A business-oriented approach for battery energy storage placement in power systems

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A business-oriented approach for battery energy storage placement in power systems

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HIGHLIGHTS
• Minimizing losses alone does not ensure business-friendly BESS placement decisions.
• Placement criteria in distinct project stages impact overall business feasibility.
• Varying BESS connection procedures apply at each grid level of the power network.
• Bornholm power system supports viable BESS business at multiple grid locations.

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ABSTRACT
Battery energy storage systems (BESSs) are gaining increasing importance in the low carbon transformation of power systems. Their deployment in the power grid, however, is currently challenged by the economic viability of BESS projects. To drive the growth of the BESS industry, private, commercial, and institutional investments in large-scale BESS projects are needed. For financiers and investors, choosing an appropriate BESS installation location is a crucial task that requires important considerations. However, so far, studies targeting the BESS placement problem have mainly focused on minimizing operational losses, solving power quality issues, and improving the voltage profile of the system. Implementing such approaches only considers the operational feasibility of BESS at the installation site while ignoring its business feasibility. Therefore, in this paper, we approach the BESS placement problem from a business viewpoint by conducting a stage-level investigation of BESS projects. First, we identify the factors impacting the business feasibility of placement decisions in projects’ construction, connection, operation, and disposal stages and propose cost and time effective measures for making them business friendly. We investigate several factors such as profitability of grid services, integrability of renewable resources, affordability of connection charges, and the usability of BESS capacity. Second, we investigate the business potential of placing BESSs in different grid-levels of the power system and examine BESS connection procedures at those levels. Third, we implement the proposed approach for installing a BESS in the Danish island of Bornholm, for which, we investigate multiple locations of the Bornholm power system.

Introduction
Rising environmental concerns and higher climate change awareness is increasing reliance on renewable energy sources (RES) in the electricity sector. However, the high intermittency and limited dispatchability of RES-based plants present challenges in transitioning toward sustainable energy solutions. Energy storage systems (ESSs), particularly BESSs are being widely recognized as a potential buffer to these challenges [1]. They can not only store excess RES generation but also provide multiple grid services at the point of their installation. Hence, BESS-based projects are becoming more common. In a large-scale BESS project, choosing a proper BESS installation location is usually the first step which implies careful considerations in different project stages. Depending on their goals, individual BESS projects may go through distinct stages, however, they have certain similarities. They usually start with constructing the BESS assembly and connecting it to the grid using transformers and power electronics devices. They then move towards the BESS operation and maintenance stage which often continues until battery cells reach their end-of-life.

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So far, numerous studies have investigated BESS placement in power systems. In these studies, factors like system losses, voltage stability, and power quality have mainly been considered, as recognized in a recent review survey [2]. This is true whether the installation is directed towards transmission system level, distribution system level, or microgrid level. In [3–6], BESS deployment in the distribution network was based on minimization of distribution system losses, and in [7–9], minimization of active and reactive power losses. Likewise, in [10], lower transmission system losses were targeted for BESS allocation, and in [11,12] loss reductions in microgrids were investigated for this purpose. Similar loss reduction approaches have also been used for the joint allocation of BESS and RES-based generators. In [13,14], the best available location was selected for a combination of BESS with wind-powered plants, and in [15,16], for BESS with solar-powered-plants. Along with loss minimizations, BESS placement literature to date has also targeted lowering of post-fault voltage recovery time [17], prevention of reverse power flow [18], reduction in environmental emissions [19], improvement in system frequency [20], and improvement in power quality [21]. A few studies have considered operational costs while investigating BESS placement. However, they have either achieved reduced costs by minimizing energy losses [22–24] or achieved energy savings by improving voltage stability [25].

The common aspect among these studies is that they have targeted the operational feasibility of the BESS at the installation location. However, they have ignored its business feasibility. Considering business feasibility is important as it investigates the likelihood of business success of the BESS project [26]. Improving power system performance, on the other hand, does not ensure a viable BESS business. This is because minimizing energy losses has no associated revenue. Similarly, improving the operational feasibility of the system is not a profitable BESS service in many markets [27,28]. Moreover, the studies mentioned above only consider the operation and maintenance stage of the BESS projects. This is problematic as a location that appears preferable for the BESS operation can still have certain implementation challenges. For example, a station might be proposed to be the best installation site for improving the voltage profile of the system as done [18,29,30]. However, if the land area available around the station is insufficient to house a large-scale BESS setup, such a proposition will cause delays in the installation and connection stage of the project. Similar problems of land access, safety permits, and connection permits often arise while making placement decisions for real projects. However, as most existing studies only consider simulation scenarios, these problems are often overlooked [31,32].

Nowadays, many governments are encouraging private sectors to take part in the BESS market. It has been recognized that a higher input from financiers can boost BESS integration in modern power systems [33]. The main concern of such entities is to ensure a viable business potential at the point of BESS allocation. This requires consideration of possible BESS applications, investigation of BESS connection procedures and associated installation charges, assessment of production levels of available RES, knowledge of consumption needs of connected consumers, inspection of safety requirements for BESS installation, and survey of land availability, land access, and associated permits. To date, no study has investigated these requirements or given a comprehensive yet holistic approach to solve the BESS placement problem from the business viewpoint.

This paper addresses the identified gaps in the literature in the following way. Firstly, placement decisions impacting the BESS projects over their lifetime are discussed in detail. This is achieved by considering the business feasibility of various stages of BESS projects. In these stages, factors affecting the profitability of BESS operation, the suitability of BESS connection, the possibility of BESS maintenance, and the practicality of BESS assembly are investigated. Secondly, the business potential of placing BESS in different voltage levels of the power network is investigated. This is achieved by considering BESS services and BESS connection charges at the high voltage (HV), medium voltage (MV), and low voltage (LV) grid levels. Because connection charges are a continuous expenditure over the lifetime of a BESS, investigating their costs at different voltage levels for varying connection types, is crucial from a business viewpoint. Thirdly, the proposed placement approach is implemented in a real power system. This is achieved by conducting a case study on Bornholm Island that represents a scaled version of the Danish power system. It has a high amount of installed RES and is thus an ideal representation of modern power systems. The investigation presented in this paper is vital for business investors, financiers, policymakers, as well as researchers to understand the business requirements of BESS projects while making placement decisions.

This paper has six sections. Section II presents an overview of the role of BESS in power systems. Section III includes a stage-level investigation of BESS projects using a business-oriented placement approach, while section IV includes their voltage-level investigation. Section V implements the proposed approach for deploying a BESS in the Bornholm power system. The paper ends with concluding remarks in section VI.

1. Role of BESS in power systems

BESS placement studies are of paramount importance as geographical flexibility is a feature unique to BESS, as opposed to the other ESSs. For example, conventional ESSs like pump hydro require special geological conditions, like mountains, water, etc. to be functional. Similarly, compressed air energy storage (CAES) requires large underground salt caverns for storing energy. BESS on the other hand can be deployed closer to where the added flexibility is needed and can provide services required at the point of installation. However, some constraints can limit BESS deployment at certain locations of a power network. To better understand the BESS placement problem from a business viewpoint, firstly, the role of BESS in power systems must be understood. Only then a reality check on the profitable deployment of BESS at proposed locations can be established. Therefore, in this section, BESS applications in power systems are comprehensively discussed.

1.1. Frequency regulation

To keep a balance between electricity supply and demand, power systems rely on frequency control services, which inject or remove power from the grid to restore balance. Traditionally, synchronous generators have provided this service. But nowadays, higher RES integration is causing greater intermittency in supply, thus making balancing tasks more challenging. Therefore, BESSs with their higher power response capabilities are providing promising solutions for quicker frequency regulation [34,35]. When a need for frequency regulation arises, BESSs are charged or discharged within milliseconds in response to an increase or decrease of grid frequency to keep it within pre-set limits.

1.2. Black start and capacity reserve

In an extreme situation of complete grid failure, BESS can provide system restart services such as black start. Traditionally diesel generators have been in use for this service as the restoration power needed to restart generation plants is quite high. But as the need for a black start is a rare event, the high capacity of diesel generators dedicated solely for a black start event remained largely unused [36,37]. On the other hand, high capacity BESSs when deployed in power systems can continue supplying other services when not being used for black start. They well suited to serve as capacity reserves as they can discharge during peak hours, displacing peak-generators and deferring investments in peaking plants [38].

1.3. Transmission and distribution congestion relief

Another important service that BESS can provide is transmission and
distribution (T&D) congestion relief. As the power demand fluctuates all year round, the peak demand can surpass the load-carrying capacity of the T&D network and result in network congestion. To cater to this problem, upgrades in these networks are essential. This is a costly solution, especially because those upgrades are needed only during periods of network congestion, which are rare. BESS address this issue by storing energy from RES and releasing it in a period of peak demand [38].

1.4. Renewable integration and flexible ramping

By incorporating BESS into the power system, more renewable integration can be made under existing network capacity as surplus power can be stored in BESS. This helps in preventing renewable energy curtailment. If intermittent generation from RES produces a large amount of energy at times when demand is low, it can be stored for later use. With higher RES integration, adjusting the output power to fulfill the requirements of time-varying loads becomes more significant, to keep a balance between supply and demand in power systems [39–40]. As BESSs have flexible ramping capabilities, they can provide quick adjustments in output power when needed. Also, BESSs can help in smoothening the output power of RES, for example, by solving the overvoltage issue via voltage regulation [41]. Power fluctuations can also be regulated, which reduces the uncertainty of supply, increases compliance with generation schedules, and allows RES to make better auctions in electricity markets.

1.5. Voltage regulation

Voltage regulation is another important service BESS can provide. On-load tap changer, step voltage regulators, and shunt capacitors are some of the many kinds of regulators in use in traditional distribution systems. However, with the larger penetration of RES, these types of regulators are not efficient enough to regulate the voltage in the fast-nonlinear dynamics. This is because the frequent switching operation reduces their regulating efficiency. This is where the fast-dynamic response characteristic of BESS comes into play and the voltage deviations of the grid can be alleviated by the charging and discharging of BESS. Hence, BESS equipped with advanced inverter can supply reactive power support to the grid [42–43].

1.6. Response time of BESS services

Frequency and voltage regulation require quick response time and have lower power requirements as compared to the black start and T&D congestion relief. Several types of BESS technologies such as lithium-ion (Li-ion), redox flow, sodium-sulphur (NAS) can fulfill requirements of majority of these services [44–45]. However, response time of ancillary services do not affect the site selection procedure. It remains unchanged at any chosen location. Moreover, strategic placement of BESS in power systems can help in targeting higher business value from these services.

2. Business-oriented BESS placement – stage-level investigation of BESS projects

BESS-based projects go through several stages during their lifetime. Even though the energy storing mechanism of different BESS technologies slightly differs from each other, there are some stages common in most BESS projects. In the first stage of BESS projects, the BESS assembly is constructed, battery cells and racks are manufactured, and their protection systems are set in place. In the second stage, the BESS assembly is connected to the electricity-grid through power electronics devices and transformers. Once the connection is complete, the operation and maintenance stage of the BESS projects begins and continues until the end of the project. During this stage, the BESS functions to provide grid-services and is periodically maintained to ensure smooth operation. In the final stage, the battery cells reach the end of their life and the BESS is disconnected from the grid. During this stage, some elements of BESS assembly are recycled while others are disposed of. In each stage of BESS projects several decisions are taken, which help in finalizing the BESS installation location. It is important to confirm the business feasibility of these decisions to ensure the overall success of the project. Therefore, this section addresses a stage-level investigation of BESS projects while considering the business-oriented BESS placement in power systems.

2.1. BESS assembly

Designing the BESS assembly is usually the first stage of BESS projects. The BESS assembly consists of battery cells, battery racks, battery housing, a cooling system, and power electronic inverters. It is important to investigate several potential installation sites during this stage to ensure an adequate land area is available for housing the proposed BESS set-up. This is important because various components in the BESS assembly have different temperature sensitivities and a risk-averse business can be promoted by deploying them in separate compartments with dedicated temperature control. Among these components, battery cells are the most temperature sensitive. Therefore, at the BESS site, sufficient space must be available to install battery cells and power electronic devices. It is also important that this space can accommodate well-functioning BESS housing equipment, which has proper racks for both battery cells and inverters. It is also important to consider the visual impacts of the housing equipment beforehand as BESSs are physically large and have a high footprint. This can be achieved by ensuring sufficient space is available to add plantation.

The footprint of different BESS technologies varies depending on their energy storage mechanism. For example, energy is stored in battery cells in lithium-ion BESSs, while it is stored in tanks in vanadium redox flow BESSs, thus accounting for their high footprint. For different BESS technologies, space requirements are presented in Fig. 1, based on the footprints of real projects discussed in [46]. The increased space requirements with the increase in energy capacity of different BESS technologies are also represented. Amongst the considered technologies, Li-ion-based BESSs have the lowest space requirement of 5 to 7.5 m$^2$/ MWh [47–49]. Vanadium redox flow BESS, on the other hand, have the highest footprint of approximately 88 m$^2$/MWh [50]. Fig. 1, also shows space requirements of other ESS technologies such as flywheels and compressed air energy storage (CAES). Their high values indicate that the BESS technologies, especially, lithium-ion BESSs are most space-efficient. The space requirements for different types of Li-ion BESSs vary slightly, depending on their energy densities. The energy density of different Li-ion BESS technologies is also presented in Fig. 1, based on information available in [44]. As BESSs with high energy densities can deliver the same amount of energy at a lower footprint than BESSs with lower energy densities, NMC assembly requires the lowest installation space.

Higher footprints also add to the construction costs of BESS projects. During the site selection process, these costs mainly amount to digging and cabling costs, which differ from country to country. The remaining costs related to an increased number of racks and containers, etc. are attributed to the BESS sizing process. In Fig. 2, the key features required to ensure business feasibility of the BESS assembly are represented in yellow color.

2.2. BESS connection

For a large-scale BESS to be fully functional, the battery assembly must be connected with the electricity grid. Power electronic converters and transformers make this connection possible, the schematic of which is illustrated in Fig. 2. Transformers enable the BESS connection at all grid levels by stepping up the output voltage to the same level as the grid voltage. It is therefore important to investigate the budget and time...
friendliness of transformer connection procedures while choosing a BESS location as these two parameters have a significant impact on the success of any project according to the authors in [51]. If a substation has a transformer connection capable of integrating the proposed BESS capacity already available, the need for a new and dedicated transformer can be avoided. Consequently, challenges related to acquiring...
transformer access and its associated network protection system can be prevented and the red tape in the project can be averted.

Another important aspect related to the grid connection of BESSs is connection charges. They include a monthly electricity tariff, a yearly connection fee, and a one-time-paid installation fee. A BESS may experience double charges for the former two types because it behaves both as a generator as well as a consumer when connected to the grid. Consequently, it is liable to availability charges as a producer and consumption charges as a consumer. Because these charges are a continuous expenditure over the lifetime of a BESS-based project, investigating their costs at different voltage levels for varying connection types is crucial from the business viewpoint. Along with that, investigating restrictions like land ownership and public access is also important to avoid time-related hindrances in the BESS projects [52,53].

For projects involving high BESS capacities, it is also important to consider the impact of the BESS connection on various network components. This can be achieved by investigating their reliability data, such as failures due to thermal effects, as well as their technical constraints like line rating limits, and current-carrying capabilities [54]. During such investigations in the BESS connection phase, considering dynamic thermal rating (DTR) of power lines, cables, and transformers, in addition to their static thermal ratings may be useful. This is because, the latter estimates line capacities based on conservative weather assumptions, which underutilizes their available potential, thus necessitating system operators to ensure system upgrades [55,56]. Consequently, causing BESS owners to experience delays in BESS connection procedures. Therefore, determining ratings of lines, cables, and transformers in real-time, may allow better utilization of their thermal capacities and enable quicker BESS connection at the desired location. In Fig. 2, the key features required to ensure business feasibility of the BESS connection are represented in orange color. The suitability of the BESS connection with the grid can be ensured by investigating transformer connection and thermal capacity, connection charges, and connection permits at the installation site.

2.3. BESS operation

Currently, manufacturing and maintenance costs associated with lithium-ion BESSs are high. Therefore, a BESS project can be a business success only if higher or comparable revenue is generated from BESS operation. Consequently, investigating potential grid services that a BESS can provide when deployed at a certain location, and the corresponding revenue streams that can be accrued from those services, hold significant importance in business set-ups. By targeting services with a high associated financial value, profitable trade decisions can be made and high investment returns can be ensured [57-60]. The business prospects of BESS services can be further enhanced by integrating RES with the installed BESS [61]. This is because, when business entities deploy stand-alone BESS units into the grid, their revenues originate from the sale of electricity while the BESS is discharging, and their costs arise from the purchase of electricity when it is charging. RES availability can reduce their grid dependence and boost profits by reducing charging costs [62].

While considering areas with RES installations, it is important to investigate the production capacity of renewable plants and the consumption profile of connected customers. This is because if the BESS is deployed in an area where the production or consumption level is substantially low, a gross underutilization of its capacity can occur, thereby reducing its business prospects. On the other hand, deploying it in an area with relatively high consumption levels would make its production insufficient to meet the demands. In other words, the generation and consumption profile of the chosen location must be comparable with the available BESS capacity.

Such considerations on the usability of BESSs at prospective installation sites are especially important as the capacity is usually fixed and highly dependent on available financial resources. Recommending variability in BESS capacity to deploy them at a predetermined location as done in [3,31,32] for simulated models is not a viable business approach for real cases. It either implies unplanned investments on the financier’s behalf or underuses their available funds. Depending on the available BESS capacity, a viable allocation site should therefore be targeted instead. In high-capacity BESS projects, a distributed installation may be considered as proposed in [54]. This implies allocating multiple BESSs of smaller capacities at different points in the network, instead of deploying the full available BESS capacity at one location, thereby increasing BESS power reachability. Such placement strategy can help in reducing the effects of high MW installation on network components available at a single location. It also allows pooling of BESSs capacities for storing excess generation from scattered RES installations. This ensures more RES integration thereby promoting higher business value. In Fig. 2, the key features required to ensure business feasibility of the BESS operation are represented in blue color.

2.4. BESS maintenance and BESS disposal

During the BESS maintenance stage, site access for construction and maintenance significantly affects the business of BESS-based projects. This is because added costs are incurred if the site is less accessible for replacement and repairs. Therefore, it is important to ensure that the chosen location has proper parking space for vehicles during the construction phase as well as for future maintenance activities. This space should also be enough to implement fire safety procedures, and house safety equipment, especially for lithium-ion-based BESS projects, as they have high fire risks. It is also important to consider the noise levels of the installation, construction, and maintenance activities. [52,53]. Similar noise-level and land accessibility investigation should also be conducted beforehand for BESS decommissioning stage. In Fig. 2, the key features required to ensure business feasibility of the BESS maintenance are represented in aqua color and those for BESS disposal are represented in green color.

3. Business-oriented BESS placement – voltage-level investigation of BESS projects

A BESS can be deployed at any voltage-level in power systems. However, each voltage-level has different requirements as regards connection charges, maintenance procedures, and grid services. In this section, we investigate the business potential of BESS installation at different voltage levels of power systems.

3.1. Grid services at different voltage levels

Primary frequency regulation (PFR) has so far been recognized as one of the greatest value applications that can be driven from BESSs, making it an attractive business prospect [63]. As the power supplied by a BESS influences the frequency in the same manner at all voltage levels, PFR can be targeted anywhere in the network. However, the MV and the LV levels being at a shorter distance from consumers serve as more reasonable points of connection [64]. They are also a practical connection site for energy management services like peak shaving and load leveling, and system restart services like black start and islanding.

All the grid services that can be targeted in the MV grid can also be targeted at the LV level; however, BESS allocation at the HV level has certain limitations [65]. In the HV grid, a BESS cannot be used for an islanded operation as island grids do not support HV structures [64]. Similarly, due to a lack of connected customers, using a BESS as an uninterruptable power supply (UPS) is also not applicable there. Usually, in the HV grid, a BESS is installed for transmission system upgrade relief [66]. But to accommodate large power flows, such an allocation is a viable business decision only for projects with a high BESS capacity [67]. Also, integrating renewables with the BESS at this voltage level requires a large BESS size to be able to compensate for the fluctuating
RES power [68,69]. Fig. 3 illustrates the grid services that can be targeted with BESS installation at different voltage levels. The circle below the MV and the LV grid stands for all services including frequency and voltage regulation, energy management, black start, and islanding. While the one below the HV level represents frequency and voltage regulation, and black start only. They are represented in green and yellow colors, respectively.

Considering service aggregation potential increases value streams available in BESS projects. It also makes up for the high investment costs of these projects and prevents the BESS from sitting idle when one particular service is not profitable or desirable [70]. During site selection process, by confirming applicability of numerous services at the installation location, viability of BESS service stacking can be ensured. Usually, BESSs deployed at lower voltage levels in the electricity network are capable of providing more services [27,70]. Moreover, investigating demand profiles of the areas where BESS installation is desired, also helps in investigating their BESS service stacking potential [70]. For example, for areas showing higher consumption patterns, energy arbitrage can be combined with upgrade deferral. Whereas, for areas with lower demand patterns, frequency regulation can be targeted for majority of the days while reserving upgrade deferral service for few unusual days that show high consumption values.

3.2. Connection charges at different voltage levels

Different connection charges are applicable for the BESS installed at different voltage levels in power systems. From Fig. 3, five types of connections are possible for the three voltage levels. A BESS installed at each of these connection points falls under a specific category and is charged according to the requirements of that category.

The BESS connected to the electricity grid directly at the HV level (60 or 50 kV) falls under the category of A high, whereas the one connected directly to the grid at the MV distribution level (10 kV), falls under the category of A low. A BESS can also be connected to a feeder of a transformer instead of being directly connected to the grid. In such cases, when it is at the high voltage side of the 10/0.4 kV transformer, its category is B high, while at the low voltage side, it is B low. Finally, a direct connection with the LV grid level of 0.4 kV puts it under category C. These connections are represented in Fig. 3.

As far as the one-time paid installation fee is concerned, it is charged according to the waterfall principle. According to this principle, for the BESS installations at a higher voltage level, the business entities contribute to the payment of the high voltage network only. On the other hand, for the BESS installations on the lower voltage grid, they contribute to the payment of systems at the higher voltage levels as well. This is because the higher voltage levels are a prerequisite for current to flow in the LV network. Therefore, if the BESS is connected to the LV grid at 0.4 kV, it falls under connection type C. For the electricity to reach the BESS during its charging process, it must first be transported through the HV grid, then transformed from the HV level to the MV level via transformer connection, and then later be transported to the MV grid main. It would then again pass through a transformer of 10/0.4 kV to reach the LV level, and finally, be transported to the connection point at the LV grid. This puts it under the costs associated with the operation and maintenance of the entire network from HV grid-level to LV grid-level. On the other hand, if the BESS falls under the connection type of B high, it does not have to pay for transformation costs from 10 kV to 0.4 kV. Thus, it experiences lower installation charges as it only pays for the costs of the overhead networks and transformer stations. The costs associated with the BESS when it is deployed under different connection types are also represented in Fig. 3.

In addition to the installation fee, the BESS is also liable to a monthly electricity tariff as well as a yearly connection fee, both as a consumer and a producer. These charges also vary according to the allocated category.

3.3. Maintenance procedures at different voltage levels

Usually, due to proximity with connected customers, stricter safety standards – such as fire safety – apply for the BESS installation at the LV grid-level. Also, factors like visual impact and noise, present greater challenges at the LV grid-level as compared to higher voltage levels. High noise levels or considerable visual impacts can cause delays in attaining land access and transformer connection permits, thereby causing delays in business timelines. Therefore, in BESS projects it is important to consider maintenance requirements beforehand and ensure the chosen area not only houses the BESS set-up but also allows its sufficient upkeep.

3.4. Business-oriented BESS placement framework

A framework to investigate the business potential of BESS
installation location considering different project stages and grid voltage levels is illustrated in Fig. 4. This framework allows quantification of the features discussed in section III and IV and assess their business value based on three-level criteria. For example, availability of sufficient land area compared to BESS footprint, along with timely access to land use permits, amounts to high business potential. It is thus assigned a value of ‘2.’ On the other hand, insufficient land area compared to BESS technology’s average footprint implies no business potential and is assigned a value of zero. Similarly, investigating the business potential of the installation site considering the BESS operation stage, grid services, integrable RES, and usable BESS capacity are quantified using the same criteria. In case both solar and wind resources are present at the installation site, higher revenues can be earned by storing and selling more energy, as compared to when one or no renewable resource is available. Hence the former case presents a high business potential, which is assigned a value of ‘2,’ while the latter is assigned a value of zero. Moreover, the features that are affected by grid voltage levels are also indicated. This includes available land area, affordable connection fee, accessible connection permits, applicable safety standards, usable BESS capacity, permissible noise levels, etc.

In Fig. 4, a flow chart for applying the proposed business-oriented approach to any BESS-based project is also illustrated. It starts with quantifying placement requirements in their assembly, connection, operation, and maintenance stage. Decisions in each stage are made based on the three-level criteria, which helps in investigating their business value. The business value of the chosen site is first identified individually for each stage. The values are then added to find the overall business potential. This process is repeated until the business potential of all locations under consideration has been calculated.

4. Business-oriented BESS placement – case study on Bornholm power system

In this section, we conduct a case study for BESS placement in different voltage levels of the Bornholm power system. To understand the network structure and generation profile of the island, we first

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### Fig. 4. Framework for Business-Oriented BESS Placement in Power Systems.

<table>
<thead>
<tr>
<th>Suitable BESS capacity</th>
<th>Available land area</th>
<th>Feasible BESS footprint</th>
<th>Affordability of connection fees</th>
<th>Accessible connection permits</th>
<th>Available transformer point</th>
<th>Possible grid services</th>
<th>Integrable renewable resources</th>
<th>Usable BESS capacity</th>
<th>Applicable safety standards</th>
<th>Accessible parking space</th>
<th>Permissible noise levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy density (large space requirement)</td>
<td>Insufficient land area compared to average footprint of technology</td>
<td>No space for separate compartments</td>
<td>High monthly tariffs</td>
<td>Inaccessible permits due to safety considerations, and effects on network components, etc.</td>
<td>No connection point available</td>
<td>No profitable grid service is possible</td>
<td>Either solar or wind plants</td>
<td>Disruptor demand and production</td>
<td>Open area</td>
<td>None</td>
<td>Low</td>
</tr>
<tr>
<td>Medium energy density (medium space requirement)</td>
<td>Enough land area compared to average footprint of technology, slow land access process</td>
<td>Enough space for separate compartments, no space to reduce visual impact of BESS assembly</td>
<td>One or two out of three are high</td>
<td>Accessible permits, with delays due to required system upgrades and land ownership issues</td>
<td>Connection point is available with control circuitry installed</td>
<td>One profitable grid service is possible</td>
<td>Both solar and wind plants</td>
<td>Similar demand and production (both low)</td>
<td>Less congested public area (occasional traffic, no public buildings)</td>
<td>Low</td>
<td>Medium (public buildings are at reasonable distance)</td>
</tr>
<tr>
<td>High energy density (small space requirement)</td>
<td>Sufficient land area compared to average footprint of technology, quick land access process</td>
<td>Sufficient space for separate compartments, sufficient space to reduce visual impacts of BESS assembly</td>
<td>Low monthly tariffs</td>
<td>Accessible permits with no system upgrades or and land ownership issues</td>
<td>Connection point is available with control circuitry installed</td>
<td>More than one profitable grid service and service stacking is possible</td>
<td>Both solar and wind plants</td>
<td>Similar demand and production (both high)</td>
<td>Open area (high traffic, public buildings, etc.)</td>
<td>High</td>
<td>High (no public buildings at considerable distance)</td>
</tr>
</tbody>
</table>

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This table and diagram illustrate the framework for business-oriented BESS placement in power systems, with a focus on the Bornholm case study, highlighting the criteria and decision-making processes involved in assessing the business potential of potential BESS installation sites.
present a brief overview of the Bornholm power system.

4.1. Bornholm power system – an overview

The meshed 60-kV network of the Bornholm power system consists of sixteen 60/10 kV substations [71]. These substations are represented in Fig. 5. The 60 kV grid is also represented in Fig. 5, by orange lines. It forms the HV transmission system, while the 10 kV grid forms its MV distribution system. Small-scale prosumers and private or commercial customers are connected to its 0.4 kV LV grid.

A combination of wind, solar, biomass, and biogas forms the energy supply resource at Bornholm Island when its power system is operating under normal conditions. Thus, the production is completely based on RES. In the circles outside the Bornholm map, in Fig. 5, the total generation capacity for the whole island is illustrated. The island has a total of 1038 solar panels and 88 wind turbines, out of which the location of large-scale producers is shown on the map. The map represents large-scale PV panels installed at two locations, and large-scale wind farms at five locations. The smaller circles on the map represent the kW capacity of installed wind plants at various locations.

Seventy percent of Bornholm’s renewable energy is produced by the island itself, while the rest is imported from Sweden through a sea cable of 60 MW capacity, which is connected to Hasle substation at Bornholm. Fig. 5, represents it by a blue circle. Borrby substation in the southern part of Sweden has two 132/60 kV transformers owned by the power company named E-ON. One of these transformers supplies the connection to the Hasle substation. Disconnecting the sea cable puts Bornholm in the islanded mode-of-operation during which it relies on its diesel generators to maintain a stable operation [72]. The diesel generators can produce up to 34 MW of electrical power. The consumption capacity of the island is also illustrated in Fig. 5. The highest peak in the year 2019 was recorded to be 55 MW for a total of 29,000 customers.

The case study on the Bornholm power system is conducted under the BOSS project. BOSS stands for Bornholm Smartgrid Secured – by grid-connected battery systems. It aims at installing the largest grid-connected, utility-scale, and lithium-ion-based BESS in Denmark [73]. The BESS has a capacity of 1 MW/1MWh. To ensure a business-oriented BESS placement, we investigate different stages of the BOSS project and look into business feasibility requirements discussed in section III. In our study, we consider the MV and the LV grid of the Bornholm power system. We do not consider its HV grid as the BESS size is small to have a viable business potential at this voltage level.

4.2. Bornholm power system – Profitable BESS operation

Grid services like frequency regulation, energy management, and black start can be targeted at both MV and LV grid levels. To supply these services, and to minimize electricity consumption costs, the BESS should ideally be charged from the RES available at the point of its installation. Therefore, an investigation on the available solar and wind-powered plants at distinct locations in these voltage levels is conducted in this section.

4.2.1. The profitability of BESS operation in the MV grid

At the MV grid-level, all the sixteen substations in the Bornholm power system have installed RES generation. Out of these sixteen substations, the ones with only residential RES installations present lower renewable integration potential and are not preferable from a business perspective. On the other hand, six substations with large-scale RES installations present a potential site for BESS installation. These substations namely: Bodilsker, Nexø, Olsker, Hasle, Snorrebakken, and Åkirkeby, along with their wind and solar potential are represented in Fig. 6.

It can be seen from Fig. 6, that all these six substations have some number of residential PVs connected. While Bodilsker and Åkirkeby are the only two that have a solar plant. The generation capacity of which is 7.5 MW. At Bodilsker, the installation of this solar plant introduced an increased short circuit level. So, recently, the wind turbine generators (WTGs) connected to Bodilsker substation were connected to Nexø substation. Nexø now has three WTGs and the second-largest capacity of Fig. 5. Bornholm power system.
residential PVs in Bornholm [72]. If the BESS is connected to the Bodilsker sub-station, only wind integration would be possible, which is less preferable as a variety in RES mix can ensure more reliable business.

Unlike Bodilsker, no large-scale PV plants are connected to Olsker or Snorrebakken substations. They only have residential PV installations. Even though they both have around 2 MW of installed WTG capacity, but the WTGs connected at Olsker are more scattered than the WTGs at other sub-stations. The less scattered and so more preferred wind plant installations are connected to the Hasle substation, which is also the largest in the Bornholm power system. Hasle does not have any large-scale PV plants; it does however have a substantial number of residential PVs. Åkirkeby substation also has many WTGs, and a high number of residential PVs, along with a 7.5 MW solar plant. It is also the only sub-station amongst the six, that has a biogas plant. Additionally, even though many wind farms are present at Bornholm, only three of them can be regulated. Out of these three, the wind farms of Kalby are connected to the Åkirkeby sub-station. The other two regulatable wind farms of Vysteby and Tornbygård are connected to the Hasle.

Therefore, Åkirkeby substation, being the only one with both large-scale PV plant as well as WTG generators along with a possibility to regulate its wind generation, representing a potential business site for RES integration. Hasle is another potential choice in this regard.

4.2.2. The profitability of BESS operation in the LV grid

In the LV grid of the Bornholm power system, several locations have an adequate RES integration prospect. We shortlisted six locations based on their available RES capacity and access permits. They are recognized by their transformer station numbers and are listed in the table in Fig. 6. along with their total generation and consumption capacity.

As clear from Fig. 6, station number 650 provides a high wind integration potential of 25 kW. However, as the consumption is less in its locality, BESS connection in this area would have a few connected customers, thus limiting its usability and so, its business potential. On the other hand, stations number 132, 296, and 690 have lower production profiles. Finally, station number 667 has one of the highest RES penetration levels. It has around 50–70 kW of domestic PV panels installed. Unlike station 650, it also has a high consumption profile of 86 kW. Thus, station 667 is a potential location for the BESS connection at the LV level.

Finally, even though high-RES capacity sites are present in the LV grid of the Bornholm system, their connected consumption, as well as their installed generation, is low as compared to the RES at the MV grid. The wind generation capacity at the MV grid is in the range of 2 MW – 12.5 MW at five of its substations, and the PV generation is 7.5 MW at two of its substations, while it is in a kilowatt range in the LV grid. Thus, the 1 MW of BESS capacity has a higher potential to be fully used at the MV grid, thereby promoting a higher business value.

4.3. Bornholm power system – Suitable BESS connection

An investigation on transformer connection, connection charges as well as connection permits for BESS installation at MV and LV grids in Bornholm is conducted in this section.

4.3.1. The suitability of BESS connection in the MV grid

In the Åkirkeby substation, two 60/10 kV transformers are present. One of them is of 10MVA while the other is 16MVA and has a connection point available to accommodate 1 MW BESS. In Fig. 7, the schematic of this available connection point, along with the already connected RES is represented on the left while on the right, the required electrical and communication network is illustrated. The electrical network includes a transformer, inverter, and circuit breakers while the communication network includes internet connections, dissemination shed connections, and billing meters. A preexisting transformer connection and control circuitry makes Åkirkeby a useful business site as prompt transformer access can be ensured. Moreover, the power rating of the transformer being 16MVA, is quite high as compared to the BOSS-BESS capacity of 1 MW. Thus, BESS connection at this location would not have any significant impact on the thermal rating of the transformer.

4.3.2. The suitability of BESS connection in the LV grid

As clear from the enlisted transformer station numbers, all the six prospective locations at the LV grid level have a transformer connection available. The BESS connection at the MV grid level of the Bornholm power system, with a substation like Åkirkeby, would give it the connection type of B high, while its placement in the LV grid, for example, station 667, would give it the connection type of C. From Fig. 8, the installation fee, yearly connection fee, as well as monthly...
electricity tariffs, are lower if the connection type B high, thus making it a more affordable option than connection type C in this regard. Additionally, access to connection permits is tedious for BESS integration at the LV grid of Bornholm because of a higher number of residential customers in the vicinity and associated safety risks.

4.4. Bornholm power system – Possible BESS maintenance

An investigation of the land area available for BESS installation and its maintenance at MV and LV grids in Bornholm is conducted in this section.

4.4.1. The possibility of BESS maintenance in the MV grid

If the BESS is connected to the Åkirkeby substation, its physical assembly would be in the Kalbyvejen. At Kalbyvejen, there is adequate area present to accommodate a BESS of 1 MW capacity, along with its inverter and site control assembly. It also has sufficient housing ability for the transformer and protection system. It can also house a dissemination site and a control and communication network. Such a network is crucial from the business perspective as it makes the BESS charging and discharging data readily available. Such data is useful for designing profitable trade strategies. In Fig. 9, this area is presented on the left. Even though sufficient area is also present in the Hasle substation, the

Fig. 7. Bird’s eye view of BESS installation at the Åkirkeby substation.

Fig. 8. Connection charges for BESS installation at different voltage-levels.
environmental impacts of placing the BESS near a sea cable are effective there.

4.4.2. The possibility of BESS maintenance in the LV grid
Station 667 is situated in an area that is owned by a municipality. Hence it is quite accessible for repair and maintenance purposes. Its surrounding land area is represented in Fig. 9, in the photograph on the right. The installed PV panels along with surrounding housing are visible in Fig. 8. The relative difference of vehicular access between the two grid levels is clear from Fig. 9. The installation area for the BESS connected to the Åkirkeby substation is an open space, while that of station 667 is a parking space. Consequently, demanding a higher business investment for added safety measures is needed in the LV grid, which would affect the project timeline.

4.5. Bornholm power system – Business framework application
A comparative summary on the business potential of BESS placement locations discussed in this section for the MV and LV grid of the Bornholm power system is illustrated in Fig. 10. Different features are quantified for all project stages, based on the criteria presented in Fig. 4. Since 16 features are considered for each location, and each feature can be assigned a value no greater than 2, the highest possible score for any location is 24. Åkirkeby shows a high business potential concerning all the key features, except for accessible connection permits, where a medium business potential has been found. This is due to the delays in land ownership. Thus, Åkirkeby presents a potential BESS installation location by achieving a score of 23 out of 24. Hasle, on the other hand, shows a medium business potential for renewable integration and transformer access and scores 20. BESS-installation areas in the LV network present medium business potential vis-à-vis renewable integration, land area availability, etc. BESS capacity utilization in LV network show a low business potential mainly because only low capacity BESS can be installed here owing to the low transformer limits. Considering distributed installation strategy for the 1 MW BESS by deploying its larger capacity in the MV grid, and smaller capacity in the LV grid may resolve BESS capacity utilization issue. It may also enhance BESS power reachability and renewable integrability. However, for such
divided installation, BESS connection charges at both MV and LV levels would be applicable. Also, as at LV level, application of safety standards and BESS maintenance procedures is challenging for both station 667 and 660. Station 667 shows low business potential while station 660 shows no business potential for all features of BESS maintenance stage. This is mainly because there are many public buildings around these areas, hence causing delays in obtaining land access and BESS connection permits.

5. Conclusion

This paper identifies limitations in current BESS placement approaches and investigates how a business-oriented approach can be applied in different stages and voltage levels of BESS projects to overcome these limitations. It proposes a placement criterion for large-scale BESSs in power systems. We concluded that a business-oriented investigation for BESS placement in power systems with high renewable shares helps in making informed, profitable, and timely decisions. To do that we investigated business requirements of placement decisions taken in distinct stages of BESS projects. We determined that placement decisions in each stage contribute to the final BESS installation site, thus signifying the importance of the stage-level investigation. We proposed several important placement decisions that must be taken to ensure a successful BESS business. This included investigating the feasibility of BESS assembly by ensuring proper BESS housing and viability of BESS connection by ensuring affordable connection charges. Furthermore, we demonstrated the variability of connection charges in power systems by conducting a voltage-level BESS placement investigation. Our study showed higher connection charges apply when BESS is installed at lower voltage levels because costs associated with electric transport through higher voltage-levels also become applicable. It also showed lower voltage-levels to have higher electricity tariffs associated with them. Moreover, we established that the installation of BESS in MV grid-level has fewer limitations with regards to land access and associated permissions from authorities as such locations have more land areas available to ensure fulfillment of safety standards.

We implemented our proposed business-oriented placement approach to investigate BESS placement in the Bornholm power system. We considered distinct locations in MV and LV grid-levels of the Bornholm network to install a 1 MW/1MWh BESS. We proved that the BESS can be installed at both MV and LV grid levels for multiple applications, and to integrate a high share of renewables. We found that all the services that can be targeted in the MV grid-level can also be targeted in the LV grid-level of the Bornholm power system; therefore, a divided installation in both MV grid-levels can be considered, and the higher capacity of BESS should be installed at the MV grid. We concluded that conducting a business-oriented placement survey in all project stages is crucial for the overall success of BESS-based projects.

Declaration of Competing Interest

The author declare that there is no conflict of interest.

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Credit Author Statement

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