV down to the standard 230 V supplied to end users. Figure 3 illustrates the geographic coverage of the four German TSOs. Collectively, the high-voltage network operated by these companies is called the Übertragungsnetz (transmission grid), which transports energy from where it is produced to where it is consumed [16].

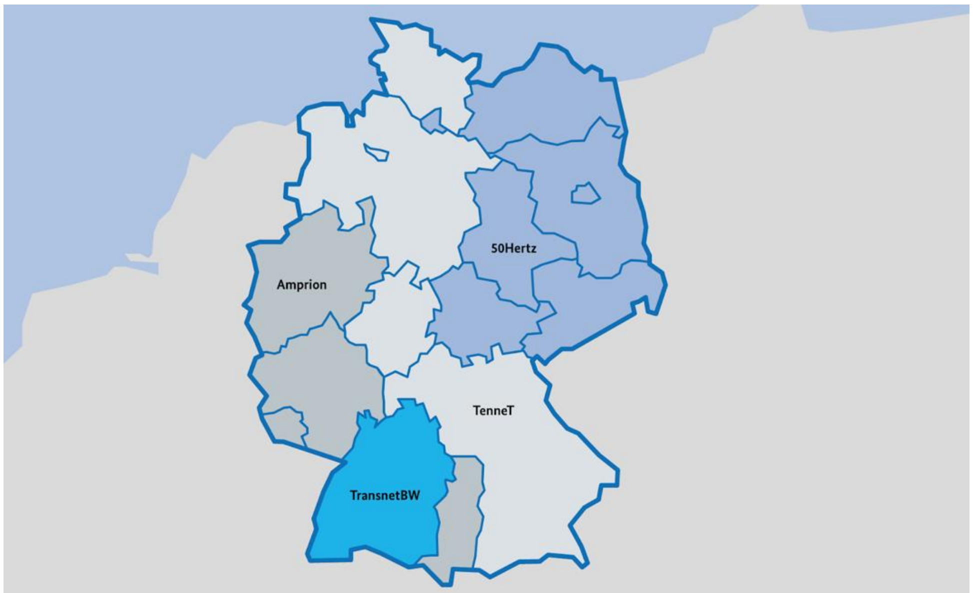


*Figure 3. The four different TSO divided in respective geographic shares [17].*

Germany, like most European countries, utilises an energy-only market (EOM). In an EOM, electricity generators are paid only for the energy they produce and sell, with no separate payment for reserve capacity [18] . The EOM relies on price signals to regulate supply and demand. During times of high electricity demand or limited supply, prices are expected to rise. By allowing the market to self-regulate in this way, the EOM aims to ensure a reliable electricity supply without relying on separate payments for maintaining reserve capacity. This approach of EMO assumes that higher prices during periods of shortages will not only cover the operational costs of electricity producers but also provide the financial incentives needed to fund new investments in power generation. In practice, the EOM underpins Germany's short-term electricity balancing, while the longer-term transition strategy is driven by policy initiatives.

In contrast to the limited number of TSOs, Germany's distribution network is highly decentralised, with over 850 distribution system operators (DSOs) operating across the Germany [19]. These DSOs are responsible for the regional and local distribution of electricity from the sub-transmission level (typically 110 kV) down to the low-voltage networks supplying end users. Unlike the TSOs, DSOs operate under diverse ownership models and technical standard.

### 2.2.2 German grid fees

In Germany, grid fees (fees for using and loading the German grid) are structured into two levels, at transmission and distribution level. Transmission grid fees are standardised nationally, set by the four TSOs and published annually [20]. These fees are composed of a fixed capacity component (euro/kW*year), this is a price on the highest load of the year and a consumption-based component (cent/kWh). In Table 1 is the fixed price for 2025 and the prices for the duration of use are shown [20]. The voltage level is described at extra high voltage (EHV) which in the German grid is 220 and 380 kV.

*Table 1. Grid fee on extra high voltage levels with power price and consumption price and duration of use (h/a =hour per annum).*

| Voltage level | Duration of use | Power price (euro per kW*year) | Consumption price (cent per kWh) |
|---|---|---|---|
| EHV | < 2,500 h/a | 24,38 | 5,46 |
| EHV | > 2,500 h/a | 127,74 | 1,33 |
| EHV/Transformation | < 2,500 h/a | 38,67 | 6,90 |
| EHV/Transformation | > 2,500 h/a | 192,66 | 0,74 |

The distribution network is based on the same components for grid fee, one for maximal consumption in a year and for usage. The structure of DSO grid fees is the same as that TSO fees, a power price based on annual peak load (euro/kW*year) and an energy price based on total electricity consumption (cent/kWh) [21]. However, the prices are set locally and are not harmonized or published at the national level. The price point may vary among the DSOs and the consumption node within the DSO.

While grid fees concern the usage and loading of a line, a connection fee is a one-time charge for connecting to the German transmission grid, known in German as the Baukostenzuschuss (BKZ). The BKZ is generally calculated based on the size of the requested connection (in kW), the extent of required grid expansion, a standardized unit cost per kilowatt (€/kW) and a regional adjustment [22] [23], see Equation 1 and Appendix A for visualisation on $R_f$.

$$C_C = R_f \times A_p(5) \times O_c$$

$C_c$ = connection cost

$R_f$ = a regional adjustment factor (which reflects where in Germany the connection is made) (see appendix A)

$A_p(5)$ = the average capacity price over the past five years (based on facilities that operate more than 2,500 hours per year)

$O_c$ = ordered connection capacity (in kW).

Although this calculation is standardized and the official equation, actual BKZ prices can vary significantly due to individual assessments made by the grid operator [23]. The same principle and formula apply at DSO voltage level. However, no national or standardized regional adjustment factor exists at that level. Instead, the applicable factor is determined independently by each DSO on a case-by-case basis [22].

### 2.2.3 Future German grid

German grid operators regularly develop long-term expansion plans. The Netzentwicklungsplan (NEP, grid expansion plan) of 2023 outlines a comprehensive strategy for modernising and expanding Germany's electricity grid within the ongoing energy transition by 2045 [24]. The plan aims to create a climate-neutral power grid by integrating large amounts of renewable energy, enhancing transmission capacity and improving interconnections between different regions and countries.

Onshore, the plan includes the construction of approximately 4,800 km of new transmission lines and the reinforcement of around 2,500 km of existing lines to meet increasing capacity demands [24]. A key part of this expansion is the introduction of five new HVDC connections, each with a capacity of 2 GW, allowing for more efficient long-distance power transmission with minimal losses. These investments are essential for accommodating the growing share of renewables while maintaining grid stability.

Offshore development is another crucial component of the plan, with up to 70 GW of offshore wind power expected to be integrated into the German grid by 2045 [24]. To achieve this, 35 new offshore grid connection projects are planned in the North Sea and the Baltic Sea. A major innovation in this expansion is the introduction of national offshore interconnections, which will enable multiple offshore wind farms to be linked together, optimising power transmission and increasing grid flexibility. The first systems are expected to be operational in the 2030s.

As part of Germany long-term energy and infrastructure planning, the TSOs have developed plan with scenarios A, B and C [4]. This plan outlines three potential development paths for electricity consumption across Germany for 2045, each reflecting different assumptions about the pace of electrification and the expansion of renewable energy.

1. **Scenario A** represents the pathway with the lowest electricity demand, assuming a delayed system transformation, high imports of hydrogen and synthetic fuels and a failure to meet national renewable energy targets.

2. **Scenario B** reflects a middle ground, with medium electricity consumption (60-80% increase depending on where in Germany [4]), efficient system transformation, high electrification and renewable energy expansion in line with legal targets.

3. **Scenario C** assumes the highest electricity demand, driven by extensive electrification, domestic hydrogen production and an overachievement of renewable expansion goals, along with stronger cross-border electricity interconnection.

### 2.2.4 Challenges in the German power system

The German electricity grid is deeply integrated into the European power system, with interconnections to neighbouring countries such as Austria, Denmark, France, Switzerland, the Netherlands, Poland, Luxembourg and the Czech Republic [25]. These cross-border connections facilitate electricity trading and stabilise the grid by balancing variations in supply and demand across Europe. As the share of intermittent renewable energy sources, such as wind and solar power, continues to grow, these international connections are becoming even more critical in maintaining a reliable electricity supply [26].

As the share of non-synchronous and power-electronics-based generation increases, the system experiences a decline in traditional synchronous inertia [27]. This reduction in rotational inertia weakens the ability to handle rapid frequency deviations during imbalances between supply and demand. Consequently, the risk of frequency instability in future power systems rises and has been identified as one of the most critical stability challenges in grids with high shares of renewable energy sources.

Another major challenge of the future German power system is the increasing congestion and curtailment of the transmission network, caused by a mismatch between production and consumption [26]. As wind power production, mostly concentrated in northern Germany, continues to expand. With large volumes of electricity that is transmitted over long distances to high-demand regions in the south and west [27]. Wind energy is expected to become the main contributor to future grid congestion, frequently pushing power flows beyond the available transfer capacity and creating systemic bottlenecks. As renewable generation capacity increases, congestion problems are projected to intensify further [2x6]. Congestion arises when actual power flows exceed a transmission lines thermal limits, leading to overloads. The severity of the problem is reflected in its economic impact. In 2023, congestion management in Germany cost approximately €2.3 billion, including around €1 billion for redispatch and countertrading, figures that do not account for the economic losses from curtailing low-cost renewable energy such as wind [26]. These issues need investments in grid expansion, new transmission infrastructure and grid management solutions.

## 2.3 Technical setup and technology of BESS

There are several different kinds of BESS on the market, each with their own strengths and weaknesses. For this study the lithium-ion battery is chosen.

### 2.3.1 Lithium-ion batteries and their key technical parameters

Battery systems containing lithium-ion batteries have developed rapidly, offering a broad variety of cell types and system designs [28]. The battery system contains several battery cells, assembled in modules that together create battery packs. These packs are then connected to form a complete storage unit, along with control systems, cooling equipment and power electronics, shown in Figure 4. BESS connect to the grid through power electronics that convert direct current (DC) to alternating current (AC). Smaller systems typically connect at low voltage, while larger systems use medium or high voltage, often with a transformer. Each battery pack can have its own inverter or share a common DC link. The choice of setup affects cost, efficiency and suitability for different grid services. The intended application determines not only the potential value of the storage system, through grid services, increased reliability, or cost savings, but also influences its optimal sizing, placement and operation strategy.

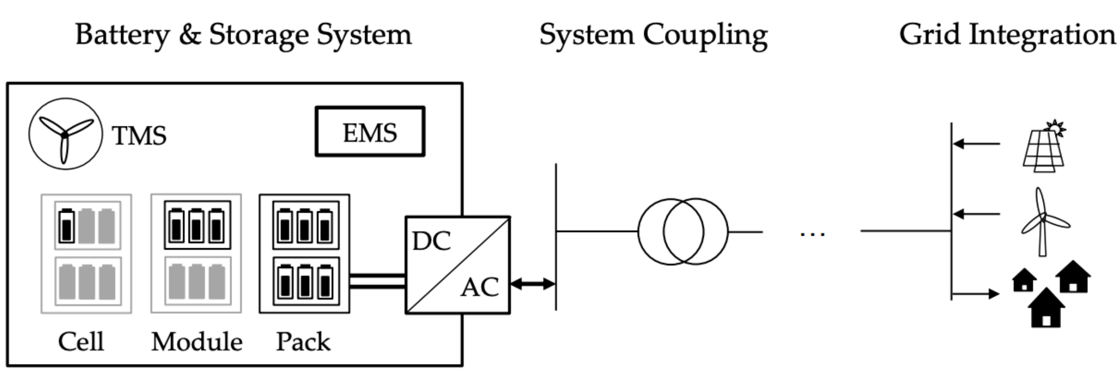


*Figure 4. BESS setup and connection to the grid.*

The technical properties of BESS are essential when assessing both the performance and placement of the system within the grid, as they influence not only the operational feasibility but also the economic viability of different use cases. The following parameters are used to describe the technical specification of BESS:

**Energy capacity (MWh):** Refers to the total amount of usable energy that the battery can store and subsequently discharge. It defines the size of the system in terms of energy volume and is critical for assessing its ability to support load over time.

**Power rating (MW):** Denotes the maximum instantaneous rate at which the battery can either charge or discharge energy. This parameter determines the system's capacity to respond to rapid changes in supply or demand.

**C-rate:** Indicates the relative speed of charging or discharging in relation to the battery's energy capacity. A C-rate of 1 implies that the battery can be fully charged or discharged in one hour. Higher C-rates enable faster operation but may accelerate battery degradation.

**State of Charge (SoC) range:** Specifies the operational boundaries within which the battery is typically used. Maintaining operation within this range helps preserve battery health and extend its service life.

**Round-trip efficiency:** Represents the proportion of input energy that can be retrieved after a full charge–discharge cycle.

### 2.3.2 System integration and siting implications of BESS in Germany

The integration of lithium-ion BESS into the German power system, requires consideration of both technical connection constraints and site-specific conditions. Technically, the grid connection must align with the voltage levels of the German grid that the BESS ought to be sited in (see 2.2) [29]. The connection point must offer sufficient thermal and protection capacity, and in some cases, network adjustments and reinforcement may be necessary. Additionally, must the construction comply with VDE-AR-N 4130 (which is the basic connection law, this is applied to all constructions) and the supplementary technical requirements issued all four TSO for BESS integration [29], [30]. To obtain permission for a BESS installation in Germany, compliance with the Federal Building Code (BauGB) is required [31]. If the BESS is planned in a rural area without a formal land-use or zoning plan, a "privileged use" permit must be granted. Such a permit confirms that the BESS project serves the public interest by contributing to a reliable energy supply and supporting grid stability.

From a siting perspective, a BESS typically requiring around 5–7.5 m² of land per MWh of installed capacity [41]. However, the site must still provide structural support for the total system weight, access for maintenance and compatibility with the power infrastructure. Environmental and regulatory considerations, such as noise limits, fire safety and visual impact, must also be considered. In the 50Hertz area, where a high share of renewable generation, particularly wind power, is already integrated, co-locating Li-ion BESS with renewable sites is a promising option.

To ensure stable integration BESS into the German extra-high voltage transmission grid (220 kV and 380 kV), some technical requirements must be met in addition to the general connection rules set out in VDE-AR-N 4130 (which is the basic connection laws) [30]. Furthermore, according to the four German TSOs, a BESS must be fully compatible with the connection codes. It must also be able to operate effectively in environments with a high share of inverter-based generation, such as wind power, to support frequency response and voltage support to stabilise the grid. Depending on voltage level of the BESS there are several different technical standards for connections, VDE-AR-N 4105 for 400 V and VDE-AR-N 4110 for 1-36 kV [30].

## 2.4 BESS applications and services

This section outlines several applications of BESS. The focus is on selected services that directly support the integration of renewables and enhance grid flexibility, specifically storing excess power, reducing curtailment, meeting electricity demand and providing frequency regulation. While other services such as voltage control, uninterrupted power supply and black start capability are technically feasible, they fall outside the scope of this study.

### 2.4.1 Frequency services

To maintain frequency stability, power system operators implement various control mechanisms [32]. In continental Europe, frequency stability is defined as maintaining the system frequency between 49.8 Hz and 50.2 Hz [33]. BESS are increasingly used to provide rapid active power injection or absorption to support frequency stability [32]. As battery costs decrease and lifetimes, meaning the period or number of cycles a battery can operate before its capacity or performance drops below a defined threshold, improve, deploying BESS for frequency support is becoming more economically attractive.

To maintain the nominal system frequency of +/- 50 Hz, a hierarchy of frequency control mechanisms, shown in Figure 5, are used across Europe [34]. The first level of defence is Frequency Containment Reserve (FCR), which provides the first response to deviations and activates automatically within seconds to stabilise the system. It includes both upward and downward regulation and is harmonised across all participating TSOs. The second level is automatic Frequency Restoration Reserve (aFRR) which is activated within 30 seconds, reaching full power within five minutes. It is triggered by TSO control signals rather than direct frequency measurements and is coordinated through regional platforms such as PICASSO [35]. Finally, the manual Frequency Restoration Reserve (mFRR) serves as a tertiary control, activated manually within 15 minutes to handle persistent imbalances or unexpected outages. BESS can participate in all these frequency control reserves by rapidly adjusting their power output as directed [35].

Through such services, battery storage effectively provides synthetic inertia and fast frequency response, helping to stabilise the system after disturbances.

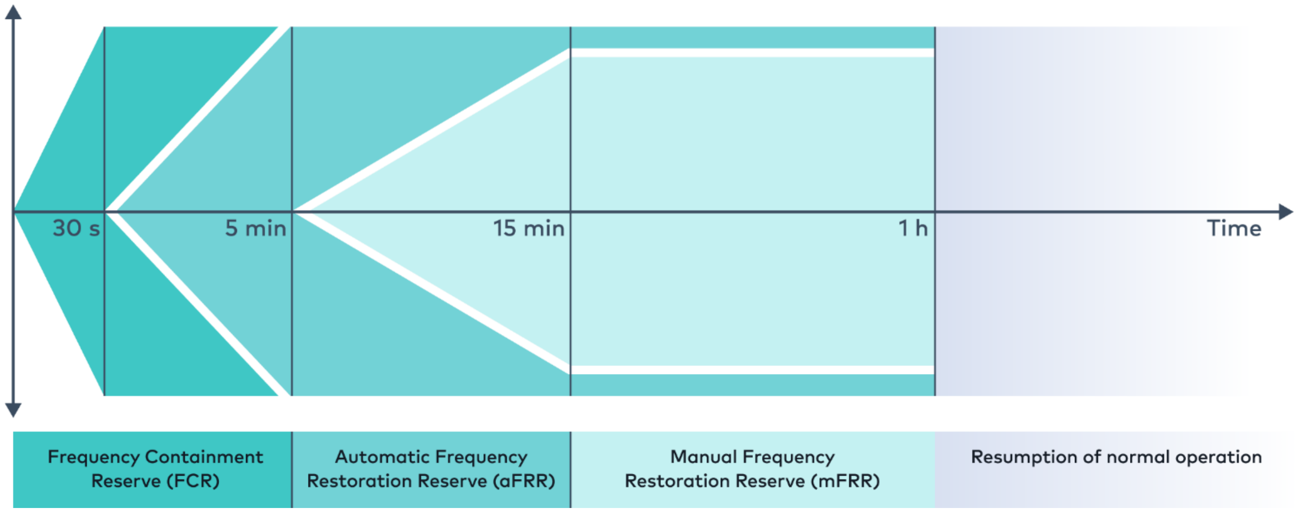


*Figure 5. Time of availability for the different balancing services [36].*

### 2.4.2 Congestion and curtailment management

Power grid congestion occurs when the grid's transfer capacity is insufficient to meet market demand for active power [37]. In other words, if generators in one area produce more electricity than can be transmitted, or if consumers demand more than can be imported, the affected lines and transformers can become overloaded or not able to maintain grid stability. To ensure reliability, transmission system operators must also account for N-1 security, which means the grid must be able to withstand the unexpected loss of a single line without causing further congestion or system failure. This can cause bottlenecks in the grid, requiring different management strategies to ensure that electricity can be transferred effectively without violating system limitations [38]. When transmission limitations constraints certain electricity sources from serving demand, operators may be forced to rely on more expensive or less efficient power plants, leading to higher electricity prices [39]. Additionally, congestions can pose reliability challenges, particularly in areas with high VRE penetration. It may lead to curtailment of wind and solar power, which forces renewable energy generation below its available potential [40].

Curtailment poses economic and environmental challenges [41]. Economically, it negatively impacts investor confidence by reducing expected returns on renewable energy projects. From an environmental perspective, curtailment results in a reduction in carbon-free power generation, hindering progress towards emission reduction targets and sustainable energy transitions. A major complication in addressing curtailment effectively is the absence of standardised, universally accepted methodologies for assessing and quantifying curtailment across different energy systems. This makes it challenging for policymakers to develop effective regulations and investment strategies.

There are two primary strategies to handle congestion; capacity limitation and grid reinforcement [37]. The first involves limiting active power transfers by, for example, instructing generators to reduce output or using demand response to lower consumption. This strategy affects consumption and production patterns and eases flows on constrained lines. The second approach involves increasing the network's capacity through infrastructure investments. This method requires substantial infrastructure investments.

A third strategy, related to grid reinforcement investments, is deploying BESS. When strategically placed in or around congested areas, BESS can help reduce both congestion and curtailment [37]. The battery system can be integrated on either the supply- or demand-side of the congested area, or on both sides [42]. On the supply side, BESS can store surplus renewable energy during periods of high production and low grid capacity, reducing the need for curtailment. The stored energy can later be discharged to the demand side when transmission capacity becomes available. Alternatively, on the demand side, BESS can discharge energy locally during peak hours, easing pressure on congested lines and improving load balancing. Charging occurs during off-peak hours or when grid capacity is available to move energy from generation sites, also reducing the need for curtailment.

When BESS units are deployed in at least two interconnected grid areas, they can form a virtual power line (VPL) [37]. A VPL simulates increased transmission capacity by enabling energy exchange between the batteries. This allows for greater operational flexibility without the need for physical grid expansion. VPLs can offer a faster and potentially more cost-effective solution to enhance grid flexibility, reliability, and the integration of renewable energy sources.

### 2.4.3 Energy arbitrage and peak shaving

BESS can provide value by shifting energy use over time, and two closely related applications are peak shaving and energy arbitrage.

In BESS applications, peak shaving is a strategy that redistributes electricity consumption by moving usage from periods of high demand to times when demand is lower [43]. Peak shaving is a strategy that reduces electricity consumption during periods of high demand by discharging stored energy [44]. This lowers the need for additional generation capacity to cover short-term demand spikes, easing stress on the grid infrastructure and contributing to overall system stability. When peak loads coincide with high electricity prices, peak shaving can also lead to cost savings by shifting energy consumption to off-peak hours [44]. However, it requires careful battery control to avoid rapid depletion and maintain flexibility. Optimal shave levels are typically determined through historical load analysis and statistical forecasting [45].

Energy arbitrage, on the other hand, focuses on economic optimisation by storing electricity during periods of low prices and discharging it when prices are high [34]. While the primary driver is financial, arbitrage also supports grid balancing by smoothing demand and supply patterns, similarly to peak shaving. Moreover, it can enhance energy security by ensuring locally stored energy is available during supply shortages, price spikes, or grid constraints [28]. This can make BESS particularly valuable in systems with high shares of renewable energy, where reliability and real-time balancing are critical [46]. When strategically sited, BESS used for arbitrage can therefore contribute not only to market efficiency but also to reliable energy delivery and system resilience.

## 2.5 Siting of BESS in previous research

Most previous research on BESS placement has focused on technical optimisation, aiming to improve system performance by enhancing frequency stability, reducing congestion or minimising voltage deviations. While these approaches offer valuable operational insights, few studies incorporate business feasibility, regulatory conditions or real-world implementation challenges. This represents a gap in the literature, especially given the commercial and logistical complexities of integrating large-scale BESS.

From a technical perspective, the optimal placement of a BESS depends heavily on its intended system function. For instance, Lee at al. [47] developed an active power sensitivity index to identify grid buses with the highest frequency impact, showing that a well-placed small BESS can match the effect of a larger one placed less optimally. Njoka et al. [48] extended this idea by combining frequency sensitivity with reactive power constraints. This combined approach enables cost-efficient siting that supports both frequency and voltage stability, especially in high VRE penetration scenarios. The study demonstrates that such integration not only enhances resilience but also reduces required BESS capacity, thereby improving cost-effectiveness. In another recent study, Okafor et al. [49] used optimisation algorithms, Particle Swarm Optimisation (PSO), Genetic Algorithm (GA) and Fmincon, to evaluate placement options under contingency conditions, demonstrating the importance of dynamic system behaviour in siting decisions. The results show that strategically placing BESS in low-inertia systems with high renewable penetration can significantly reduce power imbalances and improve system frequency recovery.

Beyond frequency support, BESS have also been considered for congestion management and relief. Shabbir et al. [50] proposed siting batteries at nodes with significant peak loads and voltage deviations, using real-time and historical data to predict congestion. To find these ideal locations, they propose a method that involves identifying weak points in a grid where BESS can mitigate overvoltage and overloading through controlled charging and discharging cycles. The method is tested and confirmed through a case study of an Estonian low voltage grid. The approach is analytics-driven, utilising local data such as load consumption patterns, PV generation, voltage levels and line loading to anticipate congestion and operate the BESS accordingly. This predictive control based on real-time and historical data enhances the overall performance and stability of the distribution network, making it a scalable and practical solution for increasingly stressed power systems. Other methods go further co-optimising both placement and sizing of BESS. Barla and Sarkar [51] used the Water Cycle Algorithm (WCA) to minimise voltage deviations and power losses, outperforming more common algorithms like GA and PSO. Peña et al. [52] approached the issue from a system-wide flexibility angle, using mixed-integer linear programming to incorporate curtailment forecasts, hydro dispatch and unit commitment in siting decisions, highlighting the need for flexibility-aware placement strategies.

However, only one study among the reviewed literature directly incorporates business and implementation feasibility into the siting process. Hameed et al. [29] developed a multi-stage framework that evaluates BESS feasibility across all project phases—from assembly and grid connection to operation and disposal, see Figure 6. The framework maps practical constraints and value generation opportunities across different grid voltage levels and service types. For example, while low-voltage siting may offer lower installation costs and proximity to end-users, high-voltage connections enable broader system services but involve greater complexity. Depending on whether the BESS is intended for frequency support, arbitrage, congestion relief, or renewable integration, different placement strategies become more or less viable. This application-specific variation is visualised in the framework, which combines qualitative and quantitative inputs, technical data, regulatory considerations and real-world conditions, and is applied to a case study on the Danish island of Bornholm. The study shows that sites appearing technically ideal may face significant economic or logistical barriers. It concludes that incorporating business feasibility is essential for developing investable, large-scale BESS projects, particularly in deregulated and service-stacking electricity markets.

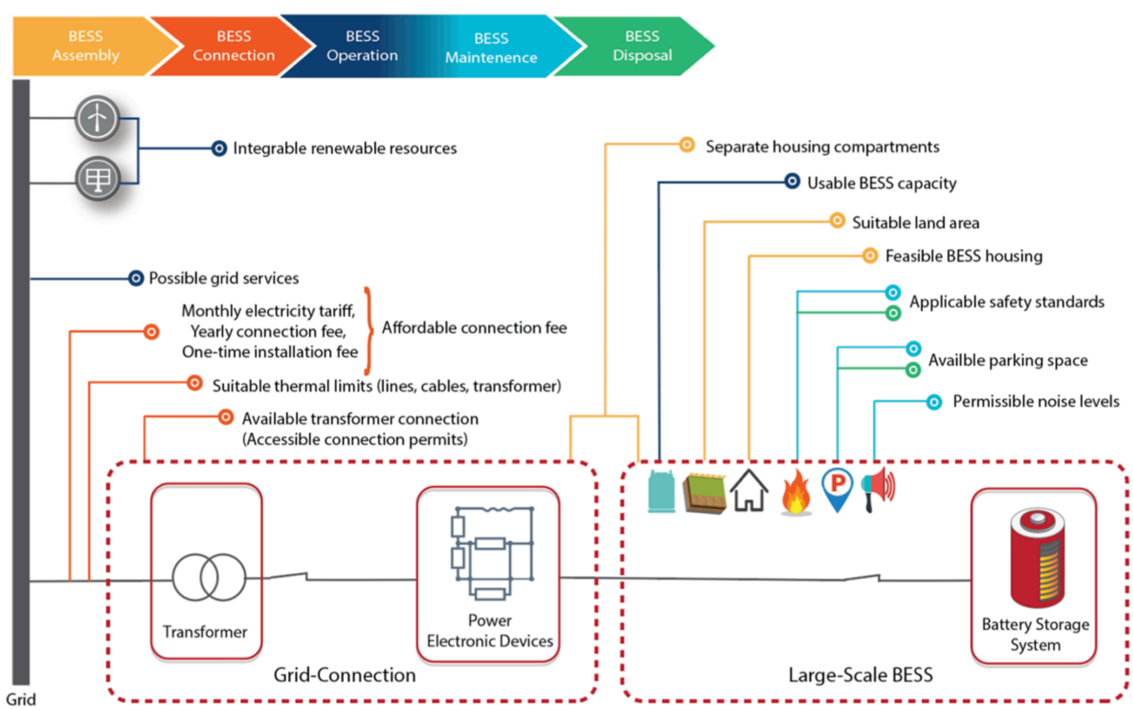

*Figure 6. Grid-connection diagram for large-scale BESS [29]. The figure offers a holistic perspective of BESS integration ranging from BESS assembly to BESS disposal.*

The reviewed literature reveals that most studies focus on narrowly defined technical use cases or isolated performance metrics when determining optimal BESS locations. While these methods offer valuable insights, they often neglect broader factors such as regulatory constraints, land use and market design. Only one identified study incorporated a structured, multi-stage approach that spans both technical and commercial feasibility. This indicates a gap in the research, few methodologies attempt to integrate multiple siting factors into a cohesive, scalable framework that can support screening of future BESS locations.

Taken together, the reviewed literature, regulatory conditions and grid characteristics highlight the need for a structured, data-driven framework that integrates technical, economic and spatial siting factors.

# 3. Methodology

This chapter outlines the methodological approached used to develop and test a suggested framework for identifying suitable locations for BESS in Germany. Firstly, a motivation for the study is presented. Then the research approach is outlined followed by an explanation of the framework development process. Moreover, the case study is motivated and explained in detail. Thereafter the methodology´s limitation and assumptions are accounted and summarised. The primary contribution of this work lies in the methodology, the structured siting framework, rather than in the specific case study results. The following sections detail each phase of the methodology, keeping a focus on how the siting framework is constructed and validated.

## 3.1 Motivation of study

The research is motivated by the growing interest in and need for flexibility solutions in power systems, with BESS increasingly seen as a key enabling technology. As renewable energy production increases, so does the complexity of maintaining grid stability, particularly in countries like Germany undergoing rapid transformation towards 100 % renewable energy production in 2045. This growing demand highlights the importance of scalable, data-driven approaches to BESS siting. However, existing studies tend to focus on narrow technical optimisations and often overlook broader practical considerations representing a holistic view of BESS siting. This study addresses that gap by proposing a structured BESS siting framework based academic context and expert insights. By focusing on a holistic set of criteria and the use of public data, the framework aims to support preliminary site selection in a way that balances technical, economic and spatial factors. The development of this methodology, rather than any single case-specific result, represents the main contribution of the research.

## 3.2 Research approach

To fulfil the aim of this study, a structured method-development approach was adopted, integrating both qualitative and quantitative elements. A schematic illustration of the overall research process is presented in Figure 7.

The research background served to establish a knowledge base on the German power system, the role of BESS and different evolving system needs. This contextual understanding informed the design of the expert dialogues, helping shape the topics explored in each session as the siting process of BESS was explored. The framework development was then guided by insights from both this contextual review and the expert input at Ingrid Capacity. The siting framework was tested in a case study using a simplified and modelled power grid. The outcomes were analysed to evaluate its applicability. The evaluation aimed to demonstrate the practical relevance of the framework and suggest improvements for its future studies and applications.

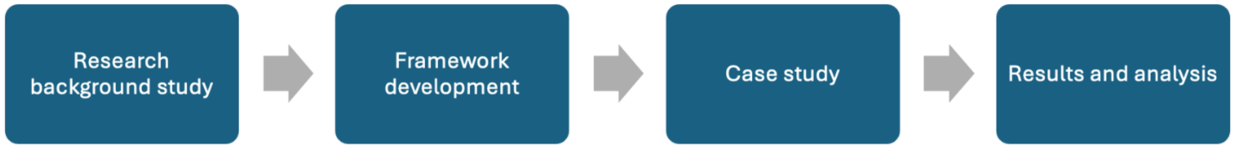


*Figure 7. Schematic illustration of the research process.*

## 3.3 Framework development and definition

During the framework development phase, insights from both literature and industry experts were combined to construct a multi-factor screening methodology for new BESS sites in Germany. The goal was to create an approach that can later be translated into a data-driven screening tool for identifying suitable BESS locations based on a chosen set of factors. The framework development involved several steps. The research background study informed the open dialogues. Next, open dialogues with industry experts were conducted to validate and increase understand of BESS siting, ensuring that practical considerations were included. Identified factors were then defined clearly and grouped into categories. Finally, a preliminary ranking of selected factors was performed to guide how each factor would be evaluated and then implemented in case study.

### 3.3.1 Open dialogs with experts

To complement the theoretical insights from the research background study, three unstructured interviews, referred to as open dialogues, were conducted with experts at the company Ingrid Capacity. Ingrid develops, owns and optimises grid-scale BESS and flexible assets across Europe.

Interviews in qualitative research are used to collect knowledge from interviewees, offering insights into opinions, experiences, processes, attitudes and values [53]. Unstructured interviews focus on a few key themes, allowing for open exploration of expert insights. The flexible format enables the interviewer to adapt questions based on the expert's responses, encouraging deeper discussion and greater knowledge exchange. Following this approach open dialogues were chosen to maximise depth and flexibility of discussion.

The dialogues aimed to gather insights about previous BESS placement decisions and practical challenges from an industry perspective. Three dialogues were held with members from different teams at Ingrid Capacity. Since the teams have expertise in different aspects of BESS placement, the aim was to gain insight to different perspectives of BESS siting. Mainly the interviewees got to explain how they have found new BESS sites previously, what they believe has been most important for the success of current BESS implementations and what they believe will be important in the future when identifying potential sites. Factors important for BESS that do not vary depending on the location were excluded from the dialogues. The interviews were not recorded but summarised manually during and immediately after each session.

The expert dialogues covered three key areas of BESS development: economic feasibility, spatial and regulatory constraints and technical grid integration. Each dialogue reflected the specialised perspective of a particular team within the company, allowing for a comprehensive understanding of practical siting considerations. The business development perspective contributed insights on cost structures and how financial viability can vary across locations. The project development team highlighted land-use requirements, environmental restrictions and planning regulations that must be addressed in the siting process. Finally, the engineering perspective provided input on grid infrastructure and operational constraints, emphasising the importance of integrating BESS into the existing network in a technically robust and efficient way. Together, these dialogues grounded the framework in real-world challenges and opportunities across economic, spatial and technical dimensions.

### 3.3.2 Analysis of siting factors

Building on the literature review and expert input, a structured BESS siting framework can be developed. The framework development process was iterative, first translating key insights from literature and the three expert dialogues into a candidate list of siting criteria, then refining and grouping these criteria into a final set of key factors. The selection aimed to ensure coverage of technical, economic and geographical dimensions of siting, reflecting the holistic approach of the study. Each selected factor is defined to avoid overlap and to facilitate later analysis. Ultimately, seven critical siting factors were identified as the foundation of the framework. These seven factors are listed below, along with a brief definition of each:

**Grid connection fee:** The one-time cost charged by the grid operator to connect a BESS at a given location (an upfront capital expense specific to the site). High connection fees can make otherwise favourable sites economically unviable, so this factor captures the entry cost barrier for each site.

**Grid fees:** The structure and level of ongoing electricity network charges at the site (i.e. usage tariffs or transmission/distribution fees). These operational costs vary by region, affecting the long-term profitability of a BESS at that location.

**Proximity to substation:** The distance from the candidate site to the nearest suitable substation. A shorter distance reduces the need for new power infrastructure and minimises project costs, making this a highly influential factor for practical site screening. In practice, experts recommend locating a BESS within roughly one kilometre of a substation.

**Land suitability:** The availability of sufficient, appropriate land at the site for installing the BESS and its infrastructure. This factor includes both physical space requirements and land-use constraints. Land suitability is fundamental, even a technically ideal location is not viable if the land is unavailable.

**Capacity at substation:** The available electrical capacity at the connecting substation to accommodate additional power input/output from the BESS. In essence, this factor states whether the local node can handle the connection of a BESS without requiring grid upgrades.

**Residual energy:** The mismatch in energy production and consumption in an area. A site with high residual energy is viable because a BESS there can improve renewable energy utilisation and provide flexibility services.

**Grid congestion:** The occurrence of transmission bottlenecks near the site, indicated by frequent grid constraints or overloads in that area. Locating a BESS in such an area can be beneficial for the system, the BESS helps relieve transmission congestion by shifting energy from peak load periods to times of lower grid utilisation.

These seven factors form the core of the siting framework. The factors align with three broader categories of analysis: *geographic factors* (land suitability and proximity to substation), *energy topology* (residual energy, congestion and substation capacity) and *economic viability* (grid connection fee and grid fees). By covering these domains, the framework ensures that essential practical considerations for BESS siting are addressed. At this stage of development, the factors are treated qualitatively, the framework specifies *what* criteria to consider, while the quantitative evaluation of sites against these criteria is conducted in the further analysis.

### 3.3.3 Evaluation and ranking of factors

To rank the seven key siting factors, each factor was evaluated in terms of data availability and relative importance to determine its practical utility in early-stage screening. The data availability assessment recognised that a siting factor is only actionable in a data-driven screening if it can be measured using accessible information. For each factor, the presence of open-source or public data was examined within the German context. A qualitative five-point scale (1–5) was used to score availability, where 1 indicates very limited or no data and 5 denotes openly accessible data. The aim was to ensure the framework could be implemented using transparent and replicable data sources. Factors with low data scores were flagged as requiring further assumptions or later-stage investigation, while high-scoring factors were considered directly usable in a scalable, data-driven tool.

In parallel, each factor was qualitatively ranked by importance based on insights from both literature and expert interviews. This ranking reflects the factor's relevance for BESS siting, whether it plays an initial role in determining site viability or offers more deepened value in certain contexts. The purpose was not to apply strict numerical weighting but to support a transparent understanding of which criteria should guide initial decisions. This allowed to differentiate between essential filters and those better suited for later-stage refinement. This ranking range between low, medium and high relevance.

To integrate these two assessments, a four-quadrant matrix was used to visualise the relationship between relevance and data availability for each factor. This helped structure the framework by identifying which factors should be prioritised in early screening stages. This approach ensured the framework remained both grounded in practice and adaptable to data limitations. The outcome is not a static checklist but a structured, scalable method where each factor's role is evaluated in one certain context. The prioritisation matrix thereby laid the foundation for how the framework was operationalised in the case study.

## 3.4 Case study

To demonstrate the practical application of the proposed BESS siting framework, a case study was performed for the Lubmin area in northern Germany. Even though the case study aims to select the single best site for BESS integration in the modelled grid, the overall goal is rather to show how the methodology can be applied using available data. Lubmin was chosen due to its relevance to Germany's evolving energy landscape and the richness of its grid context. Lubmin located on the Baltic Sea coast in Mecklenburg, Western Pomerania, is a key connection point for offshore wind farms and has a history in the power sector, having hosted the Greifswald nuclear power plant [54]. The decommissioning of that plant left behind a robust high-voltage electrical infrastructure, which today is being re-purposed to integrate a mix of renewable generation. This unique background makes Lubmin an interesting candidate for battery siting as it features strong grid infrastructure, high renewable input and regional load centres, encapsulating many challenges that the BESS siting framework aims to address. A simplified modelling approach was adopted to perform the case study, using open data and focusing on core siting factors, to balance realism with transparency and scope.

Case studies in similar research typically apply siting methods to simplified network models to allow focused analysis. In line with this practice, a reduced model of the 110 kV grid around Lubmin was developed for testing the framework. This voltage level lies between the transmission grid and the regional distribution system, capturing core challenges, such as regional congestions, curtailment and flexibility needs. The selected grid area includes high-voltage lines and substations in the Lubmin-Greifswald region and was aligned with both real-world infrastructure and the framework's siting criteria. Although the model does not aim to replicate the full grid in detail, it illustrates how openly accessible data can be used to create a representative testbed. In doing so, it enables evaluation of the methodology under realistic constraints and highlights how BESS siting decisions are affected by different conditions.

### 3.4.1 Framework alignment

Before building the grid model, the suggested siting framework was mapped onto the specifics of the Lubmin case. This step ensures that there is a link between the framework and the case study, as well as it ensures that each siting factor is address according to its ranking in the four-field analysis. Table 3 was used to summarise this alignment, outlining how the abstract framework actions were implemented with concrete choices in the Lubmin model.

*Table 3. Alignment between framework and case study.*

| Category | Action |
|---|---|
| Spatial and environmental | Selected relevant substations and transmission lines in the Lubmin region. Land-use constraints tracked qualitatively, avoiding protected areas. |
| Technical grid factors | Modelled power flow with offshore wind injection at Lubmin and demand at Greifswald and Wolgast. Included key substations and a 220/110 kV transformer. Simulated power flows. |
| Economic and market | Economic aspects, e.g. tariffs, revenue, were not simulated. These factors were acknowledged but excluded due to data limitations. |

### 3.4.2 Grid model setup and assumptions

The simulation model for the Lubmin case study was developed in Python using the open-source Pandapower library. Pandapower provides a convenient framework for constructing electrical network models and performing power flow analysis [55]. The model was structured to simulate hourly operation of a BESS in a regional power network during the 8760 hours of 2045. The key components of the simulation were network construction, battery system configuration and time-series simulation of one year of operation, which are all accounted for below. During the model development phase, several assumptions were made and difficulties discovered. All of which the explanations below will try to explain and highlight.

**Network configuration:** The power grid model was constructed using actual geographical data that reflects parts of the 110 kV grid in the area around Lubmin, connecting to the larger city Greifswald and the smaller city Wolgast. All lines incorporated in the model were based on the actual power lines connecting the three places and retrieved using publicly available geospatial data. The data was extracted via overpass-turbo, which is a web-based tool filtering information from OpenStreetMap [56]. This procedure was chosen to accomplish an as realistic spatial representation of the network topology as possible. The lines and cables in the model were parameterised using standard line types provided existing in the Pandapower library [57]. These standardised parameters provide reasonable impedances and thermal limits, covering for the absence of proprietary grid data. At the connection point between the transmission of offshore wind power and the 110 kV regional grid, the actual 220/110 kV transformer was included to facilitate the power flow.

In summary, the basic setup of the grid can be explained as a 220/110 kV transformer at Lubmin, connecting the grid model to a large offshore wind farm, 110 kV lines from Lubmin to Greifswald and Lubmin to Wolgast, dividing according to and shown in Figure 9. This simplification creates a network (Lubmin, Greifswald, Wolgast, plus intermediate connection nodes as needed for Pandapower representation).


*Figure 9. Basic visual explanation of the modelled grid connection Lubmin, at the top, to Greifswald and Wolgast.*

**Load configuration:** The grid model incorporates two main loads at Greifswald and Wolgast, representing regional consumption. Due to the lack of publicly available consumption data, the magnitudes of these loads were estimated according to the following procedure.

For Greifswald, the annual electricity consumption was estimated to be 191 GWh in 2019, based on the combined demand from households and industry [58]. As this number is provided as a whole, without a complete dataset for a year, a data proxy was created for Greifswald with the help of consumption data from the TSO 50Hertz [59], which the studied area belongs to. 50Hertz provides a full dataset for 2019 which was adjusted in relation to Greifswald's electricity demand, according to equations 1 and 2.

$$Mean\ power\ 2019\ in\ Greifswald = \frac{191\ GWh}{8760\ h}\ (1)$$

$$Greifswald's\ load = \frac{Mean\ power\ 2019\ in\ Greifswald}{Total\ power\ for\ the\ TSO\ 50Hertz\ 2019} = 0{,}002 = 0{,}2\%\ (2)$$

This estimation shows that the energy consumption in Greifswald was 0.2% of the total electricity consumption in the 50Hertz area in 2019. The dataset, retrieved from 50Hertz, was therefore scaled to 0.2% of its original size. Thereafter, the dataset was scaled according to Scenario B from 50Hertz's 2045 forecast, which projects a 60% increase in electricity demand compared to 2019 levels [4]. To reflect this, the consumption dataset for Greifswald was multiplied by a factor of 1.6. Since 2019 data was the only relevant source available, a decision was made to scale it according to the electrification scenario, even though the scenario was set a few years after. These assumptions are considered sufficient to provide a representative overview of energy flows within the modelled grid configuration as it is a future projection.

Moreover, the same principle was used to approximate the consumption data for Wolgast 2045. However, no official consumption statistics could be identified for Wolgast thus, electricity demand was approximated based on population size and the average German electricity usage. This number was then scaled using equation 1 and 2 as for Greifswald. It was found that Wolgast approximately uses about 0,08 % of the energy in 50Hertz, so a proxy dataset was scaled accordingly. The proxy dataset was then further scaled to match 2045 projected electrification with a factor 1.6.

**Power generation:** Wind power production is included in the model to represent offshore generation near Lubmin. To ensure consistency with the consumption dataset, wind patterns from 2019 are used, assuming that interannual variation is limited. Hourly wind power output was generated using a validated renewable energy conversion model based on historical weather reanalysis data [60], matched to the coordinates of the wind farms outside Lubmin. A standard Vestas V90 2000 turbine was used for the simulation as it is a standard model.

Rather than injecting the full installed capacity in the grid model, the generated wind power time series is scaled so that its average matches the combined annual average electricity consumption of Greifswald and Wolgast (38.81 MW). This ensures a balanced representation of production and consumption (on average) within the simplified grid model. To enable this configuration in PandaPower, a so-called exit bus or slack bus was placed at the Lubmin node. This bus acts as a connection to an external grid, allowing surplus electricity to be exported. Without such a configuration, the power flow calculation would not converge, as excess generation would have no defined outlet, leading to an unbalanced network and failed simulation.

Although no electricity is currently fed into the 110 kV grid [61] from the offshore wind site, this modelling assumption reflects a future oriented scenario where increased renewable integration likely require such connections, as energy production is projected to be 100 % renewable 2045.

**BESS configuration and logic:** The battery system is configured with a storage capacity of 20 MWh and a charge/discharge power of 20 MW, corresponding to a one-hour duration system. The battery operates within a SOC range of 5–95 %, with charging and discharging efficiencies of 91.06 % and 91.78 %.

The BESS operates based on the local residual power, calculated individually for each scenario depending on the battery's location. When placed in Greifswald or Wolgast, the residual is defined as the difference between local renewable production and local consumption. In contrast, when the BESS is placed in Lubmin, the residual is calculated as production minus the combined consumption of Greifswald and Wolgast. All simulations consider network losses, and the battery system responds within technical limits defined by the SOC and line capacities. If the residual is positive, the BESS charges; if negative, it discharges, if sufficient capacity and state-of-charge margins are met.

**Comparison of BESS locations:** In the simulations, a BESS unit is placed at one of three possible locations; Greifswald, Wolgast, or Lubmin. The model was run for the three separate scenarios, each with identical generation and load profiles. In each scenario, the BESS is assumed to serve only the local electricity demand at the bus to which it is connected. This assumption aligns with the anticipated future need for localised flexibility to ensure reliable electricity supply, even as energy production becomes increasingly dominated by variable renewable sources.

To enable robust comparison, a custom Python script was developed to segment the results into quarterly intervals and extract key performance indicators (KPIs) for each location. The include KPIs are:

**Total energy charged and discharged**: These KPIs are calculated separately by summing all individual charging and discharging events, respectively, over the evaluation period.

**Number of charging cycles:** One cycle is defined as 20 MWh of energy charged and 20 MWh discharged, and this forms the basis for calculating the KPI.

**Battery usage frequency:** This KPI is the amount of battery usage out of a maximal capacity of the BESS.

The script also captures the extent of curtailment that occurs and visualises the state of charge patterns over time in comparison to energy surplus and deficit in each node.

By keeping all other parameters constant across locations, the effect of siting alone can be isolated. This allows the case study to assess which node contributes most effectively to system flexibility, local reliability and the efficient utilisation of renewable energy. The quantitative outputs, supported by plots and KPI tables, offer a transparent basis for evaluating the relative benefits of different BESS placements within the case study context.

### 3.4.3 Sensitivity analysis

The ability of a BESS to effectively charge or discharge is physically constrained by the capacity of surrounding transmission lines. In AC power systems, power flow on a transmission line between two nodes *i* and *j* is governed by the following relation:

$$P_{(i,j)} = \frac{(V_i \cdot V_j)}{X_{(i,j)}} \cdot \sin(\theta_i - \theta_j)$$

$P_{(i,\ j)}$ = active power flow from node $i$ to $j$ (MW)

$V_i$, $V_j$ = voltage magnitudes at the two nodes

$X_{(i,\ j)}$ = line reactance (Ω or per unit)

$\theta_i$, $\theta_j$ = voltage phase angles (radians)

These relationships reveal a fundamental principle, that active power flow depends directly on the phase angle difference and inversely on the line's reactance, and it is bounded by thermal limits. When a line reaches its thermal capacity, no additional power, regardless of generation or storage potential, can flow through it without violating system constraints. Regarding publicly available data sources, these kinds of measurements are not available. It is therefore difficult to perform an extensive power flow analysis.

In the Lubmin case study, the offshore wind generation enters the grid at the Lubmin node and is transmitted via a 110 kV line to Greifswald, where a BESS is sited. If this line becomes congested, surplus wind power may be curtailed and the BESS may not be able to charge effectively despite system-wide availability of excess energy. Conversely, if the line capacity is sufficient, the BESS has greater opportunity to act both as a load and as a source.

To explore how this physical limitation affects battery operation, a sensitivity analysis was conducted by systematically varying the thermal transfer capacity of the Lubmin–Greifswald 110 kV line. This analysis reflects the physical reality that line congestion can greatly influence a BESS effectiveness. If a line is frequently overloaded, a BESS might be more valuable upstream of the bottleneck, whereas with a stronger line the placement is less critical. By deliberately constraining the line in the model, changes can be observed in the BESS performance and give insights about siting under different grid conditions. This chosen line has a nominal continuous current limit of approximately 0.366 kA. Three scenarios were then defined in which this line capacity was reduced to 75%, 50% and 25% of its original value. These scenarios simulate conditions ranging from moderate congestion to severe congestion. In each scenario, the BESS was placed at the Greifswald node, which is downstream of the constrained line relative to generation and the year-long simulation was run with identical demand and wind input profiles. By holding other factors constant and only changing the line capacity, the analysis isolates the effect of the transmission constraint on BESS operation.

In practical terms, this sensitivity analysis mimics a situation where grid upgrades are delayed or where a line outage/derating occurs. It provides insight into how resilient the siting recommendation is, if a site like Greifswald performs well only when the line is unconstrained but poorly when the line is congested, that tells us the framework should include grid congestions.

## 3.5 Methodology discussion

This study applies a mixed-method approach, combining literature review, expert input and quantitative modelling to develop a framework for BESS site screening. While this strengthens practical relevance and enables scalable analysis, several limitations must be acknowledged. The framework relies on qualitative judgement, particularly in selecting and interpreting siting criteria. Expert input was limited to a single company, which may constrain the range of perspectives. The case study builds on a simplified five-node grid model and assumes that publicly available data is sufficient for early-stage screening. While this supports transparency and reproducibility, it may limit data accuracy. For example, grid lines were sourced from OpenStreetMap and assigned standardised impedances, which reduces physical realism. The study applies a future-oriented 2045 scenario based on Germany's climate goals, which improves long-term relevance but introduces uncertainty if the energy transition develops differently. Key assumptions include fixed consumption ratios, linearly scaled renewable production, and standardised BESS configurations. Moreover, the study excludes economic optimisation and uses local-only BESS operation logic. Grid constraints were simulated through sensitivity analysis, but actual line capacities remain uncertain. As such, while the framework is practical for broad screening, more detailed assessments will be required to support investment-level decision-making.

# 4. Results

## 4.1 Siting framework outcomes

This section presents the outcome of the developed framework for screening for potential BESS sites. It begins by outlining the finalised identified set of factors influencing optimal BESS placement, then evaluates each criterion in terms of data availability and importance. Finally, a comparative *four-field* analysis is introduced to balance the importance of each criterion against the practicality of obtaining relevant data and the rationale behind the adopted scoring method is discussed with attention to transparency and academic relevance.

### 4.1.1 Finalised siting framework

The finalised siting framework includes seven key factors that influence the suitability of a location for a BESS installation, supporting a primary screening phase. These factors reflect a combination of economic, technical and spatial considerations. The final set of seven factors influencing BESS siting are presented in Table 4, with a short description of each factor's meaning and importance score for BESS siting screening.

*Table 4. Selected factors influencing optimal BESS placement.*

| Factor | Score | Description |
|---|---|---|
| Proximity to substation | High | Distance to an existing, relevant electrical substation. |
| Land suitability | High | The presence of sufficient, suitable land for the BESS facility. |
| Residual energy | High | Surplus renewable energy that is generated but cannot be used or exported due to grid limitations or low demand. |
| Grid congestions | High | Indicates whether an area is affected by frequent transmission bottlenecks, especially during high renewable generation and therefore needs infrastructure reinforcement. |
| Grid fees | Medium | The structure and level of electricity prices over time at the site. |
| Grid connection fee | Medium | One-time cost charged by the grid operator to connect a BESS at the location. |
| Capacity at substation | Low | The available capacity at a substation to accommodate additional power input/output. |

**Proximity to substation** directly affects the simplicity and cost of installing a BESS and is therefore evaluated to be an important factor when screening for potential sites. Access to a suitable connection point, including an available transformer, is a crucial requirement for the successful implementation of a BESS project [29], [30]. Expert 3 highlighted that it is preferable to place BESS within a one-kilometre radius from an existing substation, mostly to keep investment costs as low as possible. Whereas a remote site would face higher capital expense as there is a need to establish a grid link.

**Suitable land area** is a fundamental requirement for BESS installation, as it must accommodate both the BESS and associated infrastructure [29], [41]. Expert 2 supported this highlighting several geographical limitations when screening for a new BESS site. Areas such as protected areas, areas close to residential buildings and areas with already existing infrastructure are all off limit when implementing a battery system. Therefore, even if a location is technically ideal, it cannot be considered viable if the land is unavailable or unsuitable. For this reason, the framework includes land suitability as a core criterion. This criterion was derived primarily from expert input and real-world siting requirements, rather than from prior academic models, to address the noted gap in the literature.

**Residual energy** represents the opportunity to use surplus renewable power generation, that would otherwise be spilled, as well as the opportunity to contribute with energy to the system when the demand is greater than the supply. Curtailment forecasts can support optimal BESS siting by identifying areas with frequent renewable oversupply, which are promising locations for storage that can enhance grid flexibility [52]. Similarly to what Expert 3 mentioned, the analysis of residual energy as important at a first screening stage when assessing what areas in a country or region that need extra flexibility.

**Grid congestion** refers to physical limitations in lines or substations that restrict electricity flow. It is a key factor for BESS siting, as storage systems need access to excess energy and should ideally help relieve local bottlenecks [37]. A congested area may benefit from added flexibility, but only if there is still capacity to charge the BESS. As Expert 3 noted, without available grid capacity, even technically ideal sites are not viable. Therefore, grid congestion is considered a highly relevant for BESS siting.

**Grid fees** refer to the costs of using the grid, including both a capacity-based fee (€/kW*year) and an energy-based fee (cent/kWh). At TSO level, these tariffs are harmonised and published annually, offering comparisons between sites. At DSO level, however, tariffs vary depending on the operator and location and are not centrally published. Although the structure is similar across voltage levels, actual costs can vary significantly [21]. Expert 1 has same reasoning as regarding grid connection fees, that the actual cost may vary and might be hard to predict in advance. Therefore, grid fees were assessed as having medium relevance in an initial screening. The medium score is motivated that is quite accessible on a TSO voltage level but inaccessible on a DSO level. While not the most critical for identifying viable sites, they play an important role in assessing OPEX of a certain site.

**Grid connection fees** can impact project costs. At TSO level, fees are standardised nationally and vary only by a regional factor, making them predictable and comparable [21]. At DSO level, the same calculation method applies, but fees vary between DSOs and are less transparent. Expert 1 support this and states that this may very among projects and BESS sites. However, it is an important part of measuring a sites business viability as it affects CAPEX. Though, due to the mix of standardisation and local variation, grid connection fee was assessed as having medium relevance for an initial screening.

**Capacity to connect to substation** refers to the available technical capacity at a substation to handle additional power. Although important in later project stages, it was ranked as having low relevance in the initial screening due to the need for site-specific assessment by DSOs or TSOs [38]. As noted by Expert 3, connection queues are common, especially in areas with high renewable integration. However, because this factor cannot be reliably evaluated at an early stage, it is more suited for detailed analysis once priority locations have been identified based on more accessible criteria.

### 4.1.2 Data Availability of Siting Criteria

For each of the seven criteria in Table 4, data availability was assessed and scored on a 1–5 scale. Table 5 presents the data availability score assigned to each criterion, along with a brief justification:

*Table 5. Data availability scores for each siting factor where 1 = no open data and 5 = open/useful data.*

| Factor | Score | Description |
|---|---|---|
| Capacity at substation | 1 | No open data available. |
| Grid fees | 2 | Site-specific data unavailable. |
| Grid congestions | 2 | Estimated from regional load and generation mismatch and historical redispatch reports. No uniform open dataset or specific data for certain transmission lines available. |
| Grid connection fee | 3 | Site-specific data unavailable, only regional differences are accessible. |
| Residual energy | 3 | Proxy data from generation and load maps. Often refer only to installed capacity, not exact production. |
| Proximity to substation | 5 | Available via OpenStreetMap and grid maps. |
| Land suitability | 5 | GIS layers for land use publicly available. |

Table 5 states the different data availability index from 1-5. **Capacity to connect at substation** is given a data availability score of 1. This scoring is based on that this is not publicly available and based on a substation to substation and further relevant when actual site has been discovered and more closely been vetted.

For **grid fees**, the fee for load and using the grid has similar data availability as for grid connection fee. The calculation is based on usage, price and consumption, which like the connection fee is openly available and standardised on TSO voltage level. However, on DSO voltage level there are no national standardising on prices. Therefore, the price may vary among the 850+ DSOs. This gives grid fee combined data availability score of 2.

At DSO level, **grid connection fee** data are generally not available in a location-specific or standardised format. Although the calculation method is public, key inputs such as the average capacity price and regional adjustment factor may vary between operators (see equation 1). In contrast to TSO level, where grid fees are publicly available, standardised and more so up to date. However, even though the calculation method is transparent on TSO level, there are no publicly available records of historical TSO grid connection fees and no future pricing formulas beyond 2025 are currently provided. This creates uncertainty, as future structures may change and the same equation might not apply in 2026 and beyond. This gives combined score of 3 out of 5 in data availability.

With the help of connection grid fee equation, regional differences can be discovered (see equation 1), even though exact prices might be unknown. These differences can be included in a screening tool, resulting in a higher data availability score for the grid connection fee than for grid fees. But in general, an extensive assessment of these economic parameters would likely require contacting grid operators or using generic assumptions. These limitations implicate that grid fees and grid connection fees are hard to include in a first level screening for new BESS-sites.

**Grid congestion** and **residual energy** are not directly available through open data. However, both can be estimated using relevant assumptions, which makes them useful in early-stage screening. Residual energy is easier to approximate, as local consumption can reasonably (i.e.) be estimated by using population size and standard load profiles. When combined with data on installed renewable capacity, this provides a useful indication of potential production and consumption and corresponding residual. Grid congestion is more difficult to assess, since no public data exist on transmission or distribution line loadings. As a result, residual energy receives a higher data availability score than grid congestion. However, a basic residual analysis can still offer an indirect indication of congestion risk. Particularly in areas with high renewable production penetration. This motivates assigning a data availability score of 2 for grid congestion, rather than the lowest possible score.

Geographical data regarding the **land suitability** and **proximity to substation**, location of substations and proximity to developed areas is highly available and openly available through sources like OpenStreetMap. This means that the data can be directly integrated into an initial screening tool to identify potential substations for connecting a BESS. As a result, land suitability and proximity to substations are both assigned a score of 5, as the data are easily accessible and provide reliable input for initial site selection.

### 4.1.3 Importance vs. data availability, a four-field analysis

To clearly decide which factors to use in an initial screening and which to handle later, the seven factors were plotted on an importance vs. data availability chart, see Figure 10. Each factor's position in the four-field chart indicates how the factors can be prioritised when developing a data-driven screening tool for identification of potential BESS-sites. The positions are based on the scoring in Table 4 and 5.

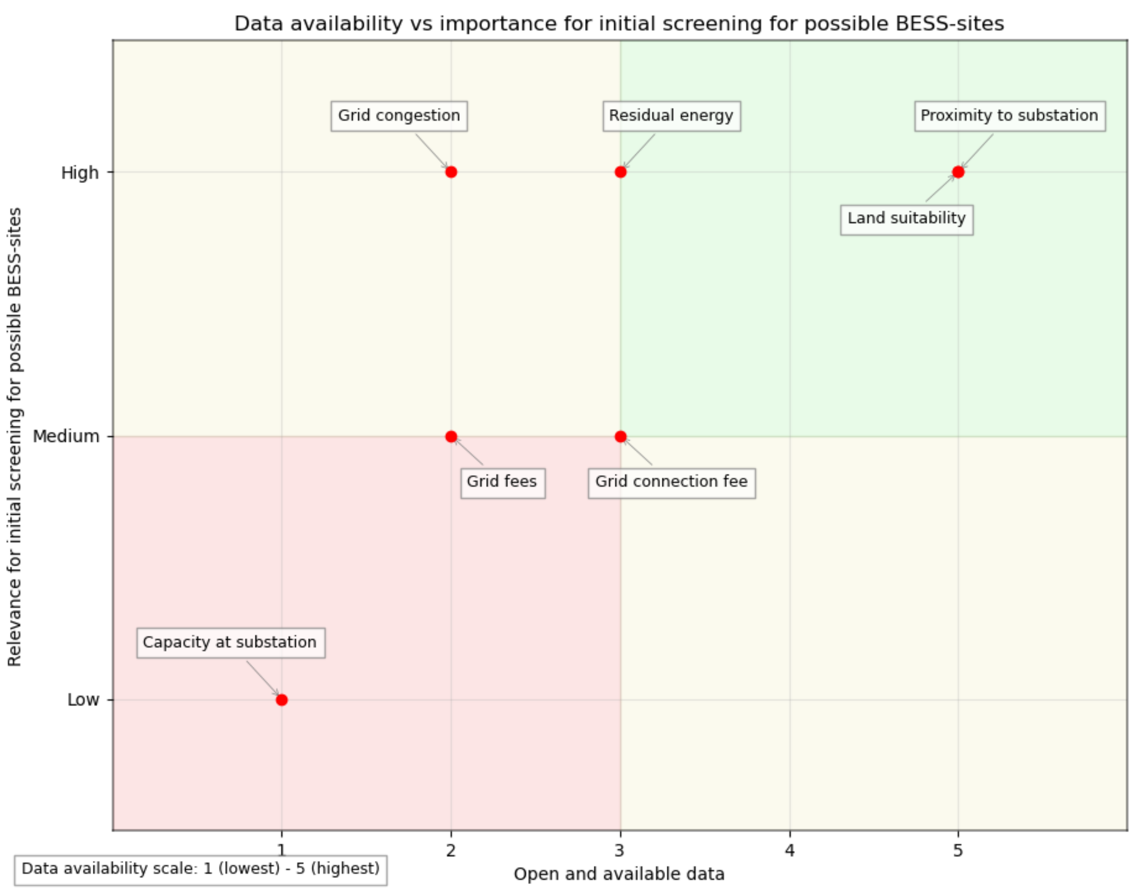


*Figure 10. Illustration of data availability vs. importance for an initial BESS-site screening. The shaded quadrants highlight how different factors are ranked. The ranking aligns with Germany.*

Based on the importance and data availability assessment, **residual energy, proximity to substation and land suitability** are the three factors selected for inclusion in the initial screening tool. These criteria offer a combination of high relevance for BESS siting and sufficient data availability for a data, which combine enable an initial data-driven screening of BESS-sites. Their placement in the top-right quadrant of the importance/availability "four-field" figure, see Figure 10, confirms that they are both impactful and usable at an early planning stage. The remaining factors, while still important, require either more detailed data or site-specific investigation and are therefore better suited for later phases of project development.

For instance, the **grid connection fee** could have played a more significant role in the initial screening model if the regional adjustment factor (Rf) were available at voltage levels below the TSO level (i.e. under 220–380 kV), especially considering that this study focus on 110 kV grid. As a result, this parameter is better suited for detailed project evaluation once a few of potential sites has been identified.

## 4.2 Case study outcomes

The following section presents the results of a case study conducted on the 110 kV grid surrounding Lubmin, based on the application of the proposed BESS siting methodology and the developed framework (see section 3 and 4.1). The aim of the study is to demonstrate how the framework can be used as a fast and simplified screening tool for identifying suitable locations for battery integration within a defined section of the German transmission grid. Drawing on production and consumption data with Scenario B for Germany in 2045, the analysis highlights mismatches between offshore wind power generation and local consumption. Based on the framework (the identified siting factors), three battery locations were selected and are presented in Figure 11. These results illustrate how the framework can support early-stage planning and decision-making in future grid development and deployment of BESS.


*Figure 11. A visualising of the three BESS sites*

In Figure11 the selected BESS sites marked in blue, the selection is motivated and shown in appendix A and based on the framework in section 4.1 and the methodology chapter in section 3.

### 4.2.1 Baseline scenario without BESS

In the modelled system representing Germany in 2045 under Scenario B, there are some discrepancies between electricity production and consumption during the year. Offshore wind power production fed into the grid at the Lubmin node exhibits high variability, ranging from as low as 0.18 MW to peaks of 57.50 MW, see Table 7. This volatility, characteristic of wind production. This is in contrast with the stable consumption profiles in Greifswald and Wolgast, where combined electricity consumption fluctuates within the range of 21.02 MW to 55.67 MW, with a mean consumption of 32,27 MW. The mismatch or residual between production and consumption results in frequent instances surplus and deficits of energy that cannot be utilized within the local system.

*Table 7. Consumption within the modelled grid.*

| Max production MW | Max total consumption MW | Min production MW | Min total consumption MW |
|---|---|---|---|
| 57.50 | 55.67 | 0.18 | 21.02 |

In the following sections, 4.2.2–4.2.4 the effects of BESS at the three different locations are analysed. The sections present quarterly breakdowns of the BESS performance at the three different locations. The key performance indicators include total energy charged and discharged, number of charging cycles and percentage of battery usage relative to the system's theoretical annual capacity.

### 4.2.2 Lubmin

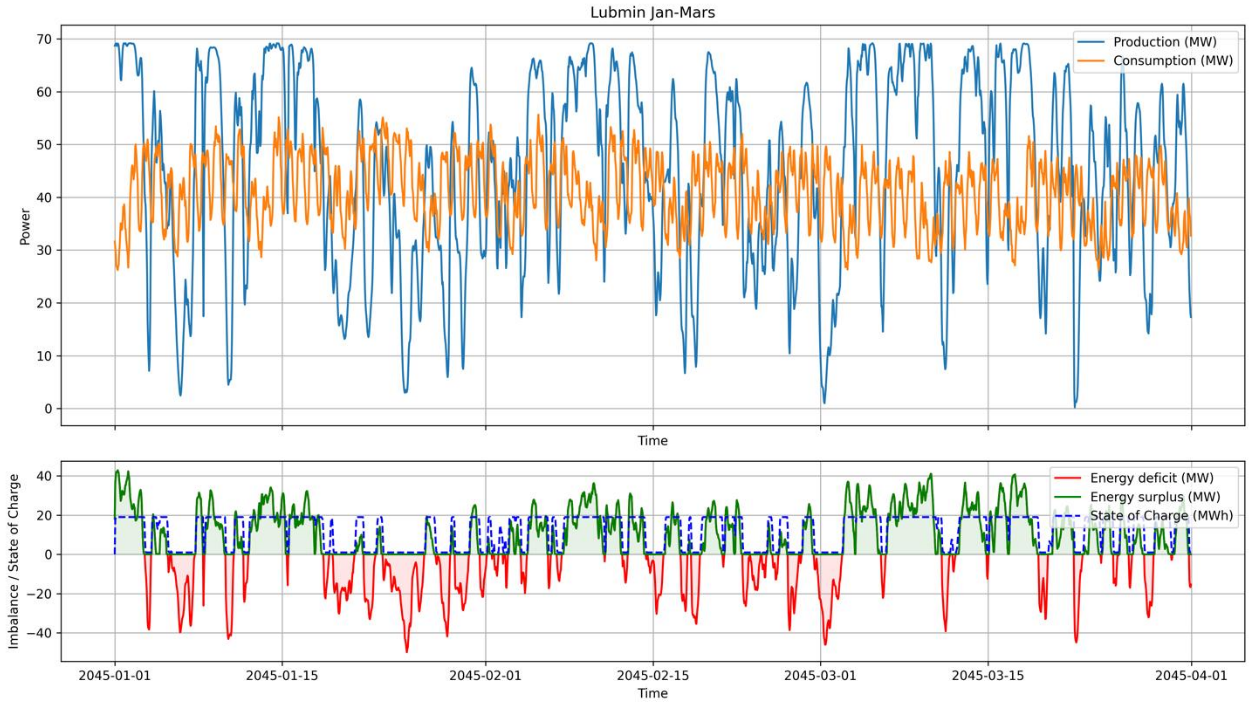


*Figure 11. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Lubmin site for the first quarter of 2045.*

Battery usage during the first quarter was relatively modest, reaching 11.67% of annual battery usage and almost 42 full charging cycles. The residual between production and consumption was quite fluctuate, most charging and discharging events were moderate in size. The state of charge (SOC) patterns suggest that the battery frequently operated near its limits, especially during extended periods of lower or no production. The volatility in production during the winter months is consistent with the intermittent nature of offshore wind production, while consumption remains comparatively stable. However, it is quite clear that there is an energy deficit in the system (se Figure 11, lower graph marked in red).

*Table 8. Breakdown of performance of the BESS at Lubmin in Q1.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Lubmin | Jan-March | 839.12 | 831.45 | 41.76 | 11.67 |

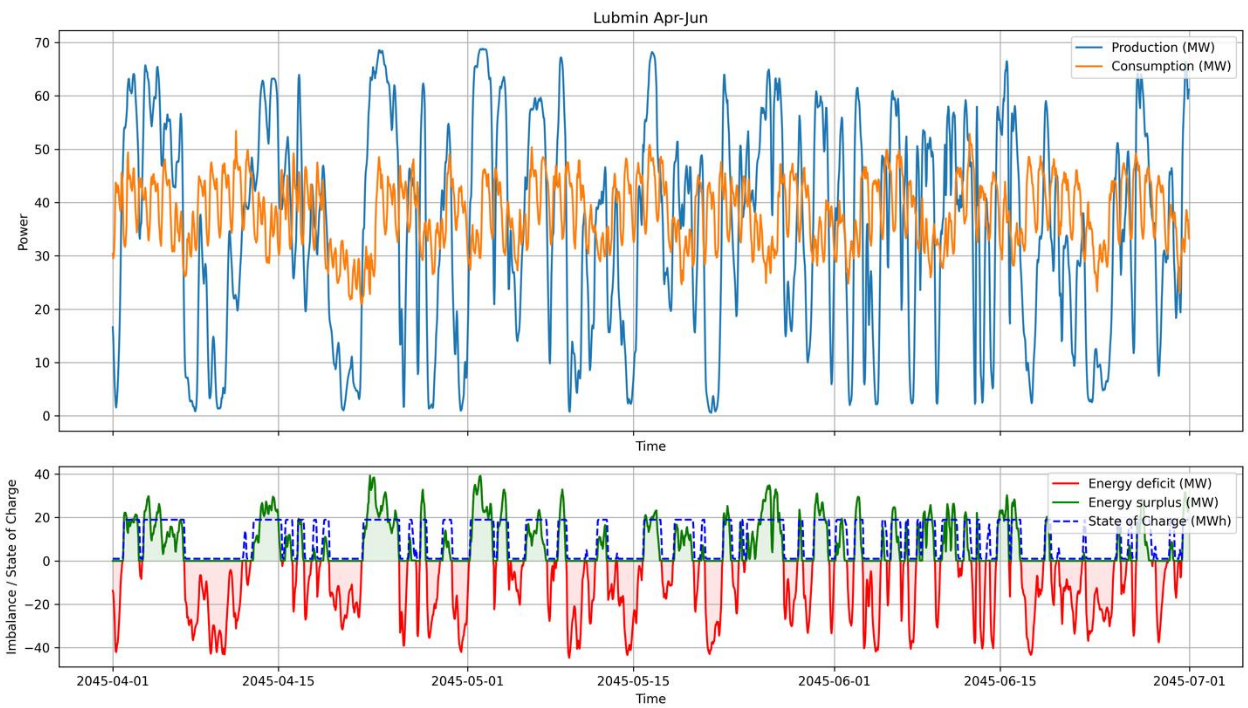


*Figure 12. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Lubmin site for the second quarter of 2045.*

The second quarter marked one of the highest activity periods for the battery, with 44.65 cycles and a usage rate of 12,13%. Figure 12, lower graph shows frequent transitions between energy surplus and deficit, often within quite short intervals. The SOC curve frequently reached maximum capacity, indicating repeated full charges. This behaviour is indicating the volatile production environment where the battery tries to handle the residual between production and consumption.

*Table 9. Breakdown of performance of the BESS at Lubmin in Q2.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Lubmin | Apr-Jun | 906.35 | 879.63 | 44.65 | 12.13 |

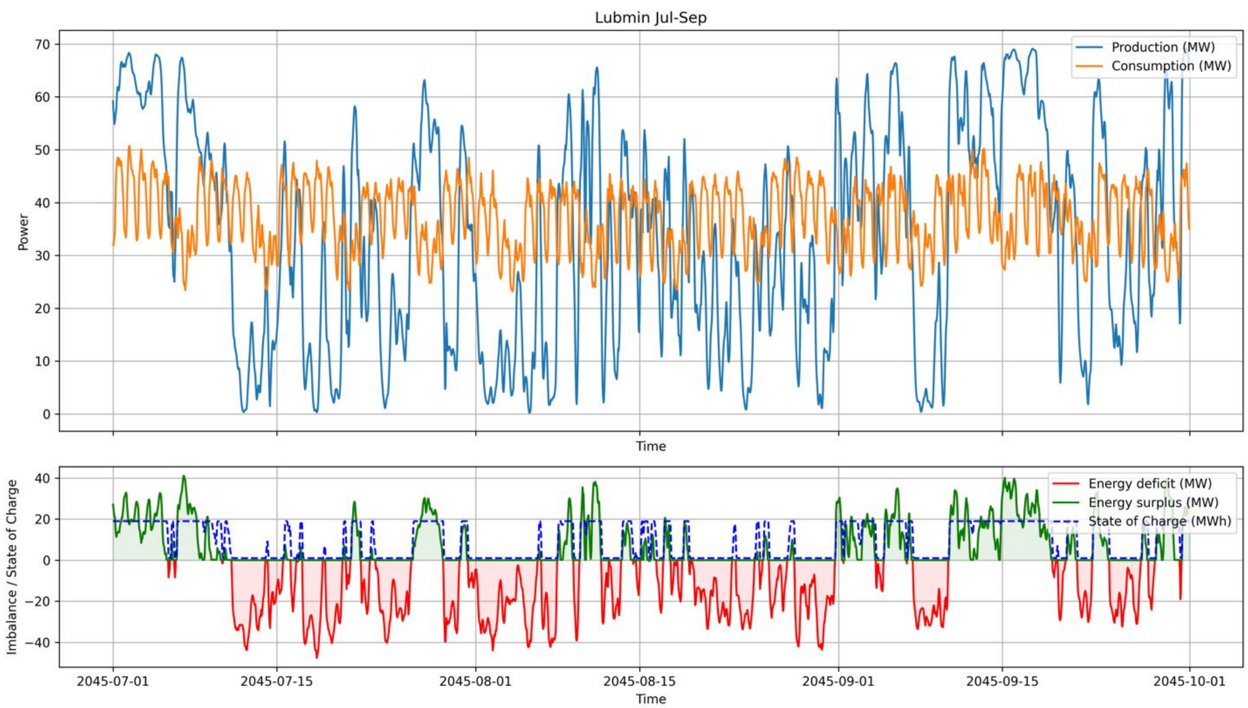


*Figure 13. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Lubmin site for the third quarter of 2045.*

Battery activity reached its lowest level 10,19% during Q3 and the least amount of completed cycles of 36, see Table 10. This likely due to prolonged periods of low or no wind production during the summer. These extended time periods of low or no production resulted in insufficient surplus to charge the BESS. This is reflected in the flatter SOC curve and reduced number of charging cycles (see Figure 13, lower graph marked with dotted blue). This suggests that the limiting factor was not demand-side variability, but the lack of available energy to store.

*Table 10. Breakdown of performance of the BESS at Lubmin in Q3.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Lubmin | Jul-Sep | 723.40 | 717.72 | 36.03 | 10.19 |

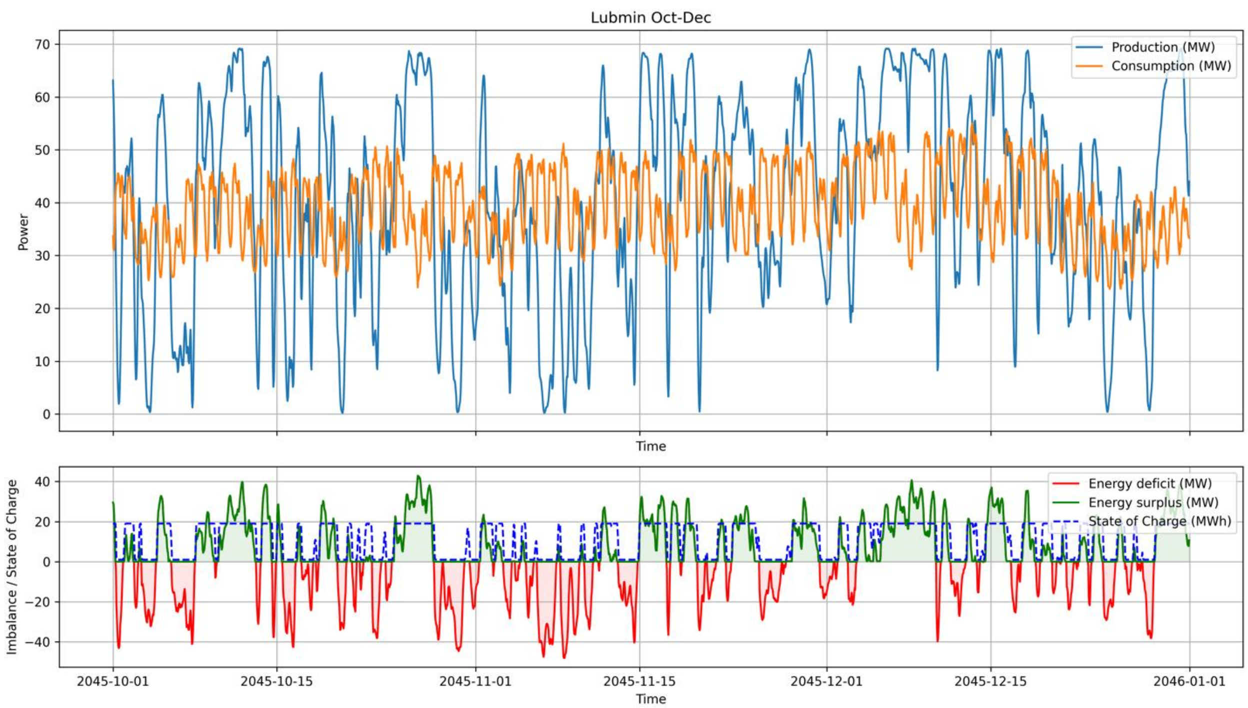


*Figure 14. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Lubmin site for the fourth quarter of 2045.*

Battery activity was highest in fourth quarter, with 45.22 charging cycles and 13.09% usage, which indicate a higher activation compared to Q3. There were clear shifts between times of deficit and surplus. The battery regularly switched between charging and discharging. The total charged and discharged energy were both at their highest levels and almost equal, showing efficient and consistent use of the battery.

*Table 11. Breakdown of performance of the BESS at Lubmin in Q4.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Lubmin | Oct-Dec | 907.88 | 900.76 | 45.22 | 13.09 |

### 4.2.3 Greifswald

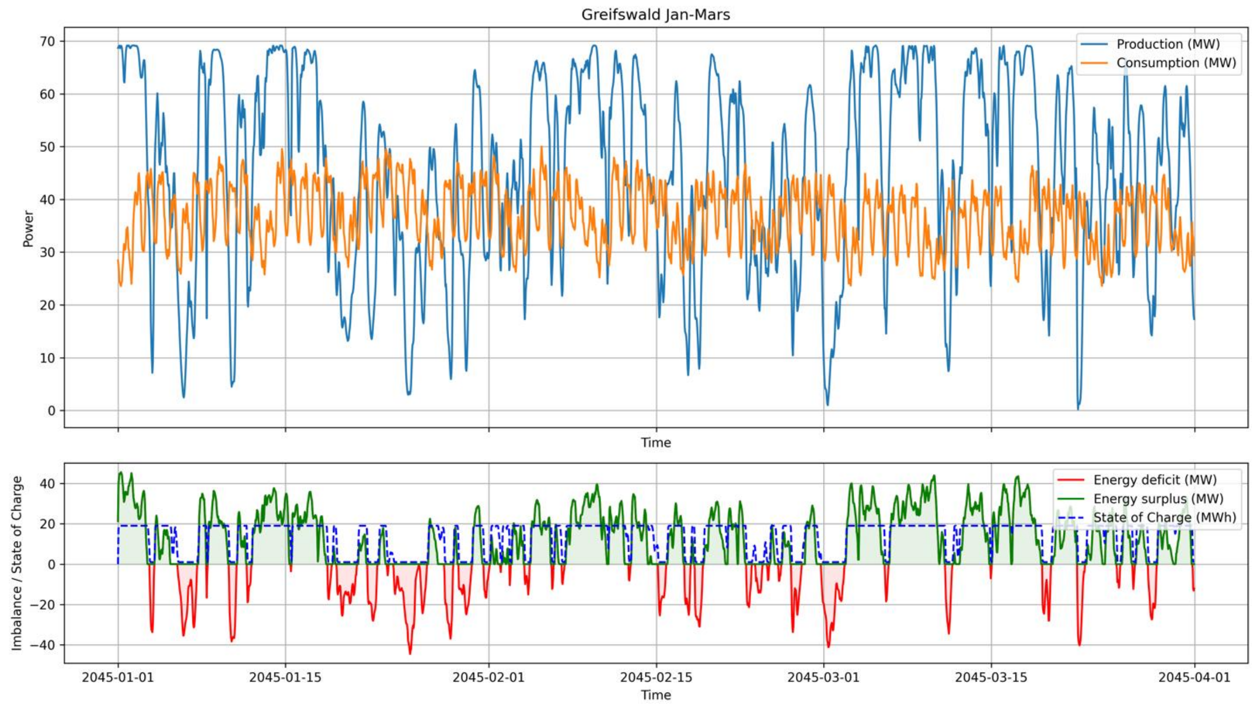


*Figure 15. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Greifswald site for the first quarter of 2045.*

Battery usage reached 11.44%, with 40.45 charging cycles, see Table 12. Despite clear variability in production, long deficit periods limited the battery's ability to recharge. The SOC curve indicates frequent cycling and extended times at low charge levels due to limited surplus energy. This extended times of deficit in the system are visualised with red and are quite extensive throughout the year.

*Table 12. Breakdown of performance of the BESS at Greifswald in Q1.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Greifswald | Jan-Mars | 812.69 | 805.22 | 40.45 | 11.44 |

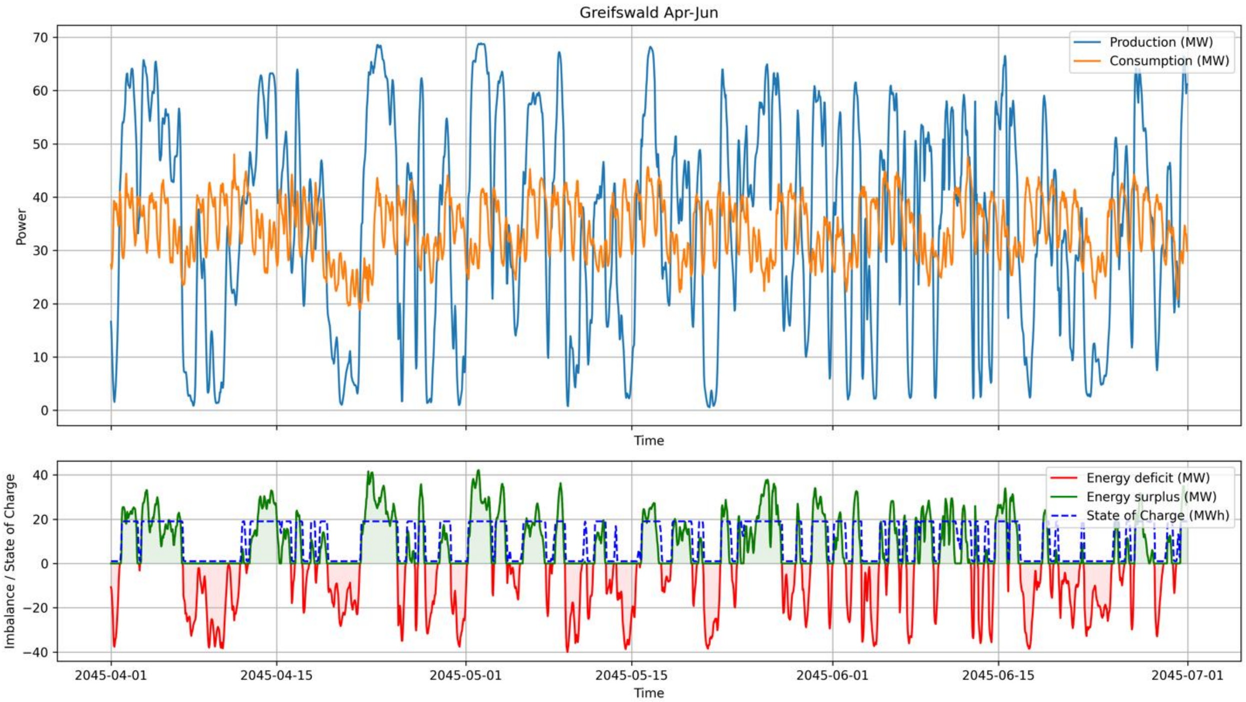


*Figure 16. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Greifswald site for the second quarter of 2045.*

The second quarter (April–June) showed the highest battery activity in Greifswald, with a usage rate of 12.59% and 45.72 full charging cycles. The battery charged 927.81 MWh and discharged 900.92 MWh, indicating that its capacity was effectively utilized throughout the period. This is consistent with the production pattern observed in the graph, where frequent power surpluses and deficits triggered regular battery engagement.

*Table 13. Breakdown of performance of the BESS at Greifswald in Q2.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Greifswald | Apr-Jun | 927.81 | 900.92 | 45.72 | 12.59 |

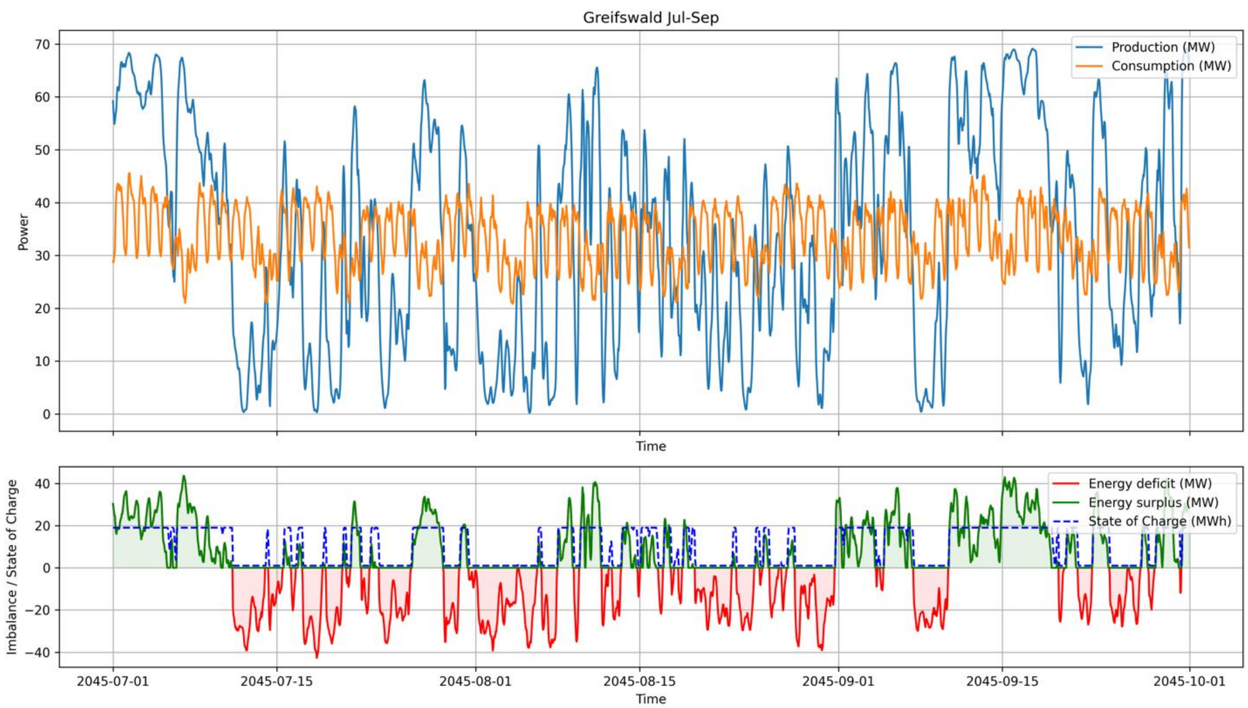


*Figure 17. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Greifswald site for the third quarter of 2045.*

BESS usage dropped to 8.88%, the lowest of the year. The main reason appears to be longer periods with low or no wind production, reducing available surplus for charging. This resulted in fewer charging opportunities, and the battery often operated near its minimum SoC for more extended periods compared to Q2.

*Table 14. Breakdown of performance of the BESS at Greifswald in Q3*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Greifswald | Jul-Sep | 673.94 | 668.65 | 33.56 | 8.88 |

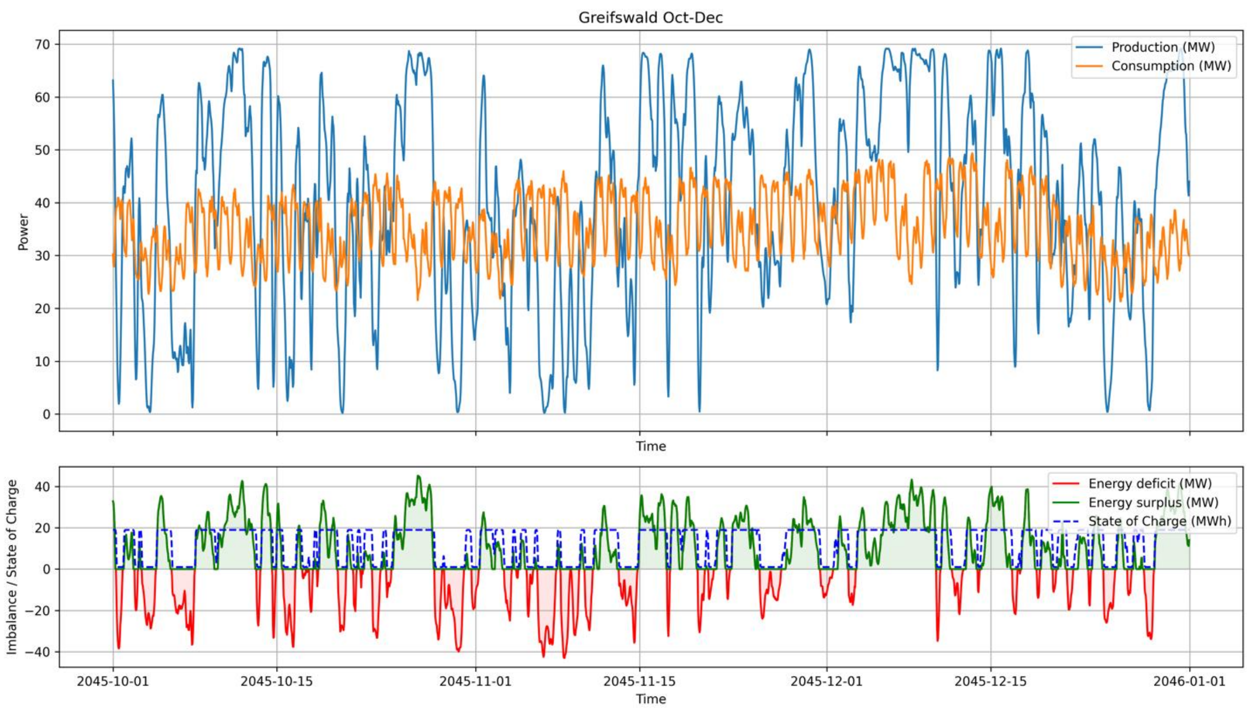


*Figure 18. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Greifswald site for the fourth quarter of 2045.*

BESS usage in Q4 peaked at 13.32%, with 44.38 charging cycles. Charging and discharging levels were again more evenly matched, showing more stable and effective charging and discharging. The SOC curve shows strong and regular cycling, confirming the BESS has active role in trying to manage frequent system imbalances residual.

*Table 15. Breakdown of performance of the BESS at Greifswald in Q4.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Greifswald | Oct-Dec | 891.18 | 884.19 | 44.38 | 13.32 |

### 4.2.4 Wolgast

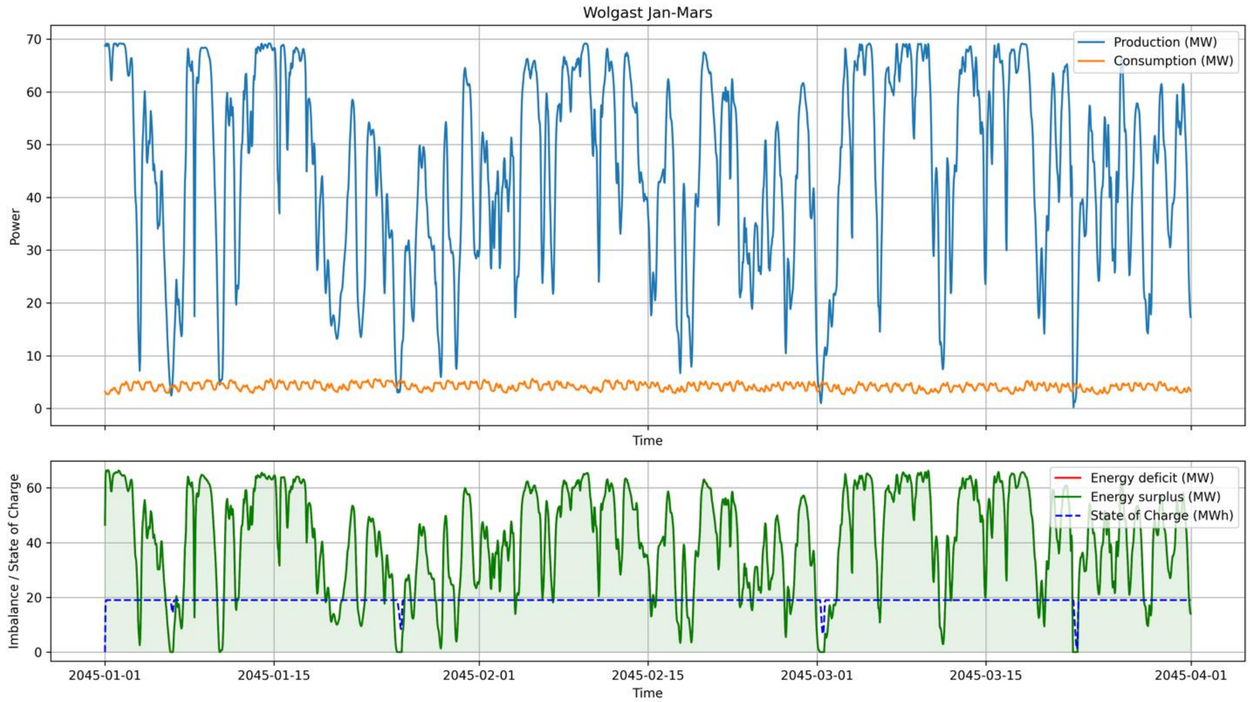


*Figure 19. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Wolgast site for the first quarter of 2045.*

During the first quarter the BESS usage at Wolgast was low, with only 71.04 MWh charged and 49.78 MWh discharged. Resulting in 3.02 cycles and a BESS usage rate of 1.06%. Despite periods of wind surplus, the battery remained largely inactive due to consistent and low local consumption. Although the battery was charged, the consistently low and steady consumption in Wolgast rarely created situations where discharging was necessary.

*Table 16. Breakdown of performance of the BESS at Wolgast in Q1.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Wolgast | Jan-Mars | 71.04 | 49.78 | 3.02 | 1.06 |

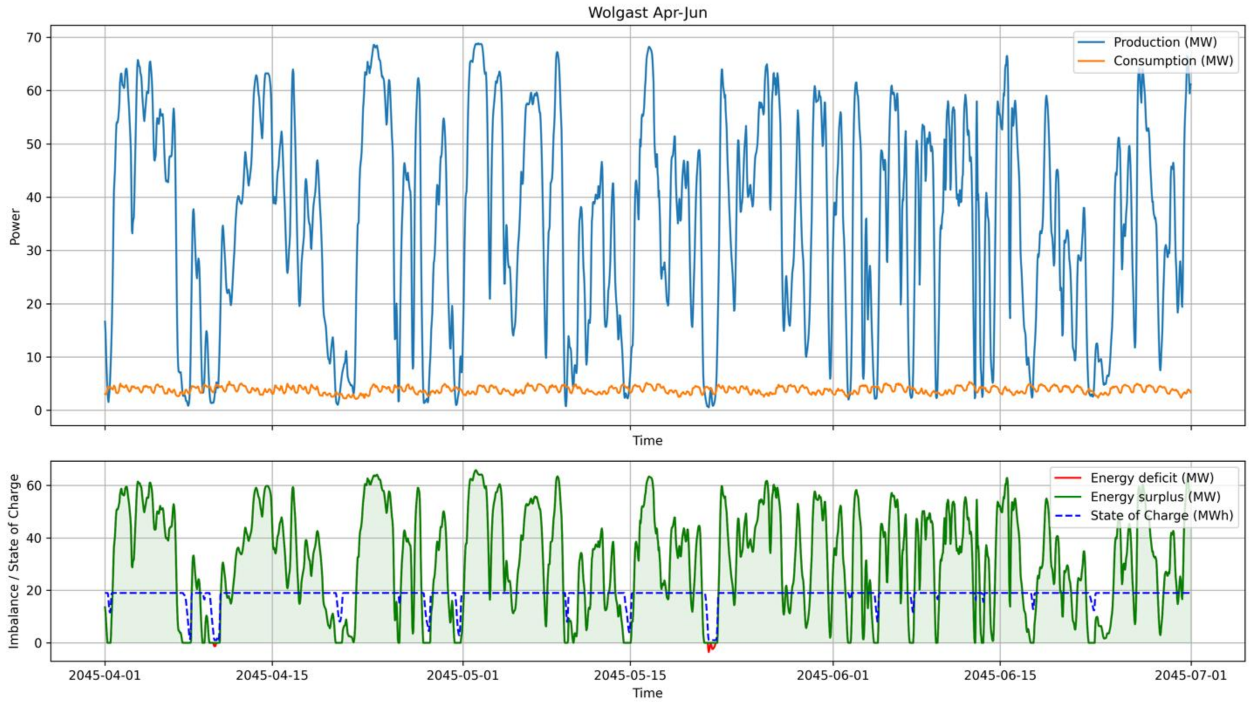


*Figure 20. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Wolgast site for the second quarter of 2045.*

In the second quarter, BESS activity slightly increased with 196.15 MWh charged and 194.61 MWh discharged, resulting in 9.77 cycles and a battery usage of 3.57%. The increased volatility in wind production provided frequent surplus events, allowing the BESS to operate more regularly. However, the low and flat consumption profile continued to limit the BESS's role in addressing local impact of residual.

*Table 17. Breakdown of performance of the BESS at Wolgast in Q2.*

| **Location** | **Period** | **Total charged MWh** | **Total discharged MWh** | **Charging cycles** | **Battery usage %** |
|---|---|---|---|---|---|
| Wolgast | Apr-Jun | 196.15 | 194.61 | 9.77 | 3.57 |

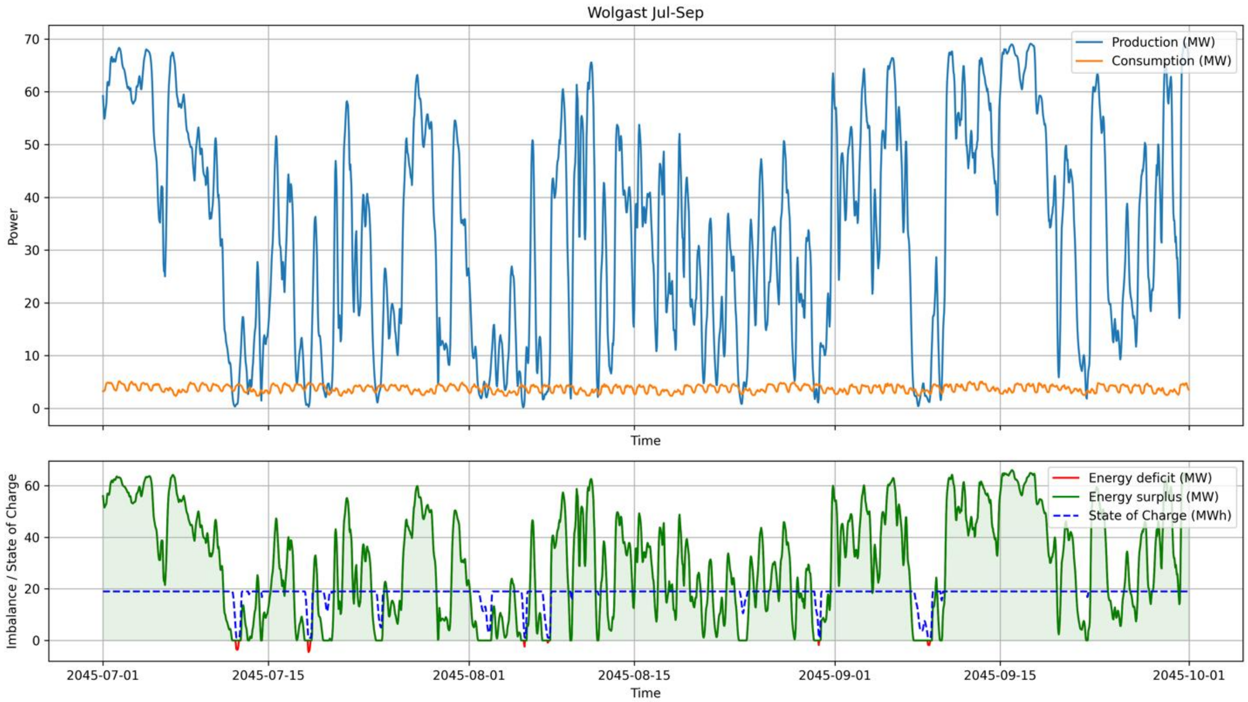


*Figure 21. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Wolgast site for the third quarter of 2045.*

The third quarter has similar pattern to Q2, with 191.10 MWh charged and 189.60 MWh discharged, resulting in 9.52 cycles and a 2.94% usage. Even with high variability in wind power, the battery frequently reached its maximum state of charge without sufficient discharge opportunities.

*Table 18. Breakdown of performance of the BESS at Wolgast in Q3.*

| Location | Period | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Wolgast | Jul-Sep | 191.10 | 189.60 | 9.52 | 2.94 |


*Figure 22. The upper graph shows the difference in production vs consumption. The lower graph shows energy balance and battery operation at the Wolgast site for the fourth quarter of 2045.*

In the fourth quarter, BESS use slightly decreased again, with 139.88 MWh charged and 138.78 MWh discharged. A total of 6.97 cycles were completed and usage stood at 2.76%. Although production variability remained high, the BESS's limited integration with local demand resulted in underutilization.

*Table 19. Breakdown of performance of the BESS at Wolgast in Q4.*

| Location | Period | Total charged MW | Total discharged MW | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Wolgast | Oct-Dec | 139.88 | 138.78 | 6.97 | 2.76 |

## 4.3 Summary of case study

A full-year comparison of battery usage across the three chosen sites, Lubmin, Greifswald and Wolgast, demonstrates significant differences in effectiveness, closely linked to local production-consumption dynamics, see Table 20. Both Lubmin and Greifswald exhibit high levels of activity, with total annual charging of approximately 3377 MWh and 3306 MWh respectively and a nearly equivalent amount of energy discharged. This results in over 160 full cycles and battery usage rates exceeding 11.5% in both cases. These figures suggest that the batteries in these locations are frequently engaged to mitigate imbalances between production and consumption. The BESS seems to be benefitting from both sufficient production surpluses and variable demand patterns. The Lubmin station is slightly better, this is properly due to the set-up of the system, where Lubmin can assist both Greifswald and Wolgast when there is deficit. While both sites show similar seasonal trends in the BESS usage, Greifswald consistently shows slightly higher total energy throughput and usage rates in the most active quarters (Q2 and Q4), suggesting a marginally higher local imbalance intensity and a stronger role for battery support compared to Lubmin during (Q2 and Q4). This is however not true when looking at the whole year.

In contrast, the battery located in Wolgast exhibits lower total utilisation, with 598 MWh charged over the year and just under 30 full cycles, resulting in a usage rate of only 2.6%. However, despite the much lower activity level, the battery plays a critical local role. Wolgast has a small and stable consumption profile, but the BESS can cover nearly all local energy deficits, effectively ensuring a continuous local energy supply. This means that while the battery does not need to operate frequently or at high capacity, its presence enables a high degree of local energy stability. In this case, the battery acts more as a reliability asset. However, it is quite clear that with a BESS, the energy residual remains quite frequently in, especially Lubmin and Greifswald (see top graph in Figure 11 throw 18).

*Table 20. Annual total charge and discharge in MW, amount of charging cycles and battery usage for the year of 2045 for the three battery sites.*

| Location | Period 2045 | Total charged MWh | Total discharged MWh | Charging cycles | Battery usage % |
|---|---|---|---|---|---|
| Lubmin | Jan-Dec | 3376.75 | 3329.56 | 16766 | 11.77 |
| Greifswald | Jan-Dec | 3305.62 | 3258.98 | 164.11 | 11.55 |
| Wolgast | Jan-Dec | 598.17 | 572.78 | 29.27 | 2.59 |

## 4.4 Sensitivity analysis

The results of the sensitivity analysis reveal a clear relationship between available line capacity and the operational effectiveness of the BESS placed in Greifswald. The three scenarios of congestion or line availability are 75 % (25 % congestion), 50 % (50 % congestion) and 25 % (75 % congestion).

*Tabell 20. Results sensitivity analysis.*

| Line Capacity % | Period | Total charged MWh | Total discharged MWh | Charging cycles | Charging hours | Discharging hours |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| 25 | 2045 | 0 | 0 | 0 | 0 | 0 |
| 50 | 2045 | 1972.53 | 1936.35 | 96.82 | 1719 | 1490 |
| 75 | 2045 | 3237.45 | 3191.35 | 162.95 | 2439 | 2700 |

In the most restrictive case (25 % of nominal capacity) the battery remains completely inactive throughout the year. Despite large residuals between production and local consumption, no charging or discharging occurs due to the limited transfer capacity. This highlights how severe congestion can entirely prevent a BESS from participating in grid support, when placed on the demand side, effectively eliminating its flexibility role. However, this is a very unlikely scenario. In a grid that is operational this will likely happen only sporadically, not constantly during a whole year. A more appropriate way to assess the impact of extreme congestion levels would be to simulate such constraints during peak hours or over shorter, critical periods of the year. This would better reflect real-world conditions, where temporary bottlenecks rather than year-round congestion are more common. On the other hand, if severe congestion is persistent or occurs frequently, the operational potential of a BESS is significantly reduced due to limited utilisation. Therefore, conducting a detailed congestion analysis could be crucial for optimal battery siting and to ensure that flexibility assets are deployed where they can deliver the most stable energy supply.

At 50% line capacity, partial functionality is restored. The battery is active approximately 37 % of the year, with 1719 hours of charging and 1490 hours of discharging. However, the SOC remains at its lower limit (5 %) for a significant portion of the time, indicating that the BESS ability to absorb excess production is still constrained (see Appendix C). Nonetheless, nearly 2,000 MWh is cycled through the system, showing that the BESS can still offer valuable flexibility for a stable and secure energy supply under these limitations.

Moreover, when applying a 75 % transfer capacity, the BESS performance approaches the same levels as for the original simulations. With 3237,45 MWh charged and 3191,35 MWh discharged over the year, the battery completes over 160 full charge-discharge cycles. This indicates that under “near-nominal” network conditions the system can operate close to its technical potential. Therefore, 75 % capacity can be considered a threshold beyond which further congestion has minimal additional benefit in reducing curtailment. While below the threshold of 75% line capacity, BESS functionality decreases rapidly (see Appendix C for the three different cases). This highlights how small changes in line availability can have non-linear effects on the value of a BESS at a given site.

From a planning and siting perspective, the sensitivity analysis shows that having enough local transfer capacity is essential for BESS to be used effectively. Even moderate congestion can greatly reduce how much energy the battery can handle and how well it supports the grid. This highlights that battery performance is closely tied to where it is placed. In regions with high renewable production, it is therefore important to assess the local grid before deciding where to place a battery, to make sure it can operate as intended and provide real benefits. In summary, the sensitivity analysis extends the methodology by testing its recommendations under varying grid stress, thereby highlighting the conditions under which a given site is preferable or how infrastructure limits can alter the benefits of a BESS.

# 5. Discussion

This chapter analyses the gained results from developing and applying a structured framework for optimal placement of BESS. The purpose of the discussion is to interpret the findings in relation to the research objectives of the study. First, the effectiveness and practical relevance of the framework are evaluated, followed by an analysis of the insights gained from the case study. Limitations of the study are acknowledged and discussed and broader implications for grid planning and flexibility are considered. Finally, recommendations for future research are proposed.

## 5.1 Analysis of framework

The results present a framework for BESS siting that supports scalable and data-driven location analysis. The study identifies seven key factors creating the framework, including *grid connection fee, grid fees, proximity to substations, land suitability, capacity at substations, residual energy* and *grid congestion*. Together, these factors support the identification of viable BESS locations by combining academic insights with industry expertise. The framework takes a holistic approach that ensures essential considerations are addressed while remaining scalable for broader applications such as national-level screening in Germany. It is built around three core areas of analysis which are identifying accessible geographic areas, examining the energy topology and evaluating economic viability. By structuring the analysis in this way, the framework can handle many potential sites without becoming unmanageable. In each area, data-driven filters based on the seven factors progressively narrow the selection, so the process remains efficient even when the initial pool of sites grows. To place the results in a broader context, it is worth noting that while this study identifies seven factors within the three areas of analysis, additional factors may be relevant depending on the country of application or the industry expertise guiding the selection process. However, the three areas of analysis do capture a broad view of BESS placement supporting the identification of suitable BESS sites.

In addition to outlining the framework, it is important to recognise that while all seven factors influence the siting of new BESS projects, their relevance and ease of implementation can vary. Depending on the stage of the site identification process, each factor may carry different importance and relevance. To support a structured evaluation, each factor can be scored based on its importance at the relevant stage. This study assumes that the framework is applied during an initial screening phase, and the evaluation is therefore based on initial relevance and the availability of supporting data. The results indicate that this evaluation helps distinguish between the three areas of analysis, with geographic and most technical factors emerging as the most relevant in the early stages. The economic factors are also relevant but can rather be used to weigh different locations against each other, followed by the assurance that there is capacity at the substation to connect. When combing these insights with the presence of usable and relevant data it is found that the geographic factors are the easiest to implement at a first stage screening.

Through this approach, large areas can quickly be reduced to certain areas that are seemingly suitable for BESS implementation. Through further analysis and application of factors, more specific sites can be found.

These results suggest that a structured framework, built around a limited set of defined factors, can support a scalable and practical approach to BESS site identification. The use of three core areas of analysis, geography, energy topology and economic viability. This provides a flexible structure that accommodates both technical insight and available data. At the same time, the evaluation of siting factors shows that relevance alone is not sufficient, factors must also be implementable based on available open source data. This highlights the value of assessing importance alongside data availability. In practice, this dual evaluation strengthens the frameworks usability in real-world planning contexts where perfect data is rarely available.

While the framework offers a structured approach to initial site screening, its practical value depends on how well it performs when applied in a real-world setting. The next section therefore explores the outcomes of applying the framework to a representative grid scenario, highlighting how the identified factors interact in practice and what insights can be drawn from a case study.

## 5.2 Analysis of case study results

The results from the case study show that siting in Lubmin and Greifswald yields similar performance. Both locations demonstrated comparable levels of activity and BESS operations throughout the year. Overall, the findings suggest that the demand for flexibility in the region is considerable. Lubmin showed slightly higher usage and more charging cycles, possibly due to its more centralised load setup. However, Greifswald displayed consistently higher energy throughput and usage during the most active quarters (Q2 and Q4), indicating a greater need for short-term flexibility. In contrast, the significantly lower utilisation at Wolgast suggests that not all locations benefit equally from BESS deployment. These results highlight the value of an effective screening process for identifying suitable sites and suggest that the framework can provide useful indications, within the boundaries of the case study’s assumptions and limitations.

Applying the framework to a real-world-inspired case provides several valuable insights. In the case study, the three factors ranked highest in relevance and data availability for initial screening were implemented. These include land suitability and proximity to a substation, both of which proved feasible to analyse using open-source data and could be integrated into a simplified grid model. The results indicate that these factors can be operationalised effectively, even in the early stages of site identification, supporting the practical usability of the framework.

The third factor, residual energy, was estimated using 2019 data scaled to reflect the 2045 Scenario B. To integrate this part of the framework into the case study, several assumptions were necessary. For example, production was linearly scaled to future levels, while consumption was treated as a fixed proportion of total demand within the broader 50Hertz area. These simplifications made it possible to model residual energy within the limits of available data, but they also introduce uncertainty. Electrification trends may accelerate or slow down. Future consumption levels may differ significantly from current projections. As a result, the local balance between supply and demand could shift in ways not fully captured by the model. However, if Scenario B occurs as assumed, the selected 110 kV grid would likely benefit from BESS deployment. Given the magnitude of the residual energy identified, it may also be relevant to test the performance of BESS with different configurations, rather than limiting the analysis to a fixed BESS setup.

The sensitivity analysis applies the fourth factor evaluated highly relevant for an initial screening, analysing the effects of grid congestions on BESS siting. The results demonstrate that congestion levels at a given site can drastically limit a BESS ability to operate effectively. In the most constrained scenario, with only 25 % of nominal line capacity, the battery placed in Greifswald remained entirely inactive throughout the year, despite clear residuals between local generation and demand. Even under moderate congestion, the BESS experienced significant operational limitations, whereas performance recovered near original levels at 75 % capacity. In this way, the analysis confirms the relevance of congestion as a screening factor and supports its high weighting in the framework. However, the simulation also reinforces the framework's assessment of low data availability for this factor. Since open congestion data is often lacking, early-stage assessments may not be able to model such constraints with precision. Altogether, this analysis strengthens the case for including congestion in initial BESS siting evaluations, even if exact data is unavailable.

Moreover, the three remaining factors in the framework, capacity to connect to a substation, grid connection fees and grid fees, were not applied in the case study during the initial screening but remain important for further site evaluation. These factors could give additional insights into which BESS site is most suitable. It can be assumed that the economic parameters will not generate great differences between the sites as they are all located within the same DSO, see Appendix C. However, a deciding factor could be available capacity at the selected substations, as it is essential for viability of BESS implementation. Given the absence of open data regarding this factor, it is not applied in the data-based case study.

## 5.3 Future studies

While the proposed framework demonstrates potential for early-stage BESS site screening, several areas remain open for further development and refinement. These can support broader applicability, increased accuracy and deeper integration into real-world planning processes.

One extension is to apply the framework to additional geographic regions in Germany. This would test its scalability and adaptability, particularly across areas with more complex grid structures, higher population density or differing renewable energy profiles. Applying the same methodology on a national scale would further demonstrate its usefulness as a planning tool for future BESS deployment.

Another area for future research is to explore how varying BESS configurations may influence the suitability of different sites. In this study, a fixed BESS setup was assumed and not adapted to local conditions, which may affect how well a site performs when screening for new BESS sites. It would be valuable to investigate how different configurations interact with the proposed framework in a future data-driven model, potentially improving the accuracy and applicability of the screening process. This inclusion could also support the optimisation of economic viability for potential BESS sites.

Finally, as the framework is further tested and refined, it could be translated into a screening tool using artificial intelligence or optimisation algorithms to support decision-making. Automating the evaluation of spatial, technical and economic data could reduce manual steps and enhance objectivity. It may also help identify the most promising combinations of placement and sizing, particularly when working with large datasets or applying the framework at a national scale.

Together, these areas of future research can support the continued refinement of the siting framework, ensuring it remains adaptable, technically sound and aligned with the evolving needs of energy system planning.

# 6. Conclusion

This thesis aimed to develop and test a structured framework for identifying suitable BESS locations using data-driven insights to support future implementation in Germany. The proposed framework consists of seven prioritised siting criteria, structured into three areas of analysis: geographic accessibility, energy topology, and economic viability. It supports scalable, transparent, and early-stage location screening by combining factor relevance with data availability.

The case study reveals that applying the framework in a real-world-inspired grid can identify performance differences between potential sites, even under simplified conditions. It highlights how local grid characteristics, such as congestion and residual energy, strongly affect BESS usability. It also shows that the most useable factors in early planning stages are those supported by accessible open-source data. While the case study confirms the usability of the framework, it also reveals limitations related to data availability and necessary assumptions. These affect the precision of site-level conclusions but not the overall value of the framework as a first-stage planning tool.

Together, the framework can guide data-driven BESS siting, while also identifying where further system analysis is needed in later stages.

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# Appendix A

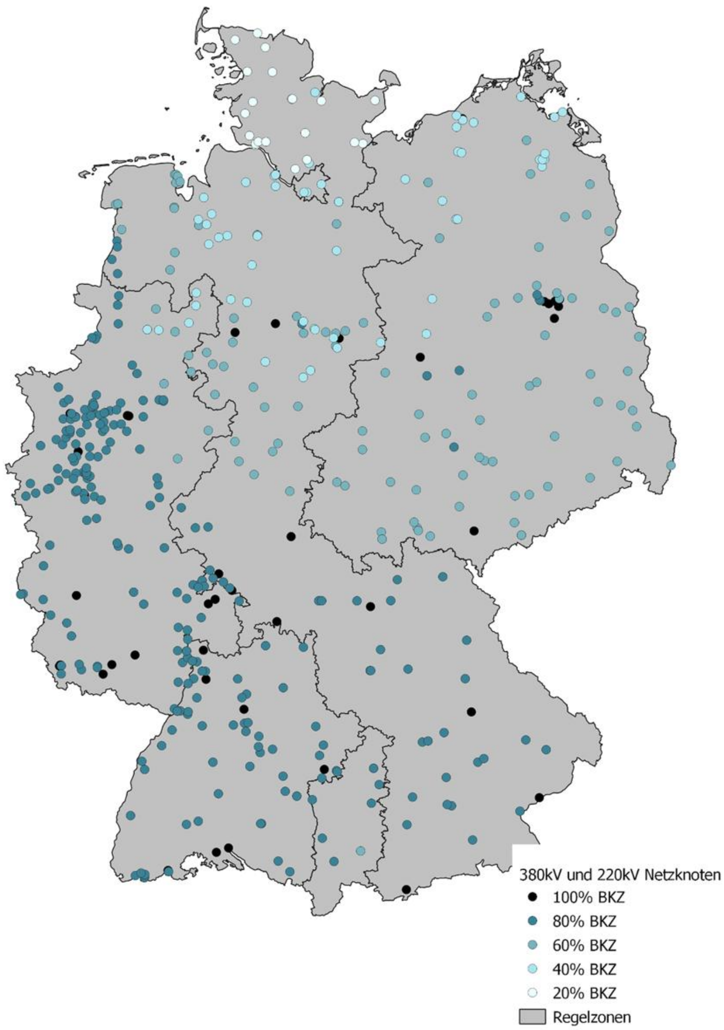


*Figure 23. Regional pricing in percent, referred as $R_f$ [23]*

# Appendix B


*Figure 24: Cable from Ostwind to shore substation in Lubmin*


*Figure 25. Grid around Lubmin not filtrated*

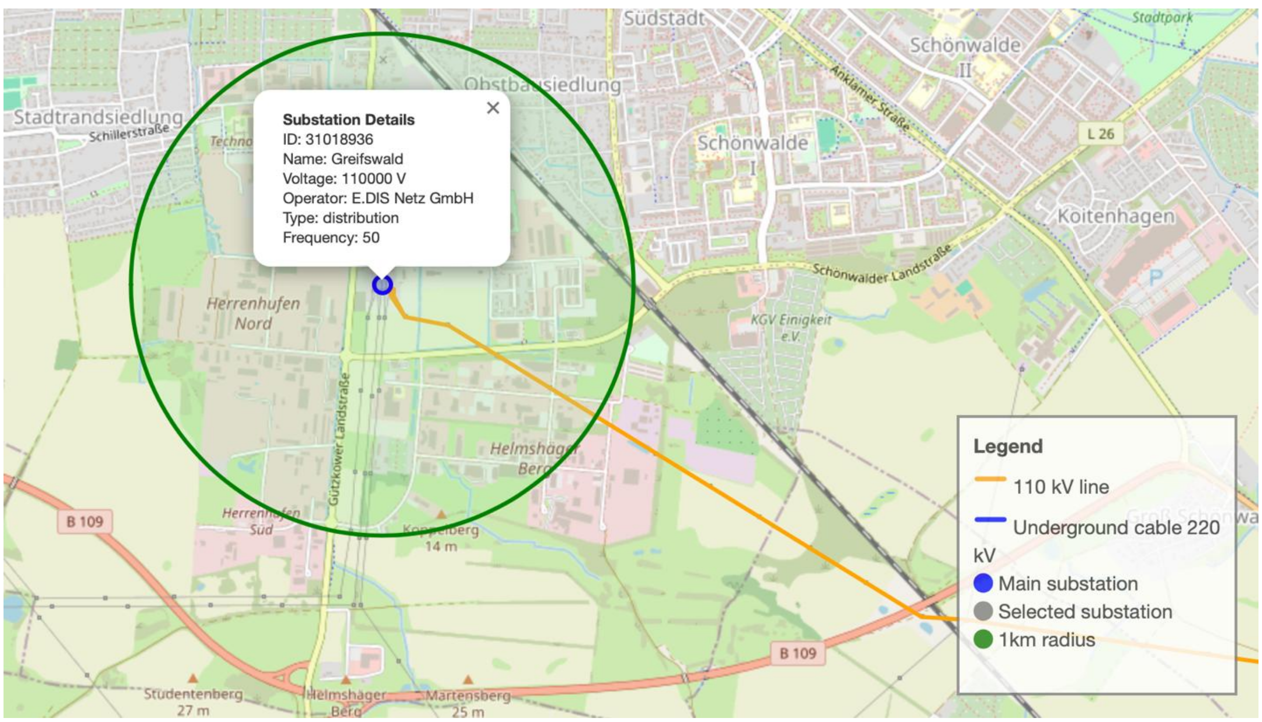

*Figure 26. Details about the substation in Greifswald*

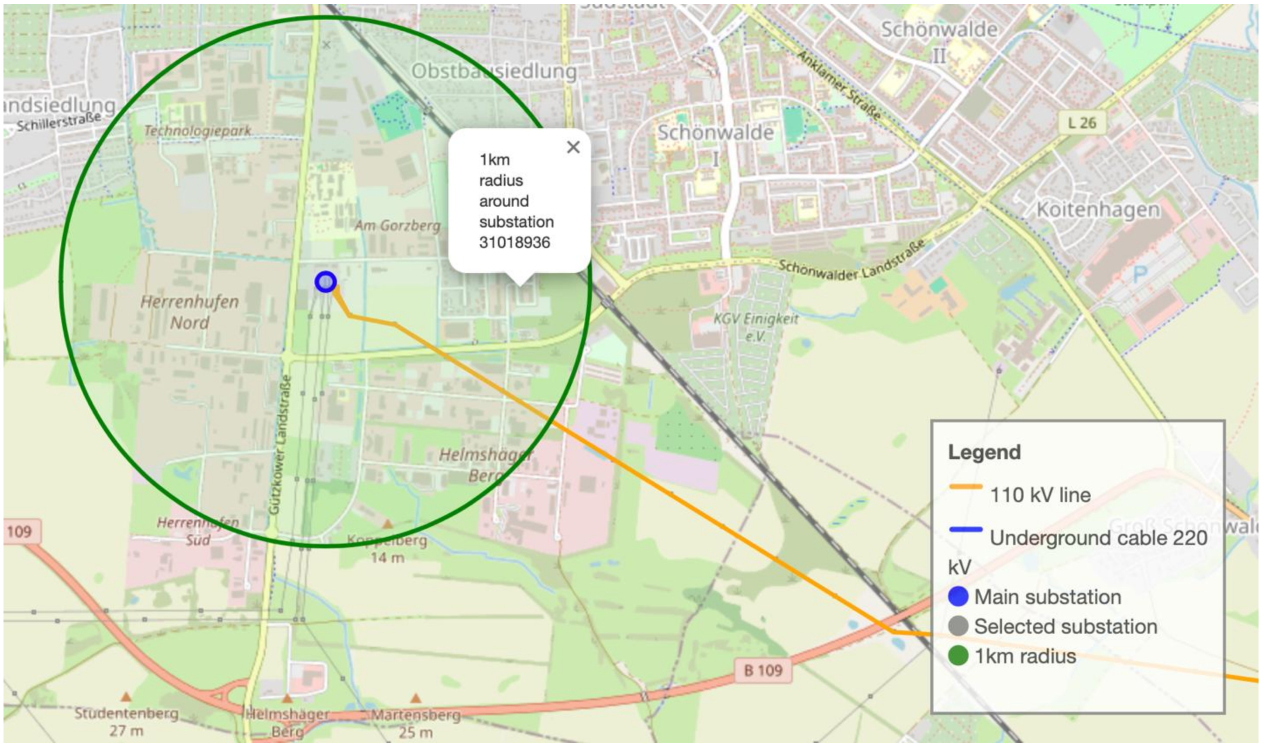


*Figure 27. The one-kilometre radius around the substation*

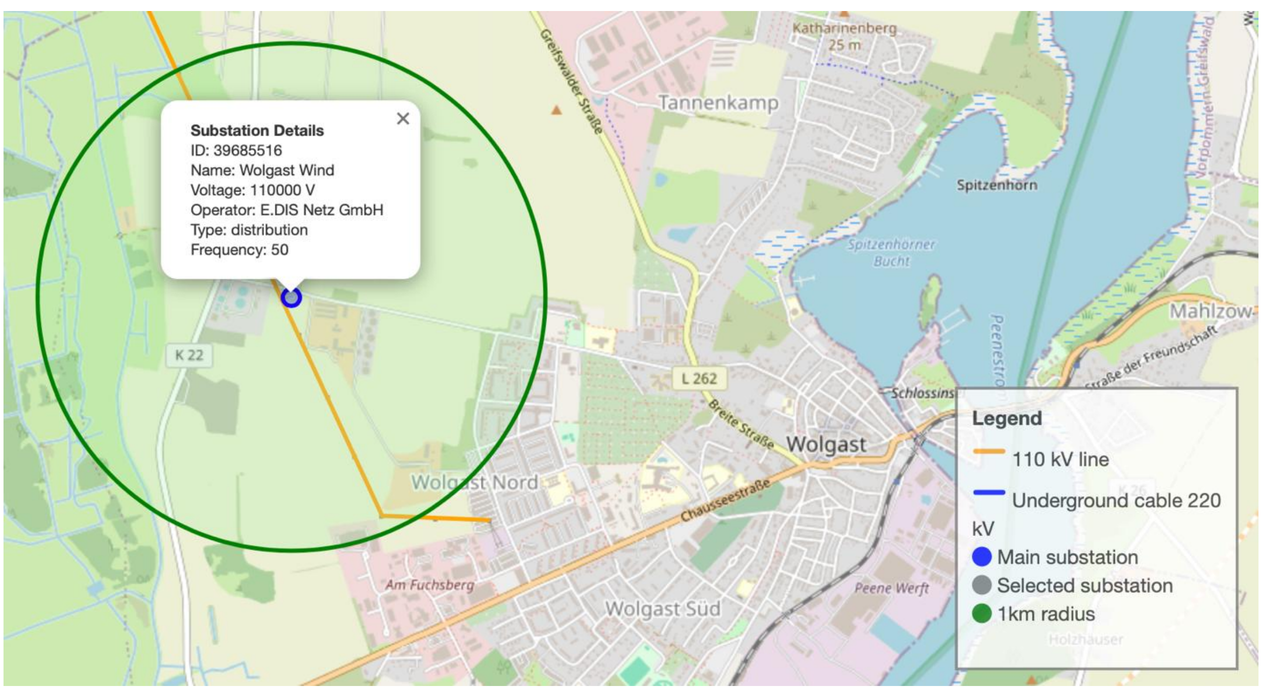

*Figure 28. Details about the substation in Wolgast*


*Figure 29. The one-kilometre radius around the substation in Wolgast*

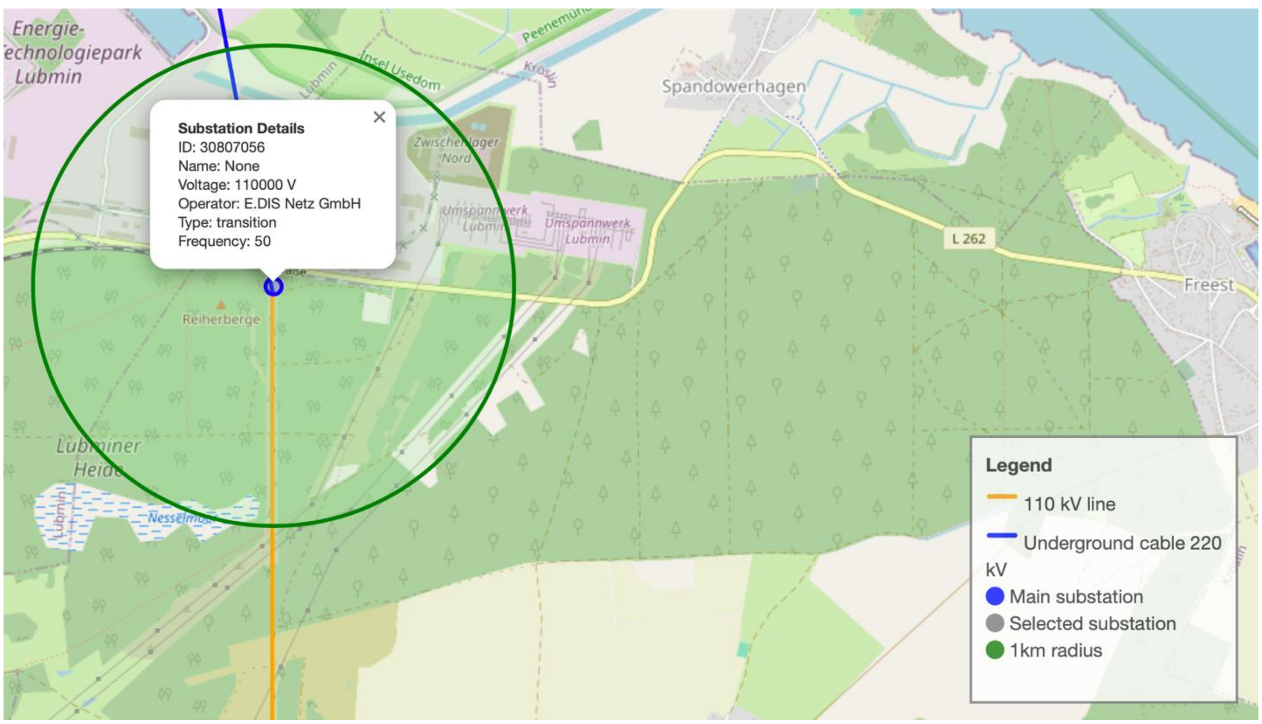


*Figure 30. Details about the substation in Lubmin*

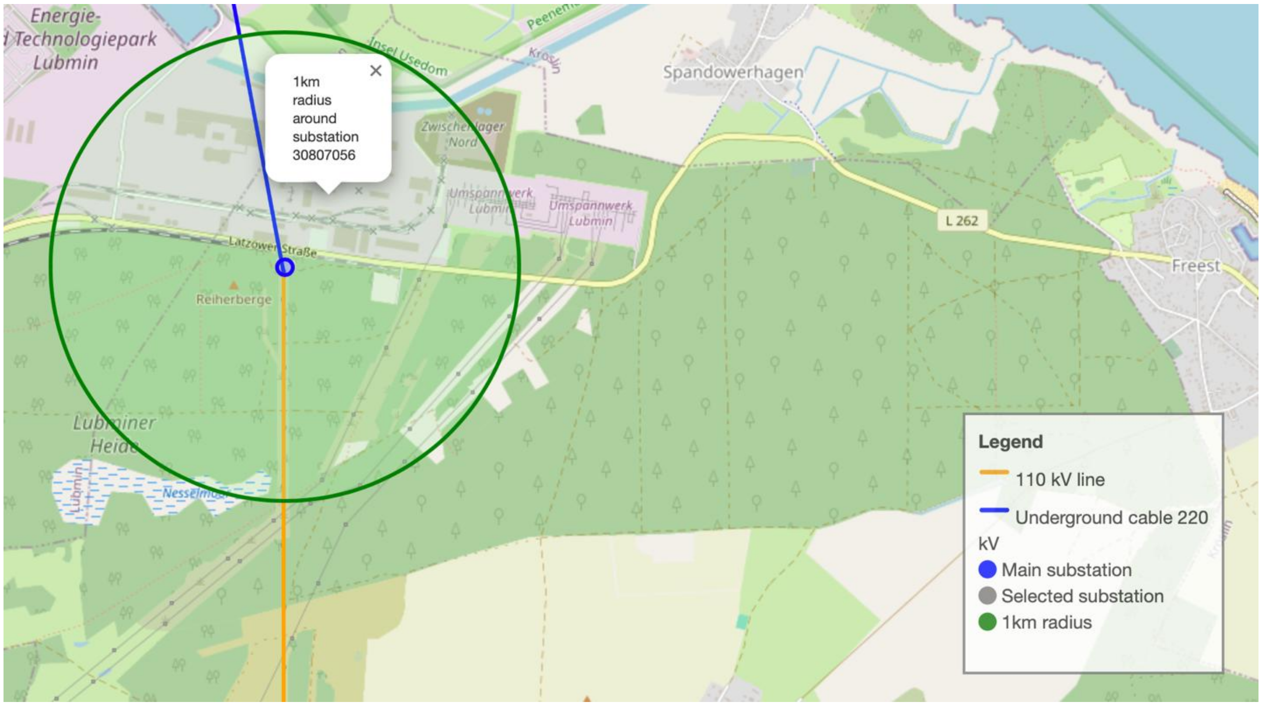


*Figure 31. The one-kilometre radius around the substation in Lubmin*

# Appendix C

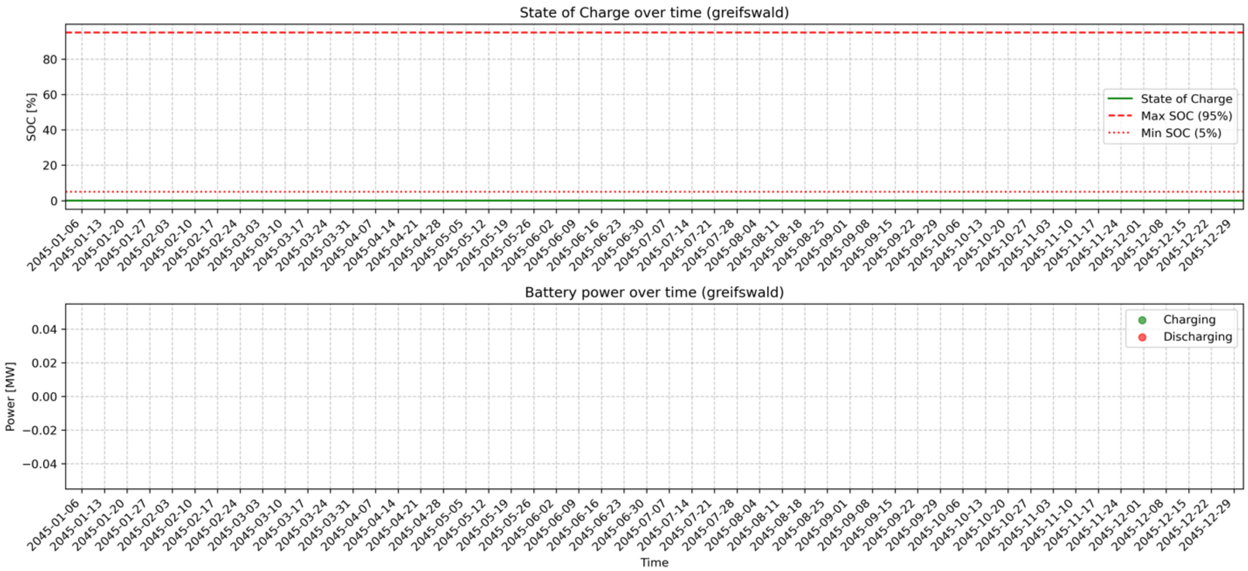


*Figure 32. SoC and BESS action over 2045 with 25% capacity.*

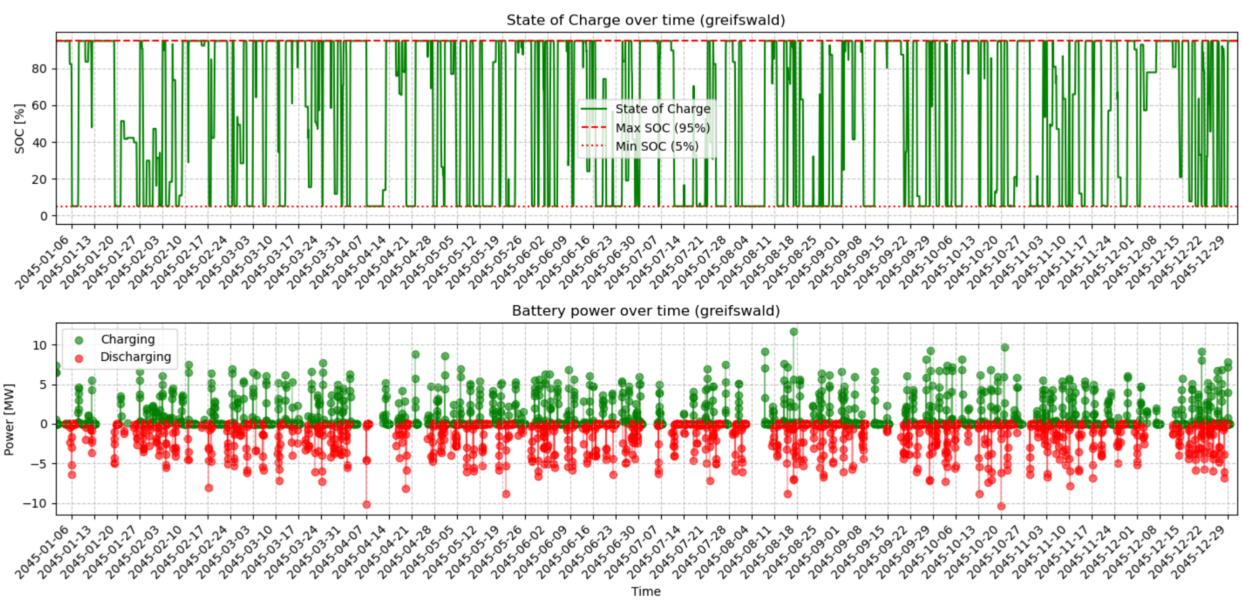


*Figure 33. SoC and BESS action over 2045 with 50% capacity.*

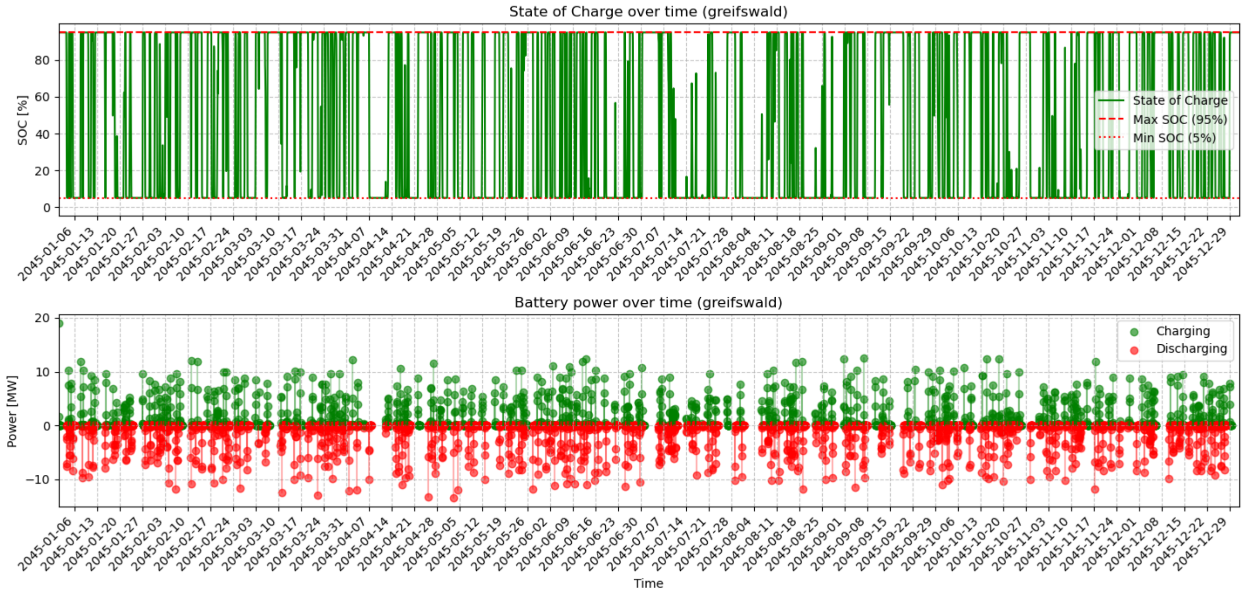


*Figure 34. SoC and BESS action over 2045 with 75% capacity.*