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Research Article

Quantitative Assessment of Sector Coupling Battery Energy Storage Systems and Their Contribution to the Resilience of the Power System

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The integration of renewable energy sources (RES) is essential for steering our energy systems towards sustainability. This transition, though, coupled with emerging trends such as digitalisation and decentralisation, introduces a number of new challenges and vulnerabilities to our energy infrastructure. To strengthen our energy systems against the uncertainties arising from intermittent RES and decentral organised power grids, battery energy storage systems (BESSs) integrated into sector-coupling strategies might play a crucial role. Such BESSs can enhance system resilience by providing increased flexibility in the face of disruptive events. Yet, the assessment of their resilience contribution is still a nascent field, particularly within the context of multi-energy systems. To address this gap, our study presents an assessment scheme utilising the open source energy system model electricity grid optimisation. We apply this scheme to evaluate the impact of sector-coupled BESS installations with a local district heating network in a mid-sized German city. Our analysis encompasses various scenarios, considering diverse BESS sizes, quantities, seasonal influences, system scales, siting, and the severity of disruptive events. The principal findings are threefold: for energy systems that exhibit high inherent robustness, such as those with existing adaptive capacities and redundancies, hybrid BESS (hBESS) has a low impact on the resilience against single disruptive events. In contrast, for less prepared systems or during simultaneous events, hBESSs can substantially strengthen the resilience of the energy infrastructure, particularly regarding the 'security of supply' and 'cost efficiency'. For instance, during short-lasting disruptive events, hBESS can potentially avert up potential power outages from 1.4% to 45% increasing the security of supply. However, the resilient design principle 'spatial diversity' could not improve the system's resilience in all scenarios. This holistic approach is essential for identifying resilient strategies capable of effectively countering unforeseen disruptive events, thereby ensuring the continued stability and sustainability of our energy systems.

Keywords: cost efficiency; energy system; power-to-heat; resilience assessment; sector coupling; security of supply

1. Introduction

The transformation of our current energy system into a sustainable future is a paramount objective in the years ahead. This transformation involves the phased substitution of fossil fuels with renewable energy sources (RES), aligning with the ambitious climate change objectives set forth by the European Commission [1, 2]. Although RES can contribute to the sustainable energy transition and, thus, are considered as crucial system elements for this purpose [3], they cause other challenges in power grid operation. These additional challenges include the decentral power generation instead of conventional centrally organised energy feed-in, digitised (real-time) control mechanisms for balancing purposes in very short-time scales and advent of new actors such as prosumer supplying and consuming power at lower grid levels [4]. Specifically, these challenges encompass the continuous balancing of supply and demand, ensuring grid stability, a task made more intricate by the weather dependent, intermittent nature of RES feed-ins.

For ensuring the grid stability, energy storages are regarded as crucial system elements because they can temporally shift supply and demand for balancing purposes [5]. Battery energy storage systems (BESSs) based on lithium-ion chemistry are increasingly installed in Germany for providing ancillary services as for example frequency containment reserve (FCR) [6] and as other flexibility options [7, 8]. Although lithium-ion–based standalone BESS has several technical and economic advantages compared to conventional energy storages, hybrid BESS (hBESS) concepts can additionally improve the overall energy systems' performance by combining either different types of energy storages [9] or coupling to other sectors, such as heat or mobility [10]. The latter aspect particularly gained more attention in recent years in the context of multi-energy systems (MESs), and it is expected that this extended view on energy systems will become even more relevant in the future [11]. The reason for this is that MESs offer enhanced flexibility by enabling the shifting of energy use over time, as well as providing options for both short-term and long-term storage [12]. Nevertheless, the balance of supply and demand in MESs will likely require more storage capacities due to the intermittent feed-in of RES, which are still limited [13]. Hence, hBESSs with sector-coupling options can contribute to the successful energy system transition and are a relevant technology to be considered in grid planning [14–16]. The modelling of such MES is a challenging task that must consider multi-energy aspects (e.g., sector coupling and interdependencies, RES integration, decarbonisation, as well as their operation and management), spatial and temporal resolution as well as implementing uncertainty [17]. Since providing energy to specific stakeholders is a vital system service, assessing the reliability and resilience of hBESSs within MESs, which are still in the early stages of development, requires a thorough evaluation.

Conventionally, reliability assessments mainly focus on *low impact* and *high probability* disruptive events that can affect the system performance causing unplanned outages [18, 19]. Nevertheless, extreme disruptive events have became more frequent in recent years presumably due to climate change [11]. Such extreme disruptive events are characterised by *high impact* and *low probability* causing potentially longer power outages. Consequently, grid planning should not only consider reliability-driven aspects but also other more severe disruptions [19–22]. In response to this need, the resilience concept has been incorporated into the planning of energy systems, drawing its origins from the field of ecological sciences as first proposed by Holling [23]. At the core of this concept lies the understanding that when confronted with disruptive events, a system progresses through four pivotal stages: preparation, absorption, recovery, and adaptation [24]. Although multiple attempts have been made to establish a universal definition of resilience, variations exist among studies. However, the principal idea revolves around a proactive approach that not only considers the pre-event status of the system but also encompasses the stages of adaptation and recovery. Given that both reliability and resilience concepts aim to enhance system performance across all resilience stages, they can effectively complement each other [25]. Likewise, the scientific literature on standalone BESSs has a rich basis on both reliability and resilience aspects, which are gradually shifting from the former to the latter, thereby acknowledging the importance of the resilience concept.

From a reliability-related point of view, standalone BESSs were consequently studied regarding their contribution to adequacy and security of power grids, minimising system costs, or increasing the profit [26]. For instance, Xu and Singh [27] developed an operation strategy for energy storages. They show the increased reliability of the bulk power system using the reliability indices loss of load probability (LOLP) and expected energy not served (EENS). Also, Edwards et al. [26] investigated the contribution of grid-scale energy storages to the generation capacity adequacy and developed a methodology for its optimisation considering positive contribution of nightly rechargeable grid-scale storages determining EENS values. In contrast, Giannelos et al. [28] focused on the security provision of energy storages and developed a methodology to quantify the contribution comprising the maximum peak reduction and did not account for the conventional reliability and economic aspects. Similarly, Dratsas, Psarros, and Papathanassiou [29] point out that energy storages can significantly contribute to system adequacy, when operated with an adopted reliability-driven strategy including peak shaving services. Ayesha et al. [30] additionally review the potential of energy storages to avoid additional transmission infrastructure using operational strategies such as demand response (i.e., peak shaving), optimal transmission switching (i.e., improved line switching) or dynamic thermal rating and also improving the systems' reliability.

However, such reliability studies usually apply conventional indicators such as the LOLP and EENS to determine the potential system's reliability when faced against low impact/high probability disruptive events. These indicators are usually averaged on an annual basis aggravating to determine the reliability contribution of certain technologies in specific known disruptive events.

Similar results are indicated by resilience studies of standalone BESSs showing positive effects on the systems' resilience. For instance, Zahraoui et al. [31] analysed the resilience performance of a standalone BESS in microgrids and propose an optimal sizing (and localisation) framework to improve the dealing with forecasted natural disasters and power supply outages. Likewise, the BESS in distribution grids can contribute to islanding modes and thereby increase the resilience and enabling cost-optimal solutions [32]. Gilasi, Hosseini, and Ranjbar [33] emphasised that standalone BESSs can also contribute to the resilience during night times compared to distributed photovoltaic installations, when probability of earthquakes can be increased. Furthermore, principal attention has been laid on the development of frameworks at a systemic level assessing the interdependencies of MESs from technical or techno-economic perspective [34–40]. Most of

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these developments focus on coupling the power sector with gas grids [35, 37] or feed-in of different RES into the power grid and considering various energy sources and sinks [13]. Unfortunately, a widely accepted framework for reliability and resilience assessments of MESs is not yet agreed on [41].

Consequently, although the research studies highlighted the positive effects of standalone BESSs against known disruptive events, the role of hBESSs as part of MESs and against unknown disruptive events is not fully understood, primarily due to the existing research gap in the perspective of vulnerability and resilience within MESs [14, 42]. In the light of this discussion, this study focuses on an already operating hBESS, which is installed in a city in North-Western Germany. This facility is connected to both the power system and the local district heating network providing functions as power storage and coupling to the heat sector.

Two research questions were addressed, that is, (RQ1) How to assess the role of such facilities in MESs as well as their contribution to system's resilience when facing disruptive events and their unknown impacts? and (RQ2) How much is the contribution of the hBESS installed at the location selected? By doing so, an approach for the resilience assessment of a power system using hBESS is proposed that is capable to consider *high impact* and *low probability* disruptive events and is applied for the exemplary system in this study. For RQ2, the following hypotheses were defined and tested:

- H1: hBESS can support the system service during disruptive events.
  - H1.1: If the hBESS has an effect on the resilience, its contribution depends on the storage capacity.
  - H1.2: If the hBESS has an effect on the resilience, its contribution depends on the power system size.
  - H1.3: If the hBESS has an effect on the resilience, its contribution depends on the seasonal variation.
  - H1.4: If the hBESS has an effect on the resilience, the contribution depends on the duration of the disruptive event.
- H2: The spatial placement of hBESS can improve the resilience of the energy system.
- H3: hBESS can increase the cost efficiency of performance.

The rest of the work is structured as follows: Section 2 introduces the material and methods used for this study. Section 3 presents the results and their discussion. Finally, Section 4 concludes this work.

2. Material and Methods

This section introduces five subsections in which the resilience definition applied in this work (cf., Section 2.1), the case study of the hBESS (cf., Section 2.2), the used modelling tool with the energy system and basic assumptions (cf., Section 2.3), the implementation of different scenarios (cf., Section 2.4), and the implementation of disruptive events (cf., Section 2.5).

2.1. Definition of the Term Resilience Applied in This Study. As pointed out in the introduction, various definitions of resilience can be found in the literature, which is why a clear and concise definition is required to have common understanding of how the study is executed. The understanding of resilience applied in this study follows the definition proposed by von Gleich et al. [43] who align with the ecosystem theory. Thus, we define resilience as '*…the ability of a (socio-technical) system to maintain the system services under internally and externally induced stress in turbulent conditions*'. The reason for selecting this definition is that no concrete causes of disruptive events are considered in the modelling but only their impacts. Also, this definition allows for focusing on unknown disruptive events as it does not require a perfect foresight.

2.2. Case Study: hBESS at Pilot Scale. The considered hBESS is operated in the mid-sized city of Bremen having nearly 0.5 million inhabitants in North-Western Germany. The hBESS consists of three main BESS modules. Each of them comprises a BESS, electrode boiler, inverters, transformers, and direct current switches. The BESS has a capacity of 14.2 MWh and uses lithium nickel–manganese–cobalt battery cells. The electrode boilers convert power to heat (PtH) with ~6 MW each, which is fed either into the thermal storage or into the local district heating network. Thereby, the PtH unit couples the heat and power sectors enhancing the flexibility of operational strategies. If the state of charge of the hBESS succeeds an upper limit of 90%, excess energy is transferred into the local district heating network. The hybrid power regulating plant is coupled to the 6-kV grid and then electricity transformed to the 110-kV high-voltage network.

2.3. Modelling Requirements and Method Selected. This subsection describes the relevant modelling requirements for assessing the contribution of a hBESS to the energy systems' resilience. This includes the definition of essential system services that are relevant for the stakeholders of the system in question. Additionally, indicators have to be selected for estimating the resilience of the energy system in case of disruptive events. These indicators should be the direct result of the model, or if indicators are not directly obtainable, the model outputs should at least enable their derivation. It has to be noted that energy system models generally do not simulate actual disruptive events, which is why the potential impacts have to be transferred into corresponding changes in the model structure and/or model behaviour.

2.3.1. Energy System Services. To define the essential system services, the most important requirements for energy systems should be considered, which can be illustrated by the so-called German energy policy target triangle [44]. This triangle comprises the targets *security of supply*, *cost efficiency*, and *environmental compatibility* that have to be fulfilled by sustainable energy systems [44]. The *security of supply* is the most important system service for ensuring the resilience of energy systems. Therefore, resilience assessments can focus on both the system design (i.e., structure) and system performance. Since the potential contribution of

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the hBESS to the resilience is related to the system performance in case of disruptive events, the security of supply is considered as the system service. The second target of the energy policy triangle refers to *cost efficiency*. Because the improvement of the systems' resilience is often accompanied by increasing costs due to additional redundancies or diversification measures, the affordable costs of the energy provision become a central requirement for the system service [2]. In this context, low electricity costs, and thus, better economic conditions, are often mentioned to prevent effects such as carbon leakage and to ensure sufficient social acceptance for the energy transition [45]. Therefore, cost efficiency is also considered as a system service indicator in this work. Although, decisions on energy system design and behaviour at affordable costs always affect the environmental performance; however, it has to be noted that the hBESS main objective is not the reduction of environmental impacts, but to stabilise potential disbalances in the grid due to its storage and buffer function. Thus, the *environmental compatibility* is not considered in this work.

2.3.2. Model Selection and Representation of the Techno-Economic Dimension. Based on the described requirements, the electricity grid optimisation (eGo) model was selected out of the multitude of available optimisation models for energy systems for this study. The eGo model handles the unit commitment problem matching the power demand at minimum total system costs:

$$\begin{aligned} &\mathrm{Min}_{g,h} \sum_{i,s,r,t} \left(o_{i,s} \cdot g_{i,s,t} + o_{i,r} \cdot \left| h_{i,r,t} \right|^{+} \right), \\ &\sum_{s,r} g_{i,s,t} + h_{i,r,t} = l_{i,t} \forall i, t, \end{aligned}$$

whereby the generator dispatch $g_{i,s,t}$ at each node i of the electrical grid for each generation type s and for each time step t is multiplied by its corresponding costs $o_{i,s}$. The objective cost function further consists of the positive dispatch by storage units $|h_{i,r,t}|^{+}$ for each storage type r times its corresponding costs. The positive dispatch prevents of minimising the cost function by charging storage units. The minimisation is constrained by the match of generation and storage dispatches with the power load $l_{i,t}$ at all nodes and for each time step.

Typically, a full-year optimisation is executed with hourly resolution solving the power flow equations in linear approximation for the power grid via the python-tool Python for Power System Analysis (PyPSA) and following a merit order to schedule power generation. Furthermore, the eGo model comes along with appropriate open source power system data, for example, power generation, including a detailed georeferenced power grid model of all elements belonging to the voltage level of 110 kV or higher. Especially due to the latter as well as its Open Source availability [46, 47], the eGo model is suitable for this work to determine system costs and to assess the system service *security of supply*.

The following data were utilised for the purpose of this work: weather-related data (e.g., wind time series), economic-related data (e.g., marginal costs), power demand data (e.g., load time series created according to data about local land use and population), power grid data (e.g., power line routes), and power generation data (e.g., power plant lists and feed-in time series) [47]. A complete description of the data model is given in [48]. The city of Bremen was cropped out of the data as a case study and subsequently the power flow equations in direct current approximation and minimal total system costs were calculated. Hereby, dummy power generation units were renounced at high costs to satisfy the matching of power demand at all times. Those are usually part of the eGo model to ensure model results although there is a lacking necessary part of power generation and/or there are critical congestions in the power grid. By this, many incalculable optimisation setups were received, which were counted as failures in the Monte Carlo simulation (MCS) approach (see Section 2.5.2) of this study. Hence, the optimisation results did not include cost penalties for load shedding or similar.

2.3.3. Analysis Environment. As mentioned above, the eGo model contains an open source dataset including the German high voltage and extra-high voltage level. This dataset consists of georeferenced grid data in terms of nodes, that is, substations, interlinked with edges, that is, power lines. Geographical coordinates, that is, longitude and latitude, were assigned to each network node, to which surrounding generators, consumers, and storages were allocated. Hence, data about generators, transformers, and consumers are aggregated in appropriate nodes. Since the hBESS was built in the German city of Bremen, the model was accordingly modified considering the city only (cf., Figure 1), considering that in the north-western region of Bremen exists an additional substation linked to the 380 kV grid level and another connection to the 220 kV grid level depicted as black and blue nodes, respectively. In the northern city centre, another substation linking the 110 and 220 kV grid level is present. For each of these substations the corresponding transformers were considered in the model. Regarding potential storage facilities, the open source dataset did not contain any information on their use. Thus, the hBESS was considered as the only storage facility in the model. The hBESS was assigned to the electricity grid node in the district Bremen–Hastedt close to its physical location.

2.3.4. Implementation of the Heat Demand Linked to the hBESS. The hBESS with the PtH unit was consistently integrated in the eGo modelling approach. For considering the PtH option, another energy flow was defined that included network nodes and edges using a separate voltage and frequency level as heat network. By doing so, the heat network could be considered in the model because the transformation between the voltage levels and provision of reactive power have no effect on the results as no costs were assigned to these processes. The network nodes for the heat provision were not assigned with spatial information, since this data does not influence the calculation and results. The demand and generation were allocated to the heat network nodes according to their corresponding amount. The hBESS feeds the heat energy to the thermal storage and local district heating network. While the thermal storage was assigned

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Figure 1: The modelled power grid of the German city of Bremen illustrating the nodes and edges for each grid level considered as well as the hBESS location (please note: only 110 kV power lines are visible at this scale). Reference: own illustration. hBESS, hybrid battery energy storage system.

to the heat network node, the electrode boiler was modelled as 'link' between power network and heat network, but allowing only flow to one direction, that is, PtH, which was feasible due to PyPSA system structure selected [49].

2.3.5. Main Assumptions Applied. The modelling approach underlies several assumptions, which include the business model, the system model, data completeness, and technology costs. The most significant assumption relates to the business model of the hBESS. The general business model for hBESS focuses on the FCR market, where the highest revenues were expected, so far. FCR is the first mechanism that is activated when the grid frequency deviates from the nominal value of 50 Hz, and the respective energy has to be provided to or retrieved from the grid for balancing purposes. Due to the volatile prices at the German FCR market, other business models are discussed for hBESS as potential income such as peak shaving, voltage control, and arbitrage trading, for instance. This study assumed that the hBESS focuses on the arbitrage trading business model and thereby acts as a normal actor with the objective reducing system costs. This assumption was necessary because of three constraints. First, the required data of the FCR provision in the system were not publicly available, second, the differing time resolution of seconds (in case of FCR) to hours (in case of the eGo model), and third, the central constraint for the mathematical optimisation is that the energy demand has to be matched by the supply in every time step. Moreover, transformers, PtH, and line components were modelled with an efficiency of 100%, and the round-trip efficiency of the hBESS was assumed with 85%. The latter value is based on data originating from real operation of the aforementioned hBESS.

Another simplifying assumption is related to the exclusive consideration of the high and extra-high voltage level for the electricity grid. Thereby, the distribution grid is omitted even though it would be essential to consider for determining potential impacts to industry, residents, and other stakeholders. The dataset of eGo does not include georeferenced grid data at lower voltage levels; hence, the grid nodes at the high-voltage level represent balanced nodes for the subsumed lower medium and low-voltage grid [47]. Thus, potential failures at these nodes do not indicate to potential severe impacts to which stakeholders might be exposed to at lower voltage levels. Also, the selected modelling approach omit potential recovery mechanisms at the lower voltage levels in which the power supply can be ensured via the distribution grid due to the system design according to the '*n*-1 criterion' [50]. Furthermore, the model does not include the possibility of drawing electricity from other generators from the transmission grid via the 380 kV grid nodes. In order not to suggest a high degree of accuracy, the existence of large generators was only checked with connection to the 220-kV level. For example, an additional power plant was added, which is located in the north-west of Bremen and was not included in the original data set.

2.3.6. Cost Assumptions. The assumption for establishing an optimised grid is based not only on the power supply and demand but also on the costs allocated to each technology considered. The eGo model focuses on marginal costs of the power generation technologies, which are shown in Table 1

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Table 1: Assumed marginal costs for power and heat generation technologies considered in the energy system.

Technology	Marginal costs of power (€/MWh)	Marginal costs of heat (€/MWh)
Coal	24	8
Gas	42	21
Waste incineration	40	—
Other non-renewables	68	—
Photovoltaics	0.07	—
Run-of-the-river	0.14	—
Wind	0.10	—
hBESS	0.00[a]	—

Note: Data from the Open Energy Platform [46].
Abbreviation: hBESS, hybrid battery energy storage system.
[a] No marginal costs were assumed for hBESSs in order to determine their maximal contribution to the power system's resilience.

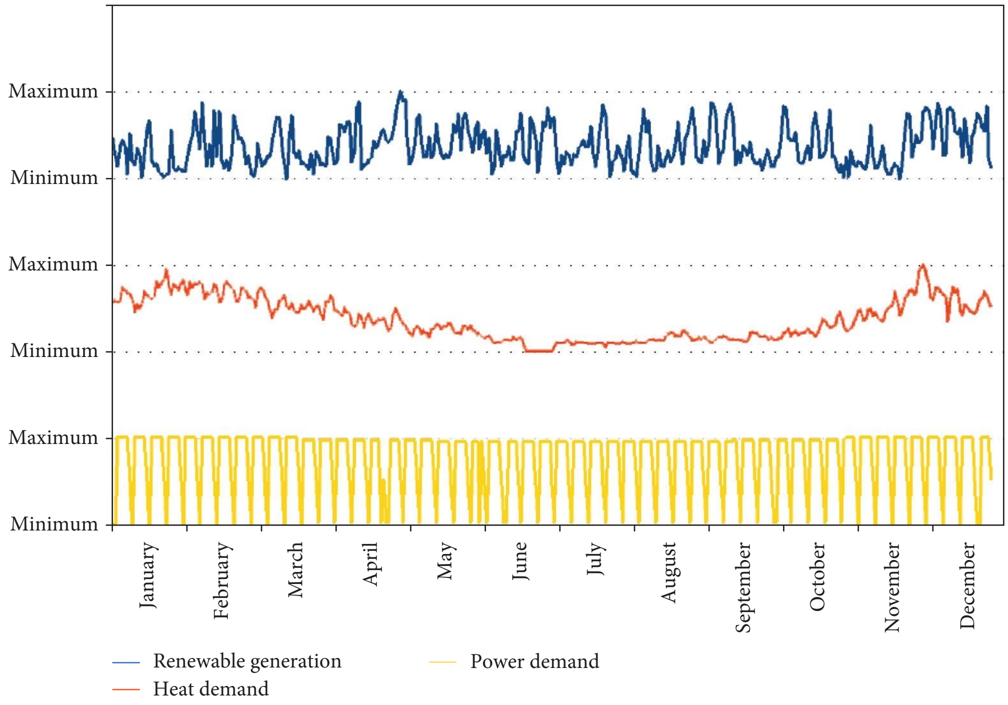

Figure 2: Exemplary demand profiles and renewable power generation for the modelled energy system during a year. Reference: own illustration.

and are included as standard in the model. This approach of using marginal costs is in line with the common practice in deployment optimisation [51]. Thereby, the main simplification is that costs caused by the operation of the power generation technologies are considered from an overall system perspective, so that the individual costs for end consumers, grid operators and other stakeholders as well as levies and taxes are not considered in this study. For the use of the respective generation technology in the context of cost-minimising optimisation, the costs in relation to each other are the decisive criterion for deployment optimisation. Investment costs, that would have to be allocated for determining the actual electricity production costs, are not included due to the focus on the operation only. In particular, power generation from wind and solar would have higher costs than the marginal costs shown in Table 1 due to their capital intensity [52]. Additionally, we assumed near-zero marginal costs for the hBESS. By doing so, the study determines the maximal contribution to the resilience of the power system considered.

Table 1 indicates that coal is the lowest marginal cost generation technology for non-renewable power and still is more expensive than the heat generation technology with the highest marginal cost, that is, gas. Hence, the heat supply is only provided by renewable electricity generators when the renewable energy generation exceeds the electricity demand. Additionally, the model omits the marginal costs of operation for the transformers and the hBESS including the PtH unit.

2.3.7. Analysis of the Power System Considered. The modelled power system has an annual consumption of electricity and heat, as depicted in Figure 2. The renewable generators, that is, photovoltaic or wind, are not sufficiently available to cover

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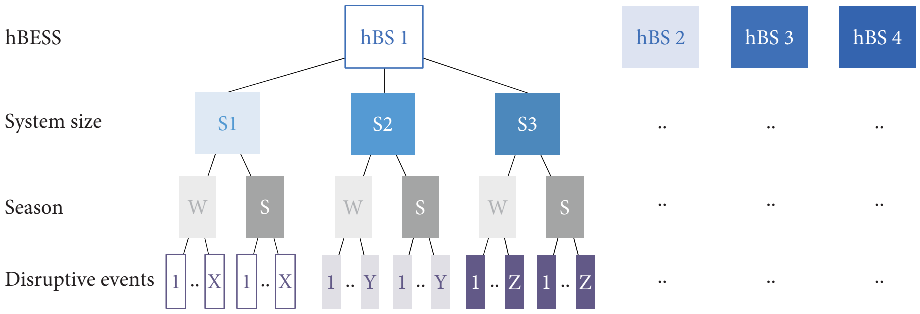

Figure 3: Hierarchically structured scenario setup applied in this study including hBESS and different hBESS scenarios (hBS), system sizes (S1–S3), winter (W) and summer (S) season as well as disruptive events (own illustration). hBESS, hybrid battery energy storage system.

the energy demand. Assuming that no power line bottlenecks occur and that renewable electricity is available in each time step, the share of renewable energy generation is 21% over the entire year. The heat demand profile follows the expected seasonal pattern.

2.3.8. Resilience Analysis. The so-called design principles can be considered as a guiding concept for resilient systems [53]. In the case of energy systems, these design principles can include diversity, variability, dispersion, redundancy, modularity, storage, buffers, dampers, feedback, cellularity, loose optional couplings, self-organisation, actor networks, subsidiarity, efficiency, and resource availability [54, 55]. The hBESS particularly features storage and optional coupling as well as the additional redundancy in heat supply provided by the electric boiler. Furthermore, if more than one hBESS is present in the energy system, it adds also geographical distribution, that is, spatial diversity.

To analyse the impact of hBESSs on the resilience of an energy system, the concept of vulnerability will be applied [56]. Vulnerability is the extent to which a system can be harmed or damaged by internal and external disruptive events. Thus, the lower the vulnerability the higher the resilience of the system. In the context of this work, the event-related vulnerability analysis is to be applied, as it considers the vulnerability related to external disruptive events [57]. The vulnerability depends not only on the severity of the disruptive events, that is, exposure, but also on the sensitivity of the energy system and its adaptive capacity, that is, its ability to compensate for the disruptive events [58, 59]. Here, only the consequences of the exposure to disruptive events are considered and thus the study focuses on a specific aspect of vulnerability. According to the resilience understanding in this work, different disruptive events, that are differentiated into known and unknown, slow and sudden appearing events, are considered. When simulating these disruptive events, their probability of occurrence and magnitude vary to derive vulnerability statements. MCSs are used to ensure that the results are not influenced by the choice of a particular disruptive event (cf., Section 2.5.2).

2.4. Scenario Setup for the Resilience Analysis. This subsection describes the scenarios systematically designed in a hierarchical manner (see also Figure 3) in order to test the hypotheses H1 with H1.1–H1.4 and H2. Each of the four principal hBESS scenarios (hBS1–hBS4) differs by the hBESS dimension and number of hBESS distributed in the power system (cf., Section 2.4.1 and H1.1 and H2). For assessing the impact of system boundaries (cf., Section 2.4.2 and H1.2), the size of power system was varied for each hBS, called system size S1–S3. Furthermore, each system size was analysed with both a representative winter and summer month, enabling the identification of the seasonal influence on supply and demand (cf., Section 2.4.3 and H1.3). Finally, for the representative winter and summer months, several system size-dependent disruptive events have been analysed (cf., Section 2.5 and H1.4).

The following subsections will describe each hierarchical level with the corresponding assumptions.

2.4.1. Hybrid Battery Energy Storage Scenarios. The base scenarios vary the technical setup of the hBESS in terms of hBESS dimension and spatial diversity, that is, location, in the energy system. Scenario hBS1 excludes any hBESS and acts as reference scenario. Scenario hBS2 represents the originally installed hBESS at the location in North-Western Germany, as described in Section 2.2. Scenario hBS3 considers different dimensioning of the hBESS depending on the system size. Thereby, it is ensured that the assumed hBESS capacities are relatively aligned to the corresponding system size, that is, total energy supply/demand, such that the comparability to hBS2 is given. Scenario hBS4 assumes a spatial diversification of the hBESS to identify the relevance of distributed hBESS on the power system. Thereby, the total hBESS capacity of all hBESS in hBS4 corresponds with the total hBESS capacity in hBS3. We further chose a uniform and homogenous spatial diversification for each system size to prevent size effects, for example, by storage clusters. These scenarios are described in Table 2 in more detail.

2.4.2. Energy System With Different System Boundaries. Since the system boundary selection, including total load as well as generation, is a crucial parameter, the selected system boundaries consider three different energy system sizes. The variation is applied only to the power system, whereas the district heating network with its four heat generators and its heat load remains unchanged. The following paragraphs introduce shortly the system sizes with their technical characteristics.

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Table 2: Scenarios modelled considering different technical setups of the hBESS.

hBESS scenario	**Description**	**hBESS specification**		
		System size 1	**System size 2**	**System size 3**
hBS1	Reference scenario	No hBESS considered		
hBS2 (standard hBESS)	Standard hBESS	Battery capacity of 14.244 MWh Electric boiler of 17.82 MW		
hBS3 (increased capacity)	Increased capacity of the hBESS depending on the system size (ensuring comparable capacity shares for the corresponding system size)	Standard hBESS increased by factor 29 (cf., Section 2.4.2)	Standard hBESS increased by factor 24 (cf., Section 2.4.2)	Standard hBESS increased by factor 5 (cf., Section 2.4.2)
hBS4 (increased capacity and spatially distributed)	System size-dependent variation of the number of hBESSs that are spatially distributed uniformly and homogenously			

Note: Own reference.
Abbreviation: hBESS, hybrid battery energy storage system.

Table 3: Seasonal energy demand for the different system sizes considered.

Representative month for winter and summer	**System size 1 (MW)**	**System size 2 (MW)**	**System size 3 (MW)**
January	550	455	94
July	537	447	92

Note: Own reference.

System size 1 corresponds to the entire energy system of Bremen as it was originally part of the eGo model. It consists of 79 nodes with 79 generators, 125 power lines, and 4 transformers. The annual electricity demand is ~3400 GWh.

System size 2 considers a smaller energy system in which the northern part is omitted, which included a coal-fired power plant with a capacity of 350 MW. The system size 2 energy system comprises 54 nodes, 57 generators, 89 power lines, and 1 transformer. The annual electricity demand is ~2900 GWh.

System size 3 represents the smallest energy system in which the eastern part of Bremen is only included. It consists of 13 nodes with 13 generators and 13 power lines. The largest generator is the coal-fired power plant installed next to the hBESS. The annual electricity demand corresponds to ~600 GWh.

2.4.3. Seasonal Impact due to Varying Supply and Demand. Seasons impact both the feed-in of RES into the energy grid and consumption of the local district heating network. In order to identify potential seasonal influences, the simulation environment distinguishes an European winter (January) and summer (July) month using consumption values provided by the Open Energy Platform [46] as depicted in Table 3 for each system size. The month of January is characterised by a lower power demand and higher thermal load compared to the month July, whereas both are the representative months regarding the peak load and generation, respectively (cf., Figure 2). The heat load is considered constant in all system sizes in January and July, respectively.

2.5. Model Implementation of Disruptive Events

2.5.1. Definition of Disruptive Events. Disruptive events can have various causes ranging from natural disasters, over technical and man-made failures to cyber attacks. Generally, these disruptive events can cause three different impacts on the system components. First, the component function is not provided, and thus, the system has to handle the loss of the affected component. Second, the component function is manipulated (intentionally or unintentionally) leading to an incorrect service provided by the component. Third, the affected component operates within normal parameters. As a result, the failure of a component can either impact the system's behaviour or go unnoticed, as these systems typically possess capacities and capabilities to respond to such situations, whereas hBESSs can offer valuable contributions.

The purpose of the eGo model is not to simulate specific disruptive events, as it solely focuses on energy grid optimisation. Thus, *the impacts* of the disruptive events were considered regardless of the cause, either causing failures or operates within normal parameters. The impact 'manipulated operation' is consequently excluded in this study.

Table 4 summarises the impacts of the considered disruptive events. The impacts are modelled as the number and type of failing components, that is, generators, supply lines, or transformers. Also, the duration of the disruptive events, that is, long vs. short, and their impacts were analysed separately. The disruptive events to be analysed should be selected such that they represent the operational limits of the system. As discussed in Woods et al. [60], this opposite

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Table 4: Simulated disruptive events and impacts as well as their specifications for the resilience assessment.

System boundary	Constant/longer lasting impacts			Abrupt/short-lasting impacts		
	# runs	# failing components	Duration	# runs	# failing components	Duration
System size 1	1000	7–14 generators 0–1 transformers 2–4 supply lines	1 month	600	26–36 generators	1–12 h
System size 2	800	6–11 generators 0–1 transformers 1–4 supply lines		600	14–25 generators	
System size 3	500	2–5 generators 1–2 supply lines		500	6–9 generators	

Note: Own reference.

to brittleness is an important aspect of resilient systems. That means, small disruptive events leading to no power outage as well as significant disruptive events that result into unavoidable power outages independent of any additional installations can be ignored. Consequently, the set of the randomly selected impacts is chosen such that a disruptive event almost leads to a power outage or results into a power outage that might be avoidable. As result, only scenarios, in which the hBESS might contribute to the resilience of the energy system, have been selected for further analysis.

It became apparent that the modelled energy system is notably robust against single disturbances. This follows from the historically selected system design of the Bremen energy system, which was built allowing islanding modes. Generally, the islanding mode is known to be robust, and therefore, it is only vulnerable to a limited extent compared to other grid topologies that are dependent on surrounding nodes and edges. Consequently, the disturbances that bring the system to its operational limit require high number of failing components. This fact is important to consider later on in the discussion of the results. Table 4 lists the configured simulation for constant and abrupt disruptive events containing (see also Table 2) the assumptions made for each system size, the number of Monte Carlo runs (# runs), the number and type of failing components (# failing components), and the duration of an impact.

The vast amount of possible disruptive events and their potential impacts prohibits an exhaustive consideration, and thus, aleatory MCS was employed. The MCS considered for all scenarios within the same system size the same disruptive event and their impacts. The number of MCS runs, that is, impacts of disruptive events, was defined to reflect a fixed relative share for each system size. By doing so, the comparison of different hBS and parameter variation could be guaranteed.

2.5.2. MCS Approach. We utilise MCS to assess the variations made according to the analysis setup described in Section 2.4. This approach was chosen as the modelled disruptive events may cause critical situations in the power grid with unmet power demand and, hence, infeasible optimisation results. To overcome this issue, we run the optimisations multiple times with a random total number of failing components and a random selection of failing power generators, power grid transformers, and power lines (see Table 4). The randomisation provided by the python package numpy is based on a discrete uniform distribution which acts as probabilities of occurrence. Concerning the longer lasting disruptive events, the selected failing components are completely removed from the input data of the eGo model and, hence, their absence last for all timesteps of the optimisation. Regarding short-lasting impacts only power generators as failing components for a time span between 1 and 12 h are considered. This is reasoned by the opportunity to define fixed time series of power generators in PyPSA, which is not possible for power grid transformers and power lines. Noteworthy, we execute a perfect foresight optimisation whereby the disruptive events are known to the optimiser.

3. Results and Discussion

This section presents the results obtained for the system services '*security of supply*' and '*cost efficiency*' which will be described and discussed in Sections 3.1 and 3.2, respectively. In Section 3.3, the general aspects of the results will be discussed. Finally, Section 3.4 will discuss the limitations related to this study.

3.1. System Service 'Security of Supply'. The fulfilment of the service 'security of supply' is defined by the ratio between the relative increase of failure-free runs, which are successful simulation runs out of the total number of calculations (cf., Table 4) for each system size. Every result is compared to the scenario hBS1 as the reference power system with no hBESS, in order to determine the contribution of the hBESS to the power system's resilience.

In the following, the results are first presented and discussed at an aggregated level summarising the different system sizes and seasonal variation in Section 3.1.1. Second, the influencing factors of system size and seasonal variation were discussed in Sections 3.1.2 and 3.1.3 in more detail.

3.1.1. Overall Contribution of hBESS to the Resilience. Figure 4a,b depict the relative contribution of hBESS to the resilience of the power system considered. Thereby, the results for each hBS aggregate all varied parameters including system size and seasonal variation for the respective average, median, and quartiles. The results in Figure 4a generally indicate to the positive influence of hBESS on the

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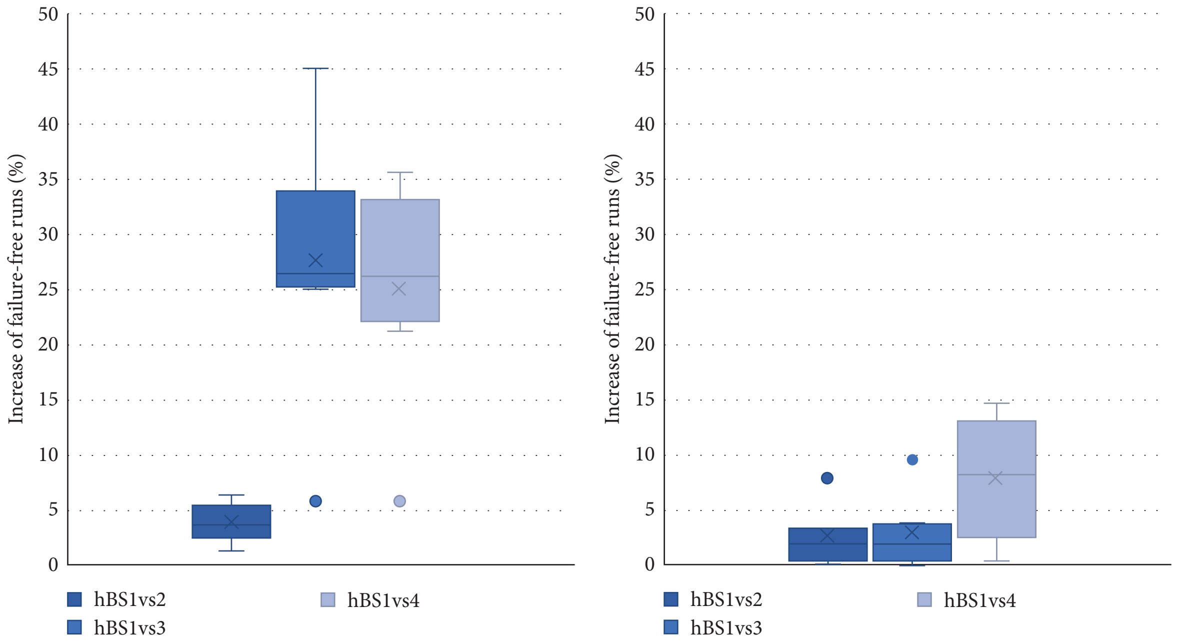

(a)

(b)

Figure 4: Boxplot results for system service ‘security of supply’ for different hBESS scenarios (hBS). The results for each hBS include all seasonal variations and system sizes considered (own illustration). (a) Abrupt/short-lasting disruptive events; (b) constant/longer lasting disruptive events. hBESS, hybrid battery energy storage system.

power system for all scenarios for short-lasting disruptive events. This supports hypothesis H1, which states that hBESSs generally contribute to the resilience of energy systems. This is shown by the higher average number of simulations without any power outages in the scenarios hBS2, hBS3, and hBS4 compared to hBS1 (i.e., without hBESS). During short-lasting disruptive events, using a single hBESS (i.e., hBS2) increases the average number of failure-free runs by 3.9%, a 29-times larger dimensioned hBESS (hBS3) caused an average increase of 27.5% as well as several spatially distributed hBESS (hBS4) result into 25% more failure-free runs without power outages in average (cf., Figure 4a and Table 5). This supports hypothesis H1.1 that the available storage capacity of the hBESS influences the contribution to the system’s resilience.

Regarding longer lasting disruptive events as shown in Figure 4b, the performance of hBESS is generally lower compared to the short-lasting disruptive events, which corroborates the hypothesis H1.4 stating that the duration of disruptive events will influence the contribution to the system‘s resilience. The single hBESS (i.e., hBS2) increases the average number of failure-free runs by 2.5%, which is in a similar range like the short-lasting disruptive events. The 29-times larger dimensioned hBESS (i.e., hBS3) results into an average increase of 2.9% and several spatially distributed hBESS (i.e., hBS4) performed the best with 7.8% more successful runs in average without any power outages in the longer lasting scenarios.

In other words, when the system operates at its limits, which is reflected by the disruptive events defined in Table 4, using a standard dimensioned hBESS only slightly increases the system’s robustness against potential power outages. This is also illustrated in Table 5 showing the contribution to the resilience in the range from 1.4% to 6.4% for short-lasting disruptive events. In contrast, using either a larger dimensioned hBESS (hBS3) or several hBESSs (hBS4) spatially distributed in the power system has a considerable positive influence in the range from 5.7% to 45% and from 5.7% to 35.6% on the resilience against short-lasting impacts, respectively (cf., Table 5).

The results can be interpreted by focusing on two aspects. First, BESSs are generally operated as short-term storages with limited capacities since no generation facility is connected to the battery enabling a grid-independent charging when a low state of charge is reached. Thus, the capability of a hBESS reacting towards outages in the grid is limited to the battery capacity and the corresponding state of charge, which is why the systems modelled in hBS3 and hBS4 with larger battery capacities perform better compared to the standard hBESS in scenario hBS2.

Second, interestingly the system design principle ‘spatial diversity’ applied in hBS4 does not necessarily increase the resilience of the system regarding the security of supply (cf., Figure 4a). The placement of hBESSs is a crucial decision in power grid planning processes and (h)BESSs are generally positioned and dimensioned according to the generally expected mismatches of supply and demand in the power system [61]. Likewise, potential mismatches of supply and demand result into nonfailure free runs in the simulations in this study and thus spatial diversity does not necessarily contribute to higher resilience. The contribution of hBESS to the power system resilience depends on their placement

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Table 5: Simulation results for abrupt and short-lasting disruptive events for different hybrid battery energy storage system scenarios (hBS), representative months and system sizes as well as the contribution compared to the hBS1.

Month	System size	Total runs	Scenario										
			hBS1 runs		hBS2 runs			hBS3 runs			hBS4 runs		
			Failure free (-)	Total share (%)	Failure free (-)	Total share (%)	Delta (%)	Failure free (-)	Total share (%)	Delta (%)	Failure free (-)	Total share (%)	Delta (%)
January	S1	600	333	55.5	344	57.3	*3.3*	483	80.5	**45.0**	449	74.8	**34.8**
July			384	64	399	66.5	*3.9*	522	87	**35.9**	466	77.7	21.4
January	S2		320	53.3	328	54.7	*2.5*	400	66.7	25.0	434	72.3	**35.6**
July			359	59.8	364	60.7	*1.4*	451	75.2	25.6	448	74.7	24.7
January	S3	500	171	34.2	182	36.4	*6.4*	218	43.6	27.4	218	43.6	27.4
July			225	45	238	47.6	*5.8*	238	47.6	*5.7*	238	47.6	*5.7*
	—	—	—	—	—	—	Ø 3.9	—	—	Ø 27.4	—	—	Ø 24.9

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which should ‘ideally’ coincide with the failure location (e.g., loss of a component at a certain node) without being affected by the disruptive event, the state of charge and dimensioning that enable to deal with the disruptive event for a certain period of time. This rebuts hypothesis H2. Furthermore, it has to be noted that ‘spatial diversity’ relates to the resilience principle ‘localised capacity’, which is also interpreted as the modularity of energy systems [62]. Modules are self-contained entities (optionally) linked to other modules of the system [63]. They are capable of self-sustaining, even if one or more nodes are affected by disruptive events [62]. Hence, the disruptive event with its intensity and the spatial vulnerability of the module plays a relevant role for the local resilience performance [64]. In this study, additional hBESS were uniformly and homogenously distributed at spatial scale. Therefore, the random outages did not always co-occur at the same nodes at which hBESSs have been installed so that the installed hBESS was not available at the affected critical nodes.

In the case of longer lasting impacts, the results of scenarios hBS2 and hBS3 only show a limited absorption ability of the hBESS with up to one order of magnitude lower than the short-lasting disruptive events (cf., Figure 4b and Table 6). The scenario hBS4 with several spatially distributed hBESSs had the best performance with ~14% in the system size S2. In contrast to the results of short-lasting disruptive events, hBS4 performed better than the hBS3 in all system sizes.

The parameters system size and seasonal variation were separately analysed to shed light on their influence on the overall results (cf., Sections 3.1.2 and 3.1.3).

3.1.2. Influence of Different System Sizes on the Results. Figure 5a,b illustrate the results comparing different system sizes for both the short-lasting and longer lasting impacts, respectively. Generally, hBESS can increase the failure-free runs for smaller system sizes when exposed to short-lasting disruptive events (cf., hBS1 vs. hBS2). This is expectable because the capacity of the hBESS was considered as constant in all system sizes S1–S3, but, in turn, the energy system annual load and generation decreased. Thus, the ratio of battery capacity to the total grid load and generation was improved enabling a higher performance of the hBESS in case of disruptive events. Furthermore, the fact that the majority of the energy supply is generated by fossil energy carriers with ~80% in the considered power system, the missing of major generation facilities such as coal-power plants can cause more severe outages as the robustness of the system is decreased and thus is more vulnerable. Consequently, higher spare capacities of hBESSs can particularly contribute more to system’s resilience in the hBS3 and hBS4 (cf., also H1.1).

In Figure 5a, it has to be noted considering the scenarios with larger and spatially distributed hBESS (i.e., ‘hBS1vs3’ and ‘hBS1vs4’), that the dimension and amount of hBESSs differ for each system size, but represent the relative scaling according to the system size so that the scenarios remain comparable. Thus, the performance in hBS3 decreased with smaller system sizes, whereas hBS4 had a slightly higher number of failure-free runs in system size S2, but was equal in the system size S3 compared to hBS3. Also, this can be attributed not only to the system structure and placement of the hBESS, but also to the occurring impacts of the disruptive event with the corresponding failure of components.

Compared to the short-lasting impacts, the results of the longer lasting impacts indicate to the decrease of failure-free runs in smaller system sizes. This can be explained by two aspects. First, batteries are technically more suitable for short-lasting impacts preventing potential outages with the help of hBESSs. Consequently, the relative increase of failure-free runs is higher in Figure 5a than in Figure 5b. Second, the definition of the system boundaries (i.e., system size) and with that also the system design have a considerable influence on the performance of the hBESS depending on the randomly selected disruptive events. Therefore, changes in the performance of hBESSs when exposed to short-lasting impacts are more sensitive than for longer lasting impacts.

The results for spatially distributed hBESSs (hBS4) are less conclusive. One reason for the relatively high peak in system size 2 (cf., Figure 5b) is the lower seasonal variation, as will be discussed in Section 3.1.3.

It is also shown in Table 5 that the smallest system size S3 had the lowest share of successful simulations runs indicating to an already pre-stressed power system, that was particularly identifiable for the month January. This winter month is characterised with low RES feed-ins and higher heat demand. However, with larger dimensioning of the hBESS in hBS3 and hBS4, the contribution to the resilient energy system was improved by 27.4% compared to hBS1.

Regarding the hypothesis H1.2, it can be concluded that hBESS generally can improve the system’s resilience. However, the extent of the contribution depends on the storage capacity, seasonal variation, and duration of the disruptive event.

3.1.3. Influence of the Seasonal Variation. The influence of the seasonal variation on the results is depicted in Figure 6a, b. Generally, the resilience contribution of the hBESS is higher for short-lasting disruptive events than for longer lasting events by a factor of three. Regarding the seasonal variation the performance of all hBESS tends to decrease in the representative summer month July when the heat demand is lower and more RES are fed into the power system (see also Figure 2), which is reasonable due to the sector coupling character of hBESSs. Consequently, hypothesis H1.3 is also corroborated.

However, the results for short-lasting disruptive events in the scenario hBS2 stand out (Figure 6a). Here, the number of failure-free simulations runs is similar for January and July in average at a low level ranging from 3.7% to 4.0%, respectively. As it is shown in Table 5, the main reason for this deviation was the results for the system size S2, which were lower by a half than those of the other system sizes in the same scenario. Since the hBS2 features the smallest capacity of the hBESS, the potential seasonal variation did not affect the resilience contribution at a noticeable level as it was

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Table 6: Simulation results for longer lasting disruptive events for different hybrid battery energy storage system scenarios (hBS), representative months and system sizes, as well as the contribution compared to the hBS1.

Month	System size	Total runs	Scenario										
			hBS1 runs		**hBS2 runs**			**hBS3 runs**			**hBS4 runs**		
			Failure free (-)	**Total share** (%)	**Failure free** (-)	**Total share** (%)	**Delta** (%)	**Failure free** (-)	**Total share** (%)	**Delta** (%)	**Failure free** (-)	**Total share** (%)	**Delta** (%)
January	S1	1000	579	57.9	598	59.8	3.3	601	60.1	3.8	617	61.7	*6.6*
July			618	61.8	621	62.1	*0.5*	621	62.1	*0.5*	626	62.6	*1.3*
January	S2	800	407	40.7	420	42	3.2	420	42	3.2	467	46.7	**14.7**
July			432	43.2	432	43.2	*0*	432	43.2	*0*	493	49.3	**14.1**
January	S3	500	278	55.6	300	60	*7.9*	305	61	**9.7**	305	61	**9.7**
July			321	64.2	322	64.4	*0.3*	322	64.4	*0.3*	322	64.4	*0.3*
	—	—	—	—	—	—	*Ø* 2.5	—	—	*Ø* 2.9	—	—	*Ø* 7.8

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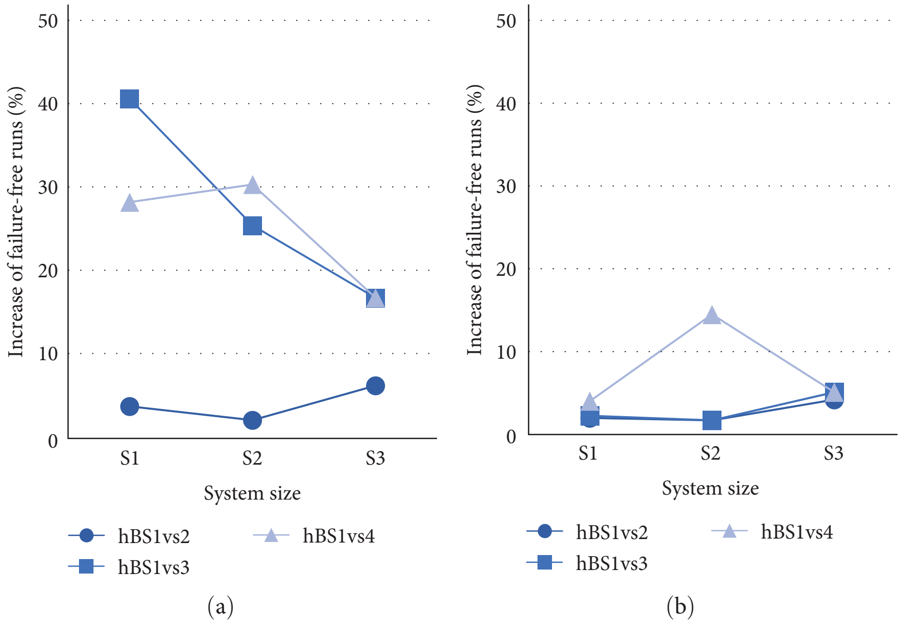
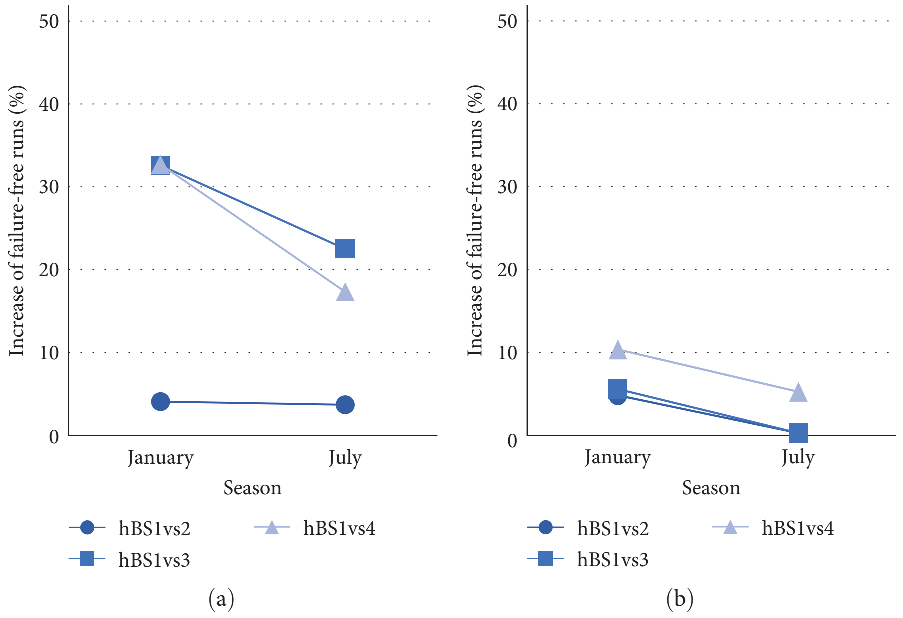


(a) (b)

Figure 5: Results for system service ‘security of supply’ for different hBESS scenarios (hBS) for different system sizes. The results include seasonal variations. (a) Abrupt/short-lasting disruptive events; (b) constant/longer lasting disruptive events. hBESS, hybrid battery energy storage system.



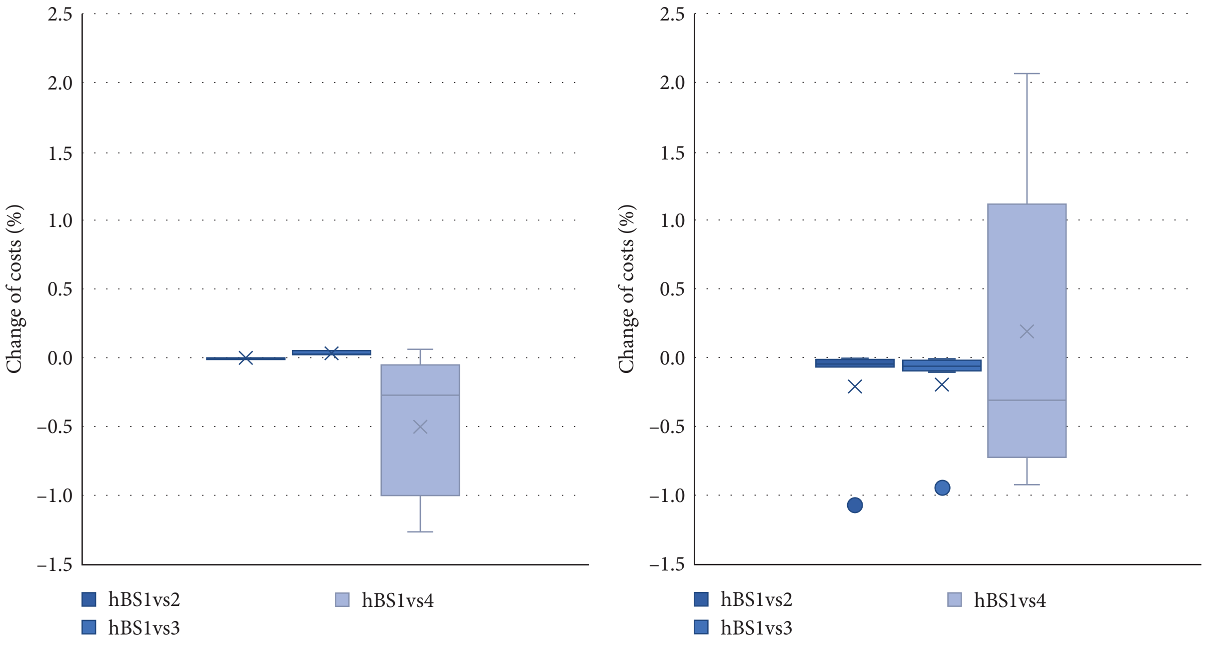
(a) (b)

Figure 6: Results for system service ‘security of supply’ for different hBESS scenarios (hBS) for the seasonal variation including all system sizes considered. (a) Abrupt/short-lasting disruptive events; (b) constant/longer lasting disruptive events. hBESS, hybrid battery energy storage system.

already at a low level. Likewise, the results for longer lasting disruptive events showed a similar pattern, with a lower contribution in the summer month by a half.

3.2. System Service ‘Cost Efficiency’. The analysis for cost efficiency was based on the marginal cost approach for determining the total cost optimum for the power system. Thereby, no marginal costs were assigned to hBESS in order to identify the maximal contribution to the power system’s resilience as the option hBESS should be always preferred over others. The cost efficiency was calculated and optimised by the eGo model in each simulation run meeting the total energy demand. Figure 7 depicts the obtained results considering each hBS scenario with all analysed seasonal variations and system sizes, respectively.

Regarding the cost efficiency, the results showed a very low effect originating from the hBESS and therefore H3 is rebutted. Only in hBS4 where several hBESSs with a higher



(a)

(b)

Figure 7: Boxplot results for system service ‘cost efficiency’ for different hBESS scenarios (hBS) for different system sizes. The results include all seasons and system sizes. (a) Abrupt/short-lasting impacts; (b) constant/longer lasting impacts. hBESS, hybrid battery energy storage system.

capacity is distributed in the power grid, costs were slightly reduced by −0.49% for short-lasting impacts in average, whereas longer lasting disruptive events the average costs increased by 0.2%. When analysing the impact of a standard hBESS (i.e., ‘hBS1vs2’) and a larger dimensioned hBESS (i.e., ‘hBS1vs3’), almost no effect can be noted. That means costs did not increase (‘hBS1vs2’) or very marginally by −0.04% (‘hBS1vs3’) in average for short-lasting disruptive events. Likewise, the cost efficiency during longer lasting disruptive events, decreased in average by −0.2% (‘hBS1vs2 and hBS1vs3’).

However, since no marginal costs were assumed for the hBESS usage, the overall economic efficiency can even decrease, when additional costs are charged for hBESS operations.

3.3. General Observations. The assessed energy system has a high inherent robustness against single disruptive events represented as failing components. The power system has already embedded several adaptive capacities and redundancies so that a single disruptive event (i.e., not cascaded) did not cause critical states in the system. Consequently, the hBESS did not notably increase the resilience of the system in terms of security of supply and cost efficiency. A different conclusion can be taken for energy systems that are less prepared, and thus, do not have redundant components or adaptive capacity to damping impacts. Simple disruptive events in such sensitive systems can lead to power outages, and far more catastrophic scenarios with higher number of failing components. In these cases, already single hBESS can have a notable influence on the security of supply in case of short-lasting disruptive events. When considering larger dimensioned hBESS or spatially distributed hBESSs, the impact on the security of supply can be even more significant with regard to resilience as shown in the results. On the contrary, the system service cost efficiency remains nearly unaffected in any scenario. The results are summarised in Table 7 in an overview rating.

3.4. Limitations. The main simplification is that the costs caused by the use of the power generation technologies are considered from the overall system perspective. For more holistic resilience assessment, the cost per stakeholder would be relevant to be considered as their needs and their affectedness can differ. For example, the individual costs for end consumers and grid operators as well as levies and taxes were not in the focus of this study, even though more comprehensive resilience assessments ought to include these aspects in future studies. Likewise, this study only included the marginal costs of operation and omitted the investment costs that would have to be apportioned to determine the actual electricity production costs. Consequently, wind and solar power generation has relatively high costs compared to the marginal costs shown in Table 1 due to their capital intensity [52]. However, in this study, the ratios of the marginal costs of the generation technologies are particularly relevant in the optimisation process as these are decisive for the use of the respective generation technology. This application of marginal costs in deployment optimisation is in line with common practice [51] for determining cost-optimal power systems. Since this study focused on identifying the (maximal) contribution to resilience, no marginal costs were assumed for the hBESS with its transformer and electric boiler. By doing so, the technology selection for the optimal

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Table 7: Rated results of the analysed hBESS with different hBESS scenarios (hBS).

Scenario	Security of supply[a]		Cost efficiency[b]	
	Abrupt/short-lasting impacts	Constant/longer lasting impacts	Abrupt/short-lasting impacts	Constant/longer lasting impacts
With hBESS (hBS2)	+	+	O	O
hBESS with increased capacity (hBS3)	+++	+	O	O
hBESS with increased capacity spatially distributed (hBS4)	+++	+	O	O

Note: Own reference.

Abbreviation: hBESS, hybrid battery energy storage system.

[a] O, no change; +, 0%–10% less failing runs; ++, >10% less failing runs; +++, >20% less failing runs.

[b] -, <0.5% higher costs; O, no change; +, >0.5% lower costs.

solution was biased in favour of the hBESS. Depending on the actual marginal costs of the hBESS, other technologies will be preferred, if the marginal costs of the technological options are lower than those of the hBESS.

The exclusive consideration of the high and extra-high voltage grid represents a simplification of the network topology. Consequently, potential disruptive events and their effects in the lower medium and low-voltage grid were not included, although the affected loads with their stakeholders should be considered in resilience studies on power grids. This particularly applies to the so-called critical loads such as hospitals, police, and fire brigades and water supply, for instance, which are crucial services not only in pre-event stages but also during disruptive events in order to activate the adaptive capacities and capabilities. Since resilience manifests itself at local scales, that is, mid and low voltage level, for the affected stakeholders, the energy system design is traditionally planned from a top-down perspective. The particular challenge is to bridge the so-called granularity gap between higher and lower system level perspectives [65]. However, the resilience of higher voltage levels can be used as an indication for the effects on lower voltage levels because they supply the majority of the loads required. In the course of the energy system transition, the main power supply may change to a more decentralised topology enabling the modular and self-autonomous operation at low voltage levels.

Counterintuitively, the results of this study also showed that uniformly and homogenously spatial distribution, that is, geographical diversity, of the hBESS did not necessarily improve the overall resilience performance, although this resilience measure is often seen as potential positive action. However, to which extent the resilience measure spatial distribution/diversity can increase or decrease the performance of energy systems cannot be generalised from this study. Spatially distributed hBESS supports the modularity of the energy system, which is usually defined by its self-sustaining characteristics (e.g., modular cells). Because unknown disruptive events can occur out of the sudden at any time and place in the system, the contribution of hBESSs to the resilience is limited insofar that both affected nodes and available adaptive capacity of the hBESS have to co-occur. The exposure to the disruptive event with its severity, and the structure of energy system or parts thereof, influences the spatial vulnerability and thus the resilience performance. Although (comprehensive) resilience assessments should not be only limited to vulnerability aspects, the solely technical perspective is related to the fact whether the affected power lines or nodes can be substituted either by additional local power supply for the node or redundant power lines enabling the energy supply of the node considered. This in turn depends on the topology of the energy grid. Here, the assessed energy system of the German city of Bremen was originally designed to have islanding capabilities regarding disruptive events. Therefore, corresponding capacities and capabilities for dealing with disruptive events are already available in this specific case study.

The challenge for future resilience assessments still persist in which the resilience is not only an emergent systemic property but also has spatial and temporal dimensions that have to be considered in assessments. Although single technological components can contribute to the resilient behaviour, the extent of this contribution always depends on the disruptive event and socio-technical context. Regarding MESs, this quest becomes even more challenging, since different critical infrastructures are interlinked and can be mutually dependent.

This study showed that with the corresponding framework sector-coupling concepts can be analysed, although the case study did not show relevant contributions to the district heating grid during different disruptive events. Even though researchers opt for case-by-case assessments and commonly agree to the limited transferability of specific results to other contexts [66], general conclusions would enable improved power system designs. Thus, future studies should focus on the dependencies of resilient design principles and the preconditions of the system in question for deriving recommendations for resilient designs. By doing so, resilient designs can be developed and implemented so that the future energy system can perform superior independently of the disruptive event.

4. Conclusions

The energy transition of our energy systems is accompanied with new challenges such as the decentral power generation,

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digitised (real-time) control mechanisms for balancing purposes, and the increasing feed-in of intermittent RES, which complicate the matching of supply and demand in energy systems and thus can jeopardise the grid stability. Consequently, the resilient design and operation of power systems are crucial for ensuring the security of supply at all times. BESS is discussed as one potential technology to face the challenges as they can buffer potential mismatches of energy supply and demand at shorter and longer time scales. HBESS can additionally couple to other sectors such as mobility and heat, which is a relevant aspect in future MES. The contribution of such hBESS to the system's resilience is not yet fully understood and potential assessment schemes were not at hand, so far. Thus, the aim of this work was to develop a quantitative approach for assessing the resilience and economic contribution of a hBESS to an energy system enabling the coupling of the sectors power and heat, which was applied to an exemplary energy system of a North-Western German city employing a hBESS.

For this purpose, the techno-economic optimisation tool eGo was used and a comprehensive scenario setup was established for a North-Western German city. The hBESS resilience contribution was analysed by varying the energy system size, seasonal variation (i.e., representative month in winter and summer), hBESS dimensioning, and site selection. For each of these scenarios, short-lasting (i.e., 12 h) and longer lasting disruptive events (i.e., 1 month) and their impacts were considered applying an MCS routine to determine the indicators 'security of supply' and 'cost efficiency'.

The results indicate that hBESS can increase the resilience of an energy system with respect to the selected indicators. Particularly, in the case of short-lasting disruptive events, a higher level of security of supply ranging from 1.4% to 45% can be ensured by the hBESS with the additional adaptative capacity for a limited period of time. The battery is preferably used for bridging outages or load peaks that exceed the maximal available capacity. When exposed to longer lasting disruptive events, hBESS contributes to a lesser extent ranging from 0% to 14.7% increase of the security of supply. Moreover, it was shown that the resilient design principle 'spatial diversity' could not improve the system's resilience in all scenarios and the placement of hBESS at critical nodes is a relevant decision to take, although the random occurrence of disruptive events aggravates the optimal siting of hBESS. Another result was the case-dependency of the potential resilience contribution of the hBESS, which notably depends on the disruptive event, the affected nodes and lines as well as the placement of the hBESS.

The cost efficiency only marginally changed in all scenarios. Furthermore, the PtH electric boiler was only used in case of insufficient generator capacity in the heat network due to economic reasons, which seldomly occurred in this study. Otherwise, the coupling of the sectors in the modelled system serves to convert surplus renewable energy into heat, thereby potentially reducing costs. The battery can reduce costs in the electricity sector by providing intermediate storage capacity for low-cost renewable energy avoiding the use of generators with higher marginal costs.

Since a techno-economic optimisation tool was applied to obtain the abovementioned results, the selection of the preferred technologies strongly depended on the marginal costs assumed. Here, the hBESS was always selected over other options in order to determine the maximal contribution to the system's resilience. However, if sector-coupling technologies are increasingly implemented in power systems, other aspects such as generation costs, levies, charges, and taxes as well as additional revenues (e.g., black start capability) should be considered as these influence the cost efficiency and the actual dispatch of the technology. Likewise, low voltage grids should be additionally included in the assessment enabling more detailed statements about the security of supply and effectiveness of potential resilience measures at local scales. Also, multiple case studies with different grid topologies should be considered in future resilience assessment in order to enable the generalisation of these findings.

Generally, one can conclude that this work indicates the resilience enhancing features of sector coupling technologies in the energy sector, and thus, motivates further research in this direction by the community. However, due the complexity of resilience assessments, the results of most studies obtain case-specific knowledge, which cannot be easily transferred to other contexts. Consequently, future research endeavours should not only focus on performance-related aspects but should also explore the interplay between system performance and its structural design characteristics, which would facilitate generalisable knowledge for power system designs. This holistic approach is essential for identifying resilient strategies capable of effectively countering unforeseen disruptive events, thereby ensuring the continued stability and sustainability of our energy systems.

Nomenclature

BESS:	Battery energy storage system
EENS:	Expected energy not served
eGo:	Electricity grid optimisation
FCR:	Frequency containment reserve
hBS:	Hybrid battery energy storage system scenario
hBESS:	Hybrid battery energy storage system
LOLP:	Loss of load probability
MCS:	Monte Carlo simulation
MES:	Multi-energy system
PtH:	Power-to-heat
PyPSA:	Python for Power System Analysis
RES:	Renewable energy sources.

Data Availability Statement

Data are available upon request, except for the confidential load profiles.

Conflicts of Interest

The authors declare no conflicts of interest.

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