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Framework for dimensioning battery energy storage systems with applied multi-tasking strategies in microgrids

Troels S. Nielsen, Jens S. P. Thomsen, Athila Q. Santos* and Jutte Kaad

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*Correspondence:
aqs@mmmi.sdu.dk

Center for Energy Informatics, University of Southen Denmark, Odense, Denmark

Abstract

The shifting from the traditional centralized electric sector to a distributed and renewable system presents some challenges. Battery energy storage technologies have proven effective in relieving some aspects of this transition by facilitating load control and providing flexibility to non-dispatchable renewable production. Therefore, this paper investigates how to dimension battery energy storage systems with applied multi-tasking strategies in microgrids. To this end, it proposes a framework to accurately depict how BESS can be financially and technically feasible by deploying multi-tasking strategies that fit the system characteristics of a microgrid while providing arguments for the financial incentive. The framework development is based on the principles of the analytical approach and is conceptualized in a three-part funnel structure. This framework has been tested using the case study of Aeroe microgrid and resulted in a proposed battery energy storage configuration. Based on the findings, the BESS implementation contributes to improve load behavior and to increase internal production utilization. A sensitivity analysis was performed, to investigate the robustness of the configurations. Collectively, the framework has proven to provide feasible results within a wide range of parameters. This framework could help the preliminary investigation phase when analyzing future battery energy storage system investments.

Keywords: Battery energy storage, Multi-tasking strategies, Funnel framework, Economis

Introduction

The electrical power system is experiencing a period of rapid evolution worldwide. More specifically, the Danish energy sector has seen a yearly increase in renewable capacity of around 5.7% in the period of 2010–2019 (IRENA 2020) and reached saturation levels of 60.5% in 2018 (Danish Energy Agency 2019). The Danish national energy and climate plans (NECPS) now strives to obtain a 100% fossil-free energy sector by 2050, which will ensure a further increase in the saturation of RES (European

Commission 2020). The task at hand, paired with the overall complexity of the NECPS inferred transition, will pose both economic and technical challenges. Therefore, the importance of finding pathways for balancing the intermittent and stochastic nature of RES while ensuring the security of supply is very high.

The current transitioning phase is slowly decommissioning conventional and controllable units and shifting towards a more decentralized energy sector, reliant on distributed energy resources (DER). This phase imposes the need for integration of technologies capable of performing tasks that can restore some of the controllable aspects of the conventional power system (IEA (International Energy Agency) 2018; Munuera and Pavarini 2020). The mechanisms used to ensure the balance of the power grid and the ability to handle the increased implementation of DERs include ideas such as demand management and distributed storage. The energy storage technologies (EST), are also identified as a balancing mechanism due to their ability to provide multiple grid-related services, e.g. acting as capacity reserves, frequency response, and congestion relief (Taylor et al. 2012). One of the ways to look at ESTs is to investigate the added benefits of integrating them into a system that can utilize the technology to an optimal extent. Energy storage is an interesting proposal to relieve some of the pressure of future power grids towards decarbonization of the energy system, allowing integration between the RES and the power grid's new 'Smart' configuration. The energy storage deployment, in 2018, reached nearly double of 2017 investment (Munuera and Pavarini 2020). Furthermore, the World Energy Council has projected that as much as 150 GWh of energy storage could be installed by as early as 2030, with large quantities of it being covered by battery energy storage systems (BESS) (Gardner et al. 2016; Renewable Energy Agency 2017). This has been driven by declining investment costs, technology improvements, and supportive governments. However, this wide scale implementation of EST calls for the investigation on how to maximize the usage of these systems.

Especially the BES technologies have proven viable options for enabling this transition due to them being able to operate as a controllable load and a dynamic generator. This controllability gives the energy storage system the capability to offer a variety of different grid benefits, depending on their configuration and relation to the grid. The consensus has, throughout recent years, been that energy storage technologies are lacking financial viability. However, the levelized cost of storage (LCOS) of many EST is decreasing over the years. The EST is also gaining momentum due to the prospects seen in a multitasking configuration. The multi-task concept relates to the use of ESTs that can handle different requests of several grid aggregators, thereby diversifying the financial prospects and furthering profitability (Tian et al. 2018; Truong et al. 2018).

Another mechanism that can help to provide reliability, stability, and security while grouping localized clusters of DERs are the microgrids (MG). The use of MGs is considered a viable option for enabling the excessive integration of DERs and can facilitate a cost-effective and reliable grid infrastructure (Mehigan et al. 2018; Allan et al. 2015; Alsaidan et al. 2018). Linking different energy integration technologies, such as energy storage, MGs and demand-side management will become valued assets of the future distributed energy system, due to their inherent ability to increase grid flexibility and resilience.

The underlying question that this paper aims at answering is: How to dimension BESS with applied multi-tasking strategies in microgrids? Because the answer is not unique, the first contribution of the paper is to provide a framework to accurately depict how BESS can be financially and technically feasible by deploying multi-tasking strategies. Herein, investigating whether the framework can collectively obtain a BESS configuration that fits the system characteristics of a microgrid (MG) while providing arguments for the financial viability. The developed framework uses a real operational environment to test the solution viability. Thus, it provides solutions that reflect critical parameters that infer the recommendation of the type, size, and capabilities of the BESS, best suited for the MG. A second contribution of the paper is to examine ways for optimizing the utilization, performance, and integration possibilities of BESS by applying a revenue stacking concept and comparing operational differences and their impact on system performance through sensitivity analysis.

With the Danish energy sector moving towards an entirely new energy production format and showing the willingness to invest in needed energy infrastructure, the future of the sector looks bright but somewhat challenging to manage. This paper analyzes some of the transition related aspects and try to provide a perspective on how to achieve this in a sufficient and financially viable way. Hereto investigate the overall viability of BESS in the context of MG, integrating DERs in the Danish energy scheme.

Methodology

The methodological framework used to identify BESS performance indicators and characteristics. This entails a transparent approach that encapsulates the essence of determining the optimal stacking of revenues for BESS technologies, and how these systems behave as DERs in a MG context. The methodology investigates the overall viability of BESS within the boundaries, set by environment constraints, technical and financial indicators, and the energy market of which the system operates. Furthermore, the qualitative benefits that a BESS delivers, when implemented into an existing energy portfolio, is investigated.

The overall structure of the framework is based on a funneling template which focuses on forcing information towards the bottom of the funnel, effectively creating a focal point, condensing data, and perfecting the proposed solution. The framework structure has been divided into three dependent stages: data acquisition, system analysis and optimization, as illustrated in Fig. 1. The overall goal with this framework structure is to develop a series of steps that ensures the right sequence of actions, that enable the user to quantify and conceptualize BESS related properties and behavior. Each stage reflects a process and is designed to reduce uncertainties by gathering adequate information (Cooper 1990, 2008).

Data acquisition

The data acquisition is used to establish the system foundation. It includes the definition of external and internal boundaries, empirical data, simulation data, relevant constraints, and simulation objective functions. The data acquisition describes the methods of data collection and selection, relevant to the case, while it also entails the prerequisites of the project. Furthermore, the data acquisition describes the

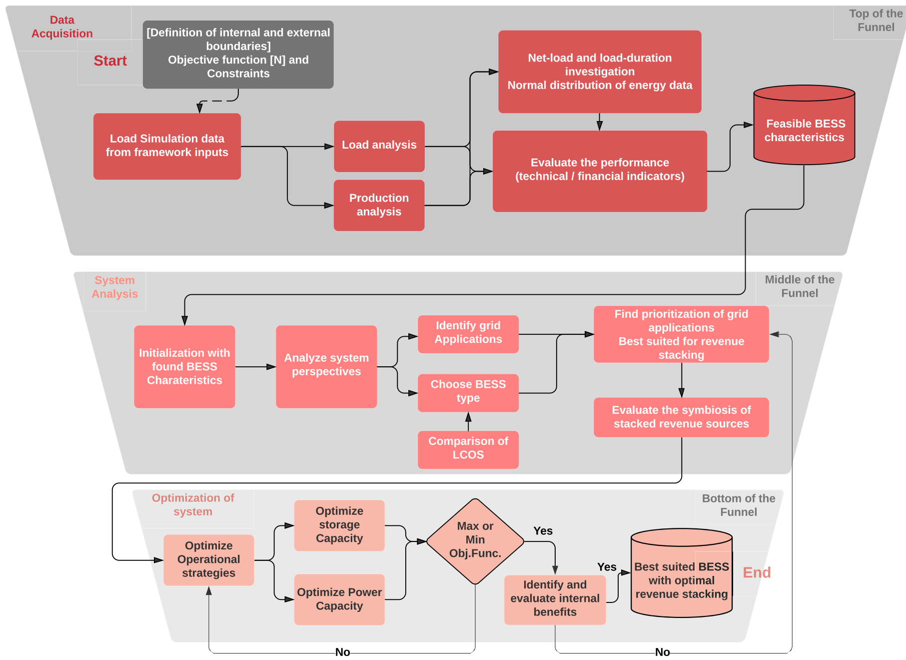


Fig. 1 Illustration of the funnel framework

sub-optimal BESS characteristics that can be used as a transitional input for the next stages in the funnel framework.

Definition of external and internal boundaries

This step defines the behavior of the BESS and sets the stage for the upcoming optimization. The internal boundaries are defined by the production, consumption, performance indicators, and local grid connections. The external boundaries are defined by the climate profiles, transmission and distribution connection, geographical location and power system integration. The collection of relevant data can be found through publicly available data hub, production prediction simulation software or onsite quantitative measurements. This section also entails the identification of relevant stakeholders and the aspects of the MG operators. This will often amass to the formation of system goal or objectives.

Objective functions and constraints

The data acquisition section also entails the identification of project relevant constraints and the goal of the project listed as objective functions. The objective function demonstrates the direction of the project and tells the developer on where to focus the attention. It reflects the desired end-goal and what problem needs solving. Consequently, this comes down to the individual stakeholders, relevant for project decision making, and how they want to manage resources. The constraints are used to define the operating parameters that are dependent on the environment of the system.

Analysis of load and production

The preliminary analysis of the system revolves around investigating the load and production characteristics of the existing investigated system. This investigation encompasses energy data visualization tools such as net load curve (NLC), load duration curve (LDC), and normal distributions of energy data. By arranging energy data, in ways that reflect the system behaviors, the visualizations can help quantify feasible BESS characteristics. The design and sizing of a system based on tools are commonly used as a rule of thumb, because it gives a quick overview of the existing system behavior. However, this approach is often subject to several limitations such as lack of load information, prediction, and assumption of ideal operation.

System analysis

The analysis and evaluation enlist investigation points such as system perspectives, identification of grid application, the selection of suitable BES technologies and the overall prioritization of stacked revenue streams. Thereby, further narrowing the funnel of the framework towards an optimal system configuration.

Analyse system perspectives

The foundation of this stage is the empirical data, gathered in the data acquisition section, yielding a disordered information assortment. This assortment of relevant data can then be analyzed to which the system perspectives can be identified, such as business economics and environmental assessments. In the life cycle assessments, the idea of adequately defining the scope of the system is highly important, and comparatively consists of investigating the ecosphere (not intentionally 'man-made') and technosphere (everything that is intentionally 'man-made') (Hofstetter 2000; Hauschild et al. 2017). The idea of analyzing a system on the basis of eco- and technospheres helps to create awareness and categorize the BESS characteristics. By categorizing the data, the work on modeling the system gets noticeable faster, and the data gets more manageable.

Identify grid applications

The clustering of grid applications is based on the labeling of applications into predefined categories. By dividing the application into categories, and by considering the BESS constraints, it narrows the number of grid applications down to only the ones that fit the BESS. Example of this could be looking at the ecosphere of the BESS and identify where in the power system the BESS is integrated, thus excluding all other applications. The identification of ancillary services consequently follows a natural selection process, in that only the service that function with the domain can be considered. This is further amplified by the technical constraints and other performance indicators.

Selection of BES technology

The knowledge of technical and financial indicators proves valuable. The definition of BES technology consists of a range of performance indicators, which can be appropriate when determining the optimal characteristics of a BESS. A strategy that can be applied when determining BES technologies is the use of comparative analysis. The goal is to compare technology characteristics and cross-reference these against each other. A common unit of individual characteristics is often used to make the technologies comparable. This comparison can happen for one or several parameters of the BES technology, and often lead to tangible evidence of which technology performs the best. The comparison can effectively be based on LCOS.

Prioritization of grid applications and revenue stacking

This step increases the value of the BESS, done by choosing the applications with multi-task strategies. This can be done by focusing on increasing the utilization of the storage system. If a battery is only used for one application, say load following, there is a large untouched potential. When investing in a capital heavy BESS, it is ideal to utilize most of its operational potential. This can be done by finding the best multi-task configuration for the investigated system. Multi-tasking makes it possible to obtain the best financial feasibility of the setup since this allows stacking revenues. Revenue stacking is one of the strategies that can make storage technologies a viable business case. This is based on adding additional utilization of the battery when it is not doing load following or peak shaving.

In order to determine these extra revenues, it is needed to find the BESS type and the best suitable tasks for the chosen BESS. The tasks also depend on the size, location and type of MG, so by analyzing the constraints that the MG is subject to, the different tasks can be ascertained. The potential tasks can then be reduced to those that add the most value while being stackable or operable in symbiosis. Meaning that the additional tasks must be able to operate alongside each other, while still providing resilience to the system without significant interference. It is often chosen to give a specific application the highest priority for the operation, this can be done on the basis of the objective function, stakeholder or constraints present in the ecosphere.

Optimization

The focus of the optimization is to find the best suited BESS technologies performing optimal multi-tasking. It consists of three main areas of optimization: operational strategies, storage capacity and power capacity of BESS. With the control mechanism being an objective function, which is maximized or minimized, subject to system constraints. The last step of the framework is to identify and evaluate the internal benefits of the MG, in order to include the non-tangible benefits and system perspectives in the decision process.

Case study of Aeroe microgrid

The proposed framework was tested by investigating the island Aeroe located in the southern part of Denmark and has an area of 88 km^2 and a population of around 6000 habitants (Kommnue 2020). The island is characterized as a grid-connected community MG, powered by its electricity production and connections to the main grid (Santos et al. 2020; Danish Energy Agency 2015). The MG strives to become 100% fossil-free and solely reliant on RES by the year 2030 (Ærø Kommune 2018). The goal covers all areas of the MG, including industry, heating, transport and electricity. The reasoning is seen in their visionary plan and the facilitation of a more flexible and energy-efficient energy sector. Hereby, stating the clear objective of finding a BESS size and type that can assist Aeroe in reaching their vision.

Framework inputs

Three meteorological datasets were collected and used to simulate the wind and solar production patterns of Aeroe. For the solar data, Heliostat SARAH 54.85N 10.40Ø 2019 dataset is used and contains both the direct and indirect solar radiation of Aeroe (EMD International 2022). The CFSR 54.80N 10.31Ø 2019 dataset provides the wind and temperature data used to simulate the production of the MG.

The costs of operating the MG are based primarily on the technology catalogues made by the Danish Energy Agency (Energistyrelsen 2022). In a Danish setting, there are several tariffs related to the energy trade seen both on the production and consumption side. On the consumption side, there are three tariffs: transmission, system and balance. On the production side, there are two minor tariffs: the injection tariff and the production-based balance tariff. All these tariffs are included in the simulation of the MG and take hold in 2020 tariff price levels (Energinet 2020).

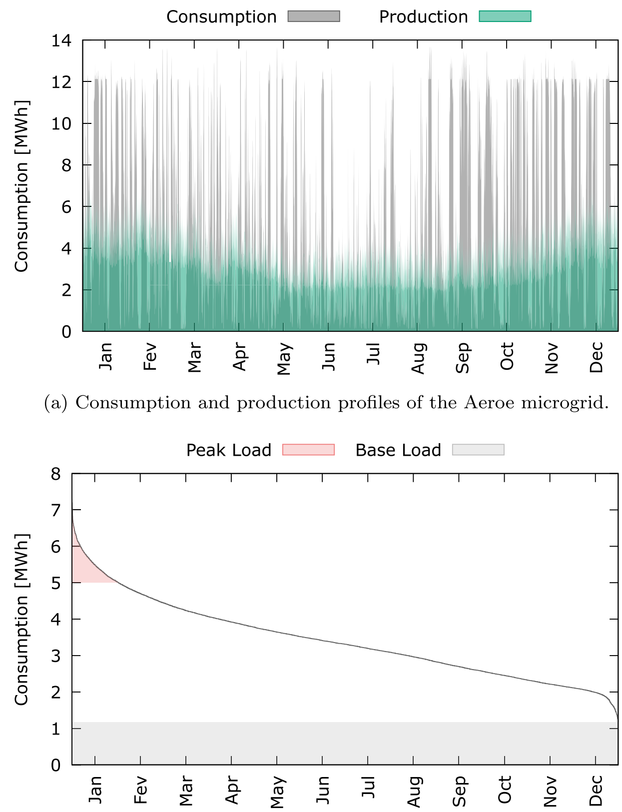
Current energy portfolio of Aeroe

The energy portfolio of Aeroe is composed by wind, solar and a small amount of heat-linked electricity generation. The wind power production comes from six 2 MW wind turbines (V80 Vestas). The power curve from these turbines is used along with the CFSR wind dataset in the simulation. The electricity production seen from the wind turbines is simulated using the software tool windPRO, which results in a yearly power production of approximately 43 GWh (same as the current energy accounts of Aeroe (Energistyrelsen 2018)). The installed photovoltaic (PV) capacity is based on generic residential installed panels with a capacity of around 1.7 MW. The MG also has a small amount of heat-bound electricity production from the district heating sector, which is also accounted. These are based on the 2017 energy accounts of Aeroe.

The island is connected with two 60 kV lines to the main electricity grid with a capacity of 21.3 and 23.4 MW. These will serve as boundaries for determining the BESS capacities. The load of the system in 2019 is around 30 GWh per year. This load includes the addition of the recently installed E-ferry (Huang et al. 2020).

With the high saturation of RES, Aeroe has a very intermittent production. Even though the MG has a larger production than consumption, Aeroe is not able to cover its demand with internal production as shown in Fig. 2a. This makes the island very dependent on the connections to the main electricity grid. With a maximum net load of around 12 MW and a connection capacity larger than 20 MW, no bottlenecks are limiting the system.

Figure 2b, displays the LDC of Aeroe, and here three load attributes can be drawn. The peak load of the system is represented by the upper grid pattern of Fig. 2b and reflects the highest load experienced by the system, here the interval for this was found to be from 5 to 7.3 MW. The intermediate load of the system is illustrated by the white section



(a) Consumption and production profiles of the Aeroe microgrid.

(b) Load duration curve of the Aeroe microgrid.

Fig. 2 Energy portfolio of Aeroe

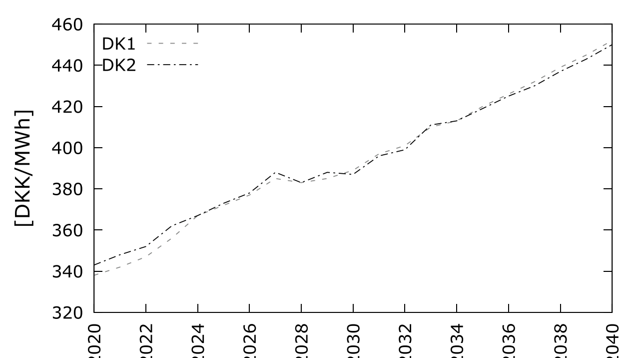


Fig. 3 Average electricity price projections

between peak and base load and relates to the most significant portion of the system load. The base load of the Aeroe MG is identified to be around 1.2 MW.

Future prices

The data gathered is in the form of hourly electricity prices from the Nordpool spot price market of 2019 (Energinet 2020). All electricity spot prices have been extrapolated using Energinet price projections for 2020–2040. Energinet estimates that during the 20 years, the average electricity price will increase from approximately 350 DKK/MWh to 450 DKK/MWh, which can be seen in Fig. 3 (Danish Energy Agency 2020).

Sup-optimal BESS characteristics

The task is to choose initial capacities for the BES technology that satisfy constraints and identified objectives. By following the framework, the Gaussian distribution is applied to both the net load and the accumulated deficits. The distribution of the net load finds the power of the system while the distribution of the accumulated deficits gives a representation of the system storage capacity. Together providing a representation of the system and is used to determine the initial size of the BESS.

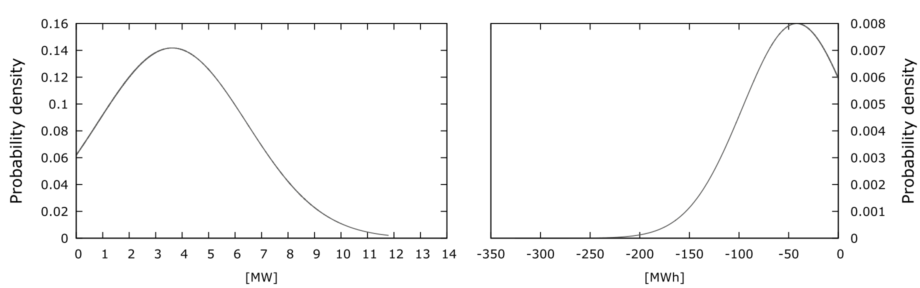
The two distributions, seen in Fig. 4, show a relatively high spread of potential usage for both of the investigated characteristics, especially the accumulated deficits, i.e. the valleys of the system. Even though the distribution of the net load seems to have a minor spread, one standard deviation is almost double the size of the mean value. Therefore, it is chosen to use the mean for both the power and storage capacity. These will be used to initialize the revenue stacking calculation and the initial optimization point. The initial capacities are found to be 3.6 MW and 42 MWh.

Analysis and evaluation of BESS

In order to identify the grid services that the system can utilize for revenue stacking, one needs to evaluate the boundaries of the investigated system. Since the MG of this case study is situated in a distribution setting, it is limited to services that can be performed within this scope. Another boundary is that it is situated within the Danish electricity market. This means that it can only perform services that the TSO aggregates or utilize the incentives present in this ecosphere. With the system perspectives of Aeroe, the first and foremost application area of the BESS is load-following, reflected by the following priority: $Microgrid > BESS > Grid_{services}$.

Identify grid applications

Within the considered ecosphere, two groups of grid services can be identified: frequency and voltage control (Energinet 2019). The initial size of the BESS allows the system to perform within different groups of grid services. These grid services can be used as additional revenue streams and are described in Table 1.



(a) Net load. (b) Accumulated Deficits.

Fig. 4 Probability density of Aero microgrid

Table 1 Chosen grid applications

Application	Description
Arbitrage	Energy time-shift: storage can take advantage of the electricity Price difference between on-peak and off-peak hour
Load following	Energy storage can serve as load following capacity that adjust Its output to balance generation and demand
Frequency Regulation	Energy storage is used to balance demand and generation

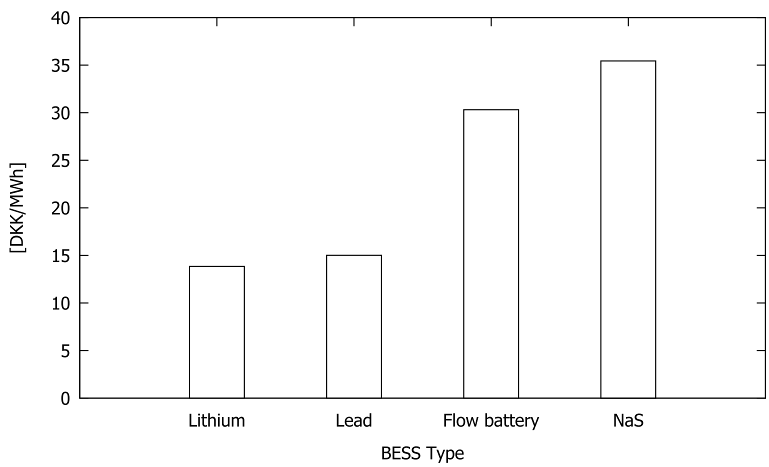


Fig. 5 LCOS results of the four investigated BESS

Since the main task of the BES technology is to complement the MG, load following will be the highest prioritized part of the revenue stacking. Load following provides revenue in the form of avoiding electricity grid taxation by utilizing internal production, while also adding value in the form of flexibility.

By investigating the potential grid services, it is found that frequency regulation within the primary reserve is the most beneficial revenue that can be utilized by the BESS. The investigation of historical market data showed that the highest price incentive is obtained through frequency regulation. One of the benefits of frequency regulation is that it is mainly based on availability payments, which can be a valuable asset for the storage since this can increase the value of the system without adding excessive degradation of the battery (Alsaidan et al. 2018).

Most of the grid services within the Danish context are closely linked, and it is, therefore, difficult to stack these as revenue streams for a single BESS. For this reason, the last stacking task for this case study will be energy arbitrage. This task is chosen due to it being able to operate alongside the other two chosen tasks. This ensures the symbiosis of the stacked revenue streams.

LCOS comparison

The LCOS is used to choose one of the four common types of BES technologies. Averages are used for the prices and technical specifications of the batteries, to ensure comparability of the LCOS results. The results of the LCOS analysis can be seen in Fig. 5.

This shows that lithium-ion batteries have the best financial indicator based on the costs of storing energy.

Revenue stacking

The stacking of the tasks is implemented using the following steps:

1. Produce load following strategy: investigate how the BESS would perform load following without the other tasks. This is done by simulating the load following task, which produces the optimal load following strategy for the MG.
2. Produce arbitrage strategy: implement an operational strategy based on the costs of buying from and selling to the grid, while also including the characteristics of the BESS, e.g. efficiency, O &M, etc.
3. Implement frequency availability payments: determined by the amount of energy stored in the battery. The bids for frequency response are released in four-hour intervals six times each day. In order to make sure that the BESS is able to provide the service, it is only able to enter the frequency stabilization market if the stored capacity is above 20 MWh in the given and following hour. The reason is to make sure the system can provide the service during the full interval, if needed. All the bids for upwards frequency regulation that is accepted will receive an availability payment that corresponds to the price of the highest accepted bid.

System model simulation

The findings of the methodology are used to comprise a model of the system. The initial model of the system is simulated using the software tool energyPRO, which is a simulation tool developed by the company EMD International A/S (EMD International 2022). This program is a modelling software for combined techno-economic

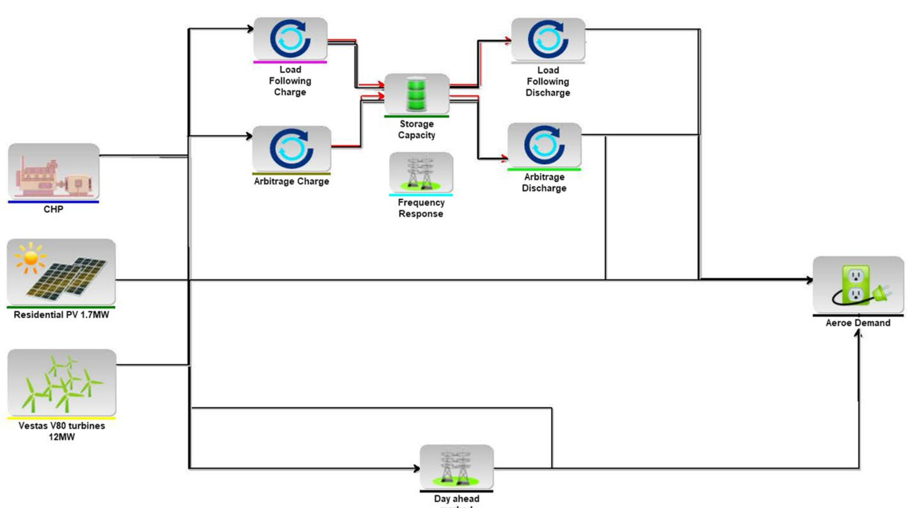


Fig. 6 Aeroe microgrid model in EnergyPro

optimization and study of a variety of energy scenarios using different technologies for a wide range of application.

Figure 6 shows the visual representation of the model from energyPRO. The model includes the present production sources at Aeroe, together with its load and a connection to the main electricity grid, found through the identified framework inputs. The electricity grid can be seen as the day-ahead market.

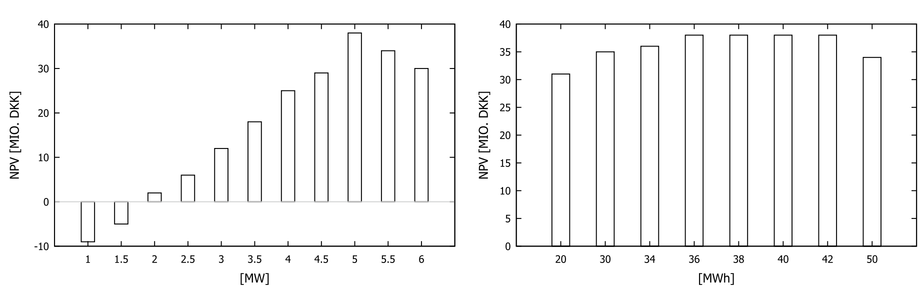
Optimization of BESS

Since the load following strategy is already based on optimally matching the net load of the system, this parameter remains fixed throughout the optimization. The part that can be optimized is the arbitrage strategy. The optimal operation strategy is here determined by assigning the operation a priority function. The priority function generally represents the production cost of each task and the one with the lowest production cost will be assigned the lowest priority number. The arbitrage task is optimized by increasing or decreasing the operational thresholds.

The optimization of the storage and power capacities, and consequently, the final BESS solution, is based on implementing the BESS into the current Aeroe MG.

The NPV results of the different power capacities can be seen in Fig. 7a. The initial storage capacity of 42 MWh is used for this investigation. The investigation of the power capacity shows that a higher power capacity results in a better NPV, although with a decrease after 5 MW. The reason for the decrease in NPV is due to system set limitations, in which the system has a maximum bid capacity of 5 MW for the frequency regulation market. This constraint is based on the Danish TSO aggregators being able to disregard bids of more than 5 MW for frequency response if this bid leads to excess fulfilment of the required reserves (Energinet 2019).

The reason that this boundary has such a substantial effect on the overall system is that the revenue gained from frequency regulation has a high contribution to the revenue of the system. This means that the additional power capacity added to the system cannot increase the revenues enough to justify the added investment costs. The investigation of the storage capacity can be seen in Fig. 7b, which shows the NPV relative to the size of the storage. The optimal storage size for the proposed BESS configuration is found to be 40 MWh, which is where there is the highest relative income related to the investment costs.

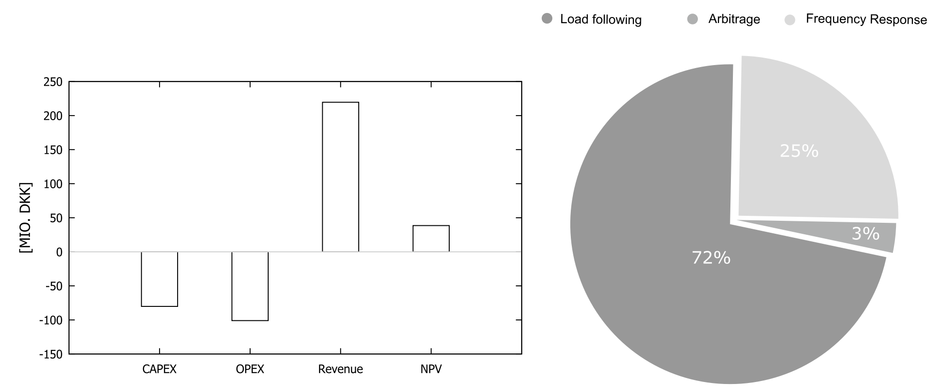


(a) Power capacity. (b) Storage capacity.

Fig. 7 NPV of the BESS

Table 2 BESS characteristics

Power capacity	5	[MW]
Storage capacity	40	[MWh]
Round-trip-efficiency	90.25	[%]
Yearly average full load	5463	[hours]
Cycles/lifetime	8202	[1C/1C 80%]
Lifespan	20	[Years]
Charge hours/lifetime	60373	[hours]
Discharge hours/lifetime	51070	[hours]



(a) NPV of the proposed BESS solution. (b) Stacked revenue.

Fig. 8 NPV of the BESS

Final BESS

Table 2 shows the financial and technical aspects of the system, including the total investment, operational costs and revenues, together with the final NPV of the entire system. This system is based on installing a lithium-ion BESS with a lifetime of 20 years and a system discount rate of 4%.

The results shown represent the operation of the entire MG system, which means that the OPEX and revenues are based on both the production of the current system and the added BESS. The total investment cost is only based on the BESS implementation. The technical characteristics are also described in Table 2 and shows the installed features of the BESS, found through the framework, paired with the operational specifications of the system.

An approximation of the proposed BESS size is based on the capacities and the rated energy and power density of the technology. This calculation can be seen in Eq. (1).

$$BESS_{size} = \frac{40\ MWh}{0.13\ MWh/m^3} + \frac{5\ MW}{0.39\ MW/m^3} \simeq 320m^3. \tag{1}$$

The placement of the BESS would have to be close to the 60 kV transmission line, to minimize capital expenditures and to ensure a connection that can handle the additional capacity of the BESS. There are only a few protected areas by Nature 2000 (Sundseth 2008) leaving areas still available on Aeroe for additional DER integration.

A visual representation of the revenue contribution of the stacked tasks is shown in Fig. 8b. The chart shows the distribution of revenue from the different tasks. The chart shows that frequency response is the highest contributing task of the system. It is also seen that the load following task provide very little direct financial value to the system. The reason for this is a very small difference between the cost of import relative to the income from exporting.

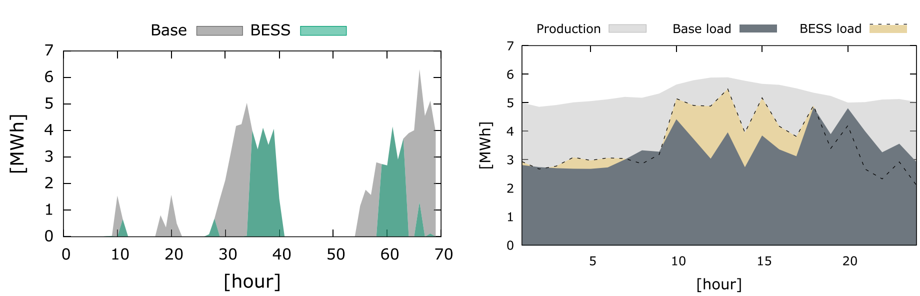
Results

This section highlights the differences between the original system, the base case, and the system with the integrated BES technology. The sections of the case study that are relevant to investigate are the production, load, and overall resilience of the system, with a minor focus towards elements such as full-load hours and BESS cycles.

To see how the behavior of the system, a representation of the Electricity import for internal load and Average yearly load and production can be seen in Fig. 9. This figure includes the current situation of Aeroe and the Aeroe MG after the integration of the BESS. Figure 9a shows the first 70 h of import of electricity that is used to cover the demand of Aeroe, where the current situation of Aeroe is noted as 'BASE' and the one including the battery is noted 'BESS'. The graph shows how the system can decrease the dependency on the main grid for covering its load, achieved by performing load following. The analysis of the import for internal load shows that the load following task is able to decrease the dependency on the grid by 38%. The decrease is based on the reduction in electricity import used solely for covering the internal demand of Aeroe.

The result of the load following task is visualized in Fig. 9b. This shows the average yearly load and production before and after the integration of the BESS, where the effect of the load following can be seen in 'BESS Load'. The curve has been shifted to hours where there is more production available. The new load profile now has a curve that fits better with the MG production curve. This shift increases the system's ability to utilize its production by 26%.

The load following operation can be seen in Fig. 10. The top graph contains the electricity production and consumption of the system, the middle graph shows the BESS charge and discharge, and the bottom graph visualizes the state of charge. By looking at the graphs, it can be seen that the battery charges when the system has excess of energy and discharges if there is a deficit. This can be seen as a form



(a) Electricity import for internal load. (b) Average daily load and production.

Fig. 9 Load following task

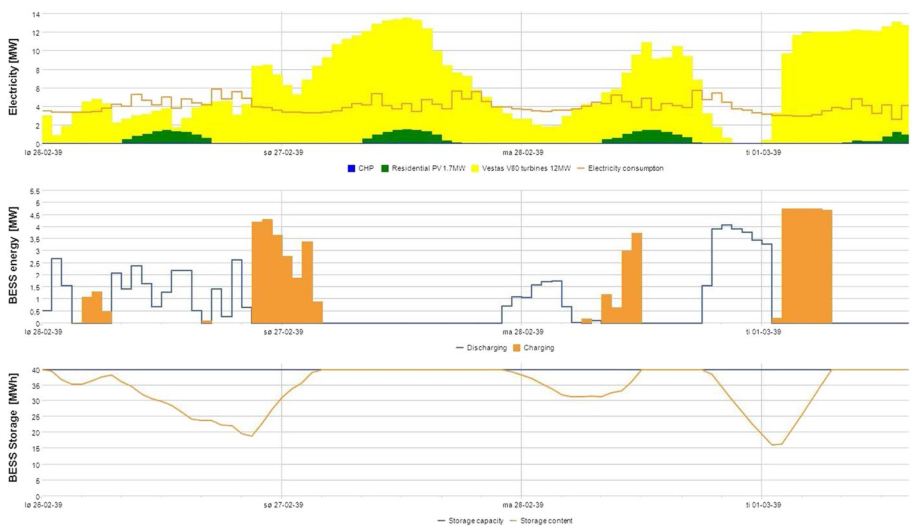


Fig. 10 EnergyPro load following production

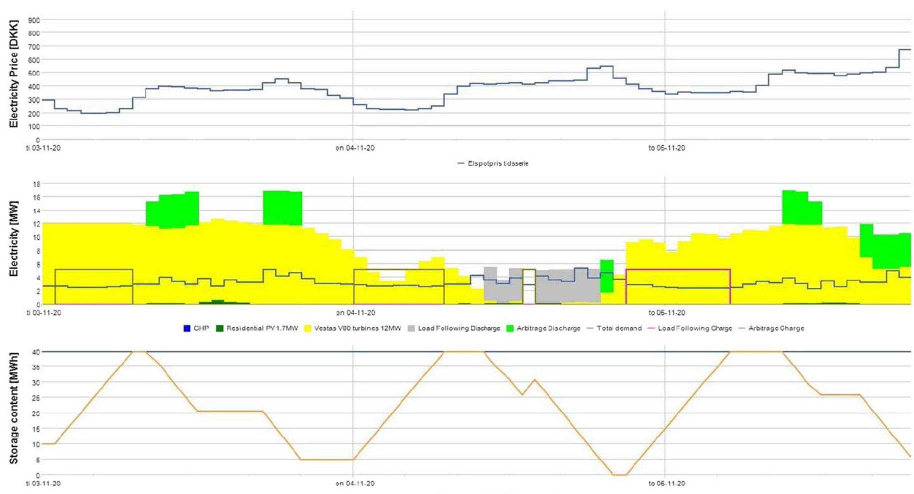


Fig. 11 EnergyPro production graphics of BESS including load following

of validation, in that the goal of the load following task is to improve the match between production and load. This shows signs of added flexibility and resilience to both the MG and the main grid.

Figure 11 shows how both the load following task and the arbitrage task is operating in the simulation. The top graph contains the spot price of the day-ahead market, the middle graph shows the system production and consumption including the BESS, and the third shows the storage state of charge. The system is doing arbitrage by utilizing the fluctuating electricity prices. This can be seen by comparing the top and the middle graph. The state of charge of the battery shows how the load following task and the arbitrage task can operate in symbiosis.

Analysis of BESS technical and financial indicators

The analysis of the technical characteristics of the BESS is used to evaluate the validity of the lithium-ion battery technology. With a total number of cycles of the investigated battery of 8202 cycles, the system is deemed valid, since the lithium-ion batteries are rated to have an operation performance between 6000–20,000 cycles.

In order to analyse how the BESS affects the financial aspect of the system, an evaluation of the NPV is made. This is based on comparing the BESS simulation to the current situation of the MG. By simulating Aeroe without the implementation of the BESS, the simulation results in a NPV of 47.7 mio. DKK. This gives a NPV of approximately 9 mio. DKK better than the simulated MG including BESS. This reveals that the additional revenue provided by the BESS is not able to justify its investment, even with the utilization of revenue stacking strategy. This finding correlates with the general tendency of battery technologies not being able to rationalize their high CAPEX (Forsight 2017). Although, it could be argued that with the increase of resilience and flexibility, the system has an increased value other than the financial aspect. The system has been improved with what can be referred to as non-tangible benefits. These benefits lie within the security of supply and power quality. The BESS makes it possible for Aeroe to utilize more of its production, thereby making the island more energy-efficient and self-reliable, which in turn help Aeroe come closer to their future perspectives.

Also, with the major developments within the battery sector, a decrease in costs is expected in the near future and could very well result in a more feasible solution. This will be investigated in the following section.

Sensitivity analysis

The sensitivity analysis of the system parameters investigates the overall robustness of BESS, and how well it reacts to certain changes within its environment. These parameters do not belong to a particular group of characteristics but rather reflect a broad spectrum of system boundaries and constraints, which could infer challenging behavior of the system if changed.

Changes in costs related to BESS

Lithium-ion based BESS suffers from high investment costs. Therefore, the investigation strives to find the magnitude of overall price reduction needed for the BESS to become financially justifiable. The analysis, in section 5, found that the overall cost of the BESS was approximately 80 mio. DKK. Resulting in a NPV of around 38.5 mio. DKK. This is seen to be approximately 9 million less than the base case of the Aeroe MG system.

Table 3 Cost comparison between Base and BESS cases [mio DKK]

	BASE	BESS	Differences
Total CAPEX	0	− 80.1	− 80.1
Total OPEX	− 82.5	− 100.9	− 18.4
Total revenue	130.3	219.5	89.2
Total NPV	47.7	38.5	− 9.2

Table 3 shows the relevant economics and highlights the financial differences between the base case and the BESS scenario.

In order to make the BESS scenario viable and competitive with the base case, a reduction in the overall capital expenditures needs to occur. The main reason for the focus solely on capital expenditures is that it is a fixed value and it indirectly ties to the maturity of the technology. Whereas the operational expenditure is not subject to the same change due to being a product of running the system, thus resulting in a more stable price level. By solving the equation, that can be made from the numerical values in Table 3, it is found that the capital expenditures need a reduction of around 12% to achieve a NPV equal to that of the base case.

Change of energy portfolio

Aeroe strives to become 100% fossil-free (Ærø Kommune 2018). For that to happen a change in the overall composition of the energy portfolio of the MG has to occur. The governing municipality has stated that this transition is going to be achieved by a combination of the implementation of additional RES production units, the refurbishment of existing units to run on RES, and increase the internal energy efficiency. By having a connection to the main grid, it greatly increases the possibilities of which RES the MG can rely on. However, by going through each of the identified transitions stated by the municipality, it is found that certain areas pose a greater potential than others.

The refurbishment strategy of changing existing units to run on RES is a necessity for the system to achieve its vision, but not of great importance for this sensitivity analysis. This is seen as a result of the Aeroe MG not having any fossil-based electricity production. The third proposed transitional action point is to increase energy efficiency internally, which correlates well with the framework proposition regarding the EU's future energy sector guidelines (European Commission 2019). One of the ways the EU is planning to increase energy efficiency is through the use of distributed energy storage. Consequently, this analysis is already assessing this transition, thereby leaving only the last proposal to be assessed. The last proposal of the municipality was the implementation of additional RES production units. To see how an increase of these would affect the system, this is investigated using the developed model. The units responsible for the energy production at Aeroe consists mainly of wind turbines with a comparably small portion of PV.

Seeing that the existing energy portfolio is heavily invested in wind turbines, it provides the argument of moving towards more implementation of PVs. In relation to the MG, adding more wind power would only increase the difficulties of achieving a stable production curve. With the opposite production curves, an increase of installed PVs makes an interesting investigation.

It can be challenging to identify which capacities of PVs would be installed in the MG. Therefore, three options at different intervals are investigated. The capacities of 1, 5, and 10 MW was chosen due to their relative sizes compared to the overall production of the MG. The results of this incremental PV capacity increase can be seen in Fig. 12.

The three scenarios depict the results, given in increased NPV, for both the base case and the BESS case. This is excluding additional investment costs of the PV. The BESS case performed noticeably better than the base case, in each of the increments. The

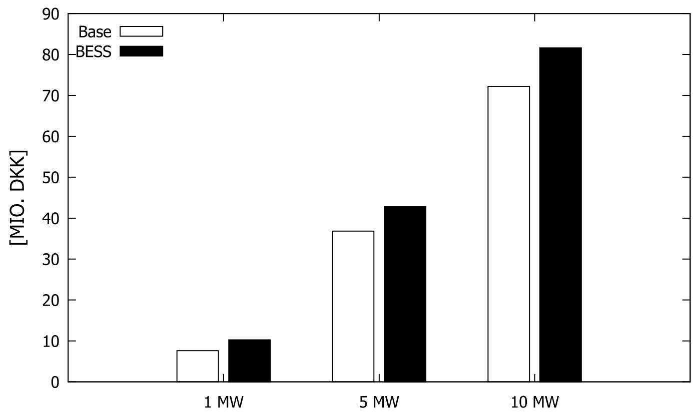


Fig. 12 NPV increase with additional PV

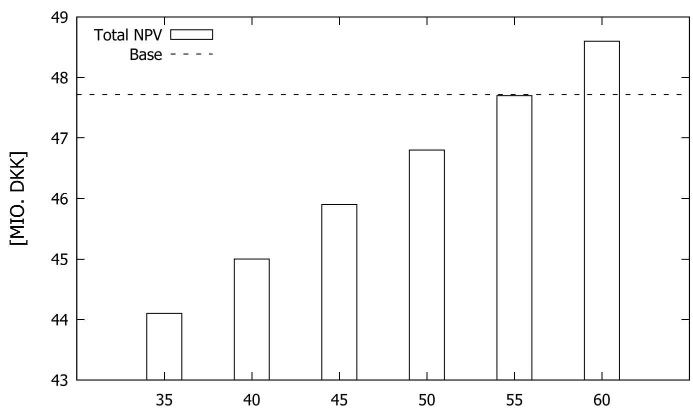


Fig. 13 Subsidy effect on the total NPV of the BESS case

highest difference is found in the increment of 1 MW installed PV capacity, where the BESS case gains 26% more value than the base case with the same setup. The other two increments experience slightly less difference, 14% and 12%, respectively. This shows the benefits of both the increased amount of solar power, but also the supplementary benefits of having a storage that can amplify the value of the additional production.

Subsidies

Figure 13 depicts the total NPV of the investigated subsidies added to the BESS case. The dashed line indicates the NPV of the base case and thereby also the breakeven point of where the BESS has the same financial profitability. Following the tendency seen in Fig. 13, the BESS obtains a breakeven point at a subsidy of approximately 56 DKK/MWh.

BESS technical performance indicators

In the case study it was chosen to use the average efficiency of the lithium-ion batteries, and since the efficiency has a significant impact on the LCOS, it was chosen to see how much a lower or higher efficiency would affect the system performance. To test this, the model was simulated using the highest and lowest identified efficiencies of the

Table 4 Technical performance indicator

Scenario	Low	Reference	High	Unit
Efficiency	85	90	95	[%]
NPV	31.37	38.45	40.25	[Mio. DKK]
Difference	− 17.5	0	4.7	[%]

lithium-ion battery. The NPV of the two simulations can be seen in Table 4, where these are compared to the final result from the case study using a 90% round-trip efficiency.

The simulations show a better NPV with the higher efficiency and worse with the lower efficiency, as expected. The interesting result of this analysis is the magnitude of the two differences. It is seen that a round-trip efficiency of 85%, makes the NPV of the system significantly worse. This correlates well with the findings of the LCOS analysis, where efficient use of energy can outweigh the higher investment costs. The significant decrease is partly due to the operational strategies of the BESS. With the lower efficiency, the threshold that the system can operate within decreases, which has a significant impact on the total operation of the system. This efficiency dependency further proves that the lithium-ion battery is the right type of BESS for the identified system and perspective of utilizing grid services as revenue streams.

Discussion

The Aeroe MG was chosen due to it being considered a smaller energy distribution system with saturated energy portfolio, which made it an ideal case for the investigation of how DERs and RESs interact. The system of Aeroe satisfies most of the MG definition criteria with the introduction of a BESS. The comparative analysis is used to identify the contribution of the BESS, showing how the system can increase the flexibility of the MG, but also showing how it becomes more "dependent" on the grid connection. This is not seen as a setback due to the stacked revenues that rely on additional exchange with the main grid. However, it causes the output of the simulation to be less transparent.

The electricity price projection reflects an average price increase based on extrapolated historical data. This input could be improved to provide better price predictions by making a more sophisticated analysis. Furthermore, the load of the Aeroe MG have been assumed to be at constant levels, resulting in no annual load increase throughout the lifetime of the simulation. This will likely not be the case since the municipality of Aeroe is experiencing a small yearly decrease in population (Kommnue 2020), together with the tendency of becoming more energy efficient.

The LCOS analysis decides the BES technology that is carried on further through the funnel framework, which occurs rather early. The earlier transition into a specific technology can have a negative effect on the proposed solution of the given case, due to it not being specifically tailored to the case. This is especially seen in relation to the full load hours used in the LCOS equation, which in the framework is based on an analysis of the estimated average of the system operation. A complete approach would have been to test every technology through the framework and then compare the findings, based on a common denominator such as NPV or return on investment analysis.

The simulation of the BESS is made with a depth of discharge of 100%. This choice can have a degrading impact on battery, which can cause a decrease in life expectancy. Although with the obtained 8202 cycles, it could be argued that the system should be able to perform as the simulation states.

Related costs

The inherent tradeoff between investment cost and the additional revenues does not justify the implementation of the BESS. The Danish TSO estimates a 39% decrease in the overall cost of lithium-ion batteries moving towards 2030 (Danish Energy Agency and Energinet 2018). This expected decrease in the cost of the CAPEX indicates that the needed decrease of 12% could be obtained in the near future. The potential is already identified with the use of electric vehicles as household batteries since the battery investment can be justified.

However, with the added amount of flexibility, provided by the BESS, together with the social-economic benefits, the additional non-tangible benefits can provide a value large enough to justify the investment of the proposed BESS. Furthermore, the perspectives of Aeroe also speaks for the implementation of the BESS, even with the lower of potential revenue than by doing business as usual.

Change in the energy portfolio

The addition of PV was identified to be the most relevant and beneficial supplement to the MG. The 'International Renewable Energy Agency' (International Renewable Energy Agency-IRENA 2019) estimates that the average cost of PVs has decreased by 77% in the period between 2010 and 2018. By 2050, they expect PVs to be among the cheapest RES available. A decrease in costs of this magnitude would provide even larger incentives to expand the energy portfolio of Aeroe with solar.

The simulation only yields the additional production from solar, meaning that the BESS is not optimized to fit the new net load of the system. The system could be optimized to match the new net load, but the idea is to see how the proposed system would handle the added production without changing the configuration. Since the system already shows an increased profit from the changed energy portfolio, the overall optimization is disregarded, as it does not convey any new information.

Conclusion

This work presents a framework that utilizes a top-down funnel structure to accurately depict how BESS can be financially and technically feasible by deploying multi-tasking strategies. The framework functionality is investigated by applying the framework steps to the Aeroe MG case study. Ways for optimizing the utilization, performance, and integration possibilities of BESS is found. The framework identified the optimal operation of the system by applying multi-tasking strategies and priority functions. This was found to be a system performing load following, energy arbitrage and frequency regulation.

The proposed solution for Aeroe entailed a lithium-ion based BESS, with a power capacity of 5 MW and storage capacity of 40 MWh. This is done by maximizing the financial indicator, NPV, while adhering to identified constraints. The comparative analysis found that the implementation of the BESS resulted in a NPV of approximately 9 mio. DKK lower than the current situation. Effectively, implying that the BESS is not able to justify its investment costs, even with revenue stacking. However, the comparative analysis identified intangible values in the form of increased flexibility and system utilization. Collectively, the proposed solution results in an optimal BESS, which will bring the MG closer to its envisioned goals while being close to financially viable. It was also found that either a decrease in investment costs of 12% or the addition of a 56 DKK/MWh subsidy could make the BESS a financially viable solution.

The framework has proven to provide feasible results within a wide range of MG parameters, all with respect to the identified objectives. Therefore, by using the framework, the user can transparently analyze different system parameters to determine the most optimal BESS solution for any specific situation. This framework can help the preliminary investigation phase when analyzing future battery energy storage system investments.

The electrical characteristics of the power system have not been accounted, as this was deemed outside the scope. As part of the future work, this could be implemented to give a better understanding of how a BESS affects the electrical characteristics, and if these could infer additional limitations. The future work investigations would help further the deployment of BESS into other regions and geographical locations, to provide an in-depth view of how the revenue stacking strategy would perform in other ecospheres.

Abbreviations

RES	Renewable energy resources
NECPS	National Energy and Climate Plans
CHP	Combined heat and power
DER	Distributed energy resources
EST	Energy storage technologies
BESS	Battery energy storage system
BES	Battery energy storage
MG	Microgrid
LCOS	Levelized cost of storage
CAPEX	Capital expenditures
OPEX	Operational expenditures
NPV	Net present value
O&M	Operational and maintenance
IRR	Internal rate on return
NLC	Net load curve
LDC	Load duration curve
BMS	Building management system
ICT	Information and communication technologies
TSO	Transmission system operator
PV	Photovoltaic

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