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Impact of shared battery energy storage system on total system costs and power peak reduction in commercial buildings

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Impact of shared battery energy storage system on total system costs and power peak reduction in commercial buildings

Ida E. U. Skoglund∗, Mette Rostad, Kasper E. Thorvaldsen
Department of Electric Power Engineering, NTNU - Trondheim, Norway
E-mail: ugleskog@gmail.com

Abstract. The power system is experiencing an increasing share of renewable and intermittent energy production and increasing electrification. However, these changes are creating high power peaks, are straining the grid and call for expensive investments in expansions and improvements. This paper examines how the operational strategy of shared battery energy storage systems (s-BESS) can address these issues for commercial buildings with relatively high power peaks. Due to the uncertainty in long-term costs when subject to a measured peak (MP) grid tariff, the scheduling of the battery is optimised with a receding horizon control algorithm. The optimisation model is used on a Norwegian real-life case study to find the best possible configuration with an already existing battery. Although current Norwegian regulations challenge the possibility for shared metering and billing for a s-BESS configuration, the results show that the total system cost was reduced by 19.2% compared to no battery. The community peak was reduced by 17.8% compared to no battery and 6.22-17.5% compared to individual storage, which indicates that s-BESS is of value for the DSO as well.

Sets		$D^{cons}_{h,b,s}$	Consumption in hour h by building b
S	Set of scenarios	η	Battery (dis)charging efficiency
B	Set of buildings	π_s	Probability of scenario s
H	Set of hours	P^{peak}	Previously measured system power peak
Indices			
s	A scenario s in set S	$P^{building}_b$	Previously measured power peak for each building
h	An hour h in set H		
k	The final hour in the first stage problem	**Decision variables**	
		$e_{h,s}$	Energy stored in the battery in hour h for scenario s
b	A building in set B		
Parameters		Δp^{peak}_s	The additional power to reach new maximum total system peak
C^{spot}_h	Energy spot price in hour h		
C^{peak}	Peak power tariff	$\Delta p^{building}_{b,s}$	The additional power to reach new maximum peak for each building
C^{vol}	Volumetric costs		
C^{fixed}	Fixed cost	$p^{imp}_{h,s}$, $p^{exp}_{h,s}$	Total power imported/exported to grid in hour h for scenario s
E^{max}	Battery energy storage capacity		
K^{max}	Battery (dis)charge capacity	$y^{imp}_{h,b,s}$, $y^{exp}_{h,b,s}$	Power imported/exported in hour h by building b in scenario s
δ_b	Battery connected to building{0,1}		
δ^{joint}	Joint metering for all buildings{0,1}	$x^{cha}_{h,s}$, $x^{dch}_{h,s}$	Power to/from the battery at hour h in scenario s
$D^{prod}_{h,b,s}$	Production in hour h by building b		

∗Corresponding author.

1. Introduction

The interest in battery energy storage systems (BESS) integration on the demand side is increasing due to the ability to handle the intermittency of renewable energy sources and the increasing power demand. This ability to provide location-specific services can in turn postpone costly grid investments [1]. Batteries can assist in peak-shaving which ensures that the grid will not experience the full effects of high energy demands [1]. In addition, other studies show that optimal operation of s-BESS between several residential buildings will result in higher energy efficiency and lower total system cost for the whole area compared to individual battery storage [2, 3]. It should, however, be noted that these studies typically include buildings with similar load and production patterns.

Due to the high consumption of commercial buildings and their varying consumption patterns and power peaks, this work will focus on the integration of a s-BESS between commercial buildings in urban areas, including a case study from Trondheim, Norway. There are already considerable volumes of work dedicated to the economic value of BESS implementation in commercial buildings under different grid tariffs [4, 5]. Work in Refs. [6, 7] considered the monetary benefits of peak shaving for commercial buildings with BESS and photovoltaics(PV), showing increased self-consumption and that costs can be efficiently reduced by peak shaving. Shared BESS between commercial buildings has been considered by [8, 9], but few others investigate the effects of s-BESS for commercial buildings with different production profiles and measured peak (MP) grid tariff.

Currently, Norwegian DSOs use MP grid tariffs for high demand commercial buildings, but regulations do not allow shared metering for more than one building or legal entity [10]. This challenges the s-BESS, as the economical benefits disappears with individual metering.

This paper investigates the monetary benefits of s-BESS and metering and compares this configurations to other configurations that are in line with current regulations. When optimising BESS operatio, a receding horizon control (RHC) approach is advantageous because of the ability to consider future uncertainties [11]. Therefore, a receding horizon optimisation model is developed to perform the analysis, with a stochastic linear program to consider future uncertainties. The contributions from this paper are:

- The development of an RHC model for shared commercial community under the influence of long-term capacity-based grid tariffs.
- Quantified gains of shared energy storage for urban area commercial buildings compared to configurations in line with regulatory regimes.

2. Methodology

The presented methodology aims at investigating the benefit of using a BESS as a shared asset in a community, or individually by a chosen building in the community. To be able to properly control the battery, while taking into account the long-term significance of the maximum power peak grid tariff, a receding horizon control (RHC) optimization algorithm has been developed. The RHC makes use of a stochastic LP problem to control the BESS optimally. Both the stochastic LP model and RHC is explained further in the following sections.

2.1. Stochastic linear program(LP) model formulation

The objective of the stochastic LP-formulation is to minimise the electricity costs by operating the BESS. The optimization model is divided into two stages; the first stage has deterministic information up until hour k, while the second stage has the problem split into three discrete stochastic scenarios for the rest of the month. The second stage allow the model to foresee the possible future peak levels and include the peak power grid tariff.

2.1.1. Objective function The objective function is dependent on whether the BESS is shared by the community or owned individually. For joint metering the binary variable δ^{joint} holds value 1, and 0 for individual metering, hence changing the objective function. As shown in Eq. (1), the objective function represents the cost from the energy spot price and the grid tariff that consists of volumetric costs, peak power costs and fixed costs from the DSO.

$$\begin{aligned} min \quad z = \delta^{joint} \sum_{s \in S} \pi_s (\sum_{h \in H} ((C_h^{spot} + C^{vol}) p_{h,s}^{imp} - C_h^{spot} p_{h,s}^{exp}) + C^{peak} (\Delta p_s^{peak} + P^{peak}) + C^{fixed}) \\ + (1 - \delta^{joint}) \sum_{s \in S} \pi_s (\sum_{b \in B} (\sum_{h \in H} ((C_h^{spot} + C^{vol}) y_{h,b,s}^{imp} \\ - C_h^{spot} y_{h,b,s}^{exp}) + C^{peak} (\Delta p_{b,s}^{peak} + P_b^{building}) + C^{fixed})) \quad (1) \end{aligned}$$

2.1.2. Energy balance constraints The electric energy balance between the buildings and the grid is shown in Eq. (2), while the balance for each individual building is captured in Eq. (3). The BESS can be placed either in the community or with a specific building, based on the parameters δ^{joint} and δ_b. δ_b holds value 1 if it is placed with building b and 0 otherwise.

$$p_{h,s}^{imp} - p_{h,s}^{exp} + \delta^{joint} x_{h,s}^{dch} + \sum_{b \in B} y_{h,b,s}^{exp} = \sum_{b \in B} y_{h,b,s}^{imp} + \delta^{joint} x_{h,s}^{cha} \qquad \forall \quad h \in H, s \in S \qquad (2)$$

$$y_{h,b,s}^{imp} - y_{h,b,s}^{exp} + D_{h,b,s}^{prod} + \delta_b x_{h,s}^{dch} = D_{h,b,s}^{cons} + \delta_b x_{h,s}^{cha} \qquad \forall \quad h \in H, b \in B, s \in S \qquad (3)$$

2.1.3. Battery constraints The BESS has an upper and lower limit on how much energy the battery can store, shown in Eq. (5), and how much power can be charged and discharged within an hour, as shown in Eq. (4). Eq. (6) addresses the energy balance for the battery based on charging/discharging quantities.

$$0 \leq x_{h,s}^{cha}, x_{h,s}^{dch} \leq K^{max} \qquad \forall \quad h \in H, s \in S \qquad (4)$$

$$0 \leq e_{h,s} \leq E^{max} \qquad \forall \quad h \in H, s \in S \qquad (5)$$

$$e_{h,s} - e_{h-1,s} = \eta x_{h,s}^{cha} - \frac{x_{h,s}^{dch}}{\eta} \qquad \forall \quad h \in H, s \in S \qquad (6)$$

2.1.4. Power peak constraints The maximum power peak grid tariff is based on the highest single-hour peak import level during a one month period, for the community or for the individual buildings. As shown in Eq. (7) for the community and Eq. (8) for the individual building, the peak power is based on previous peak levels, P^{Peak}, and the increase of peak levels during operation, Δp_s^{peak}, for each scenario.

$$\Delta p_s^{peak} + P^{peak} \geq p_{h,s}^{imp} \qquad \forall \quad h \in H, s \in S \qquad (7)$$

$$\Delta p_{b,s}^{building} + P_b^{building} \geq y_{h,b,s}^{imp} \qquad \forall \quad h \in H, b \in B, s \in S \qquad (8)$$

2.1.5. Non-anticipativity constraints The purpose of Eq. (9) is to ensure the first-stage problem has equal State-of-charge (SoC) until the stochastic second-stage problem has started.

$$e_{k,s} = e_{k,s+1} \qquad \forall \quad s \in S \qquad (9)$$

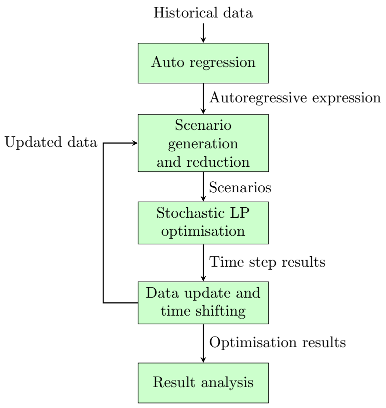

Figure 1: Flow chart showing the process of optimising with receding horizon control including scenario generation and data updates.

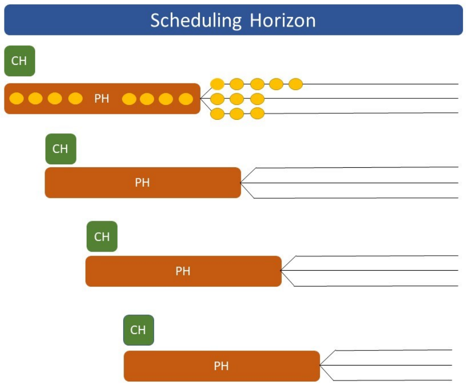

Figure 2: The iterative process of receding horizon control, showing how the scenario tree, control and prediction horizon is shifted through time.

2.2. Receding horizon control

The RHC has the following setup, as illustrated in Figure 1: First, scenarios are generated by finding an auto regressive expression for the stochastic time series, $D^{prod}_{h,b,s}$ and $D^{cons}_{h,b,s}$, used in the optimisation model. Historical data for production and consumption of the previous year is used for training the auto regressive process. Then, several scenarios are generated and later reduced to obtain a reasonable scenario tree that is representative of all the possible outcomes. These scenarios are used to solve the stochastic LP problem, and find the operational plan for the BESS within the control horizon (CH) time period. As seen in Figure 2, the CH and prediction horizon(PH) is considered deterministic, but the period beyond is stochastic with a given number of discrete scenarios to capture the uncertainty of operation. After solving the LP problem, time is shifted with a step equal to the CH, and the process is repeated with updated data concerning current battery storage and previous measured power peak. For every iteration new realistic, simulated scenarios are generated and used for solving the stochastic LP problem until the end of the scheduling horizon (SH).

3. Case studies

The presented RHC optimization algorithm has been tested for a real-life case study located in Trondheim, Norway for January 2020. The case study examines three consumers/prosumers (referred to as 1, 2 and 3). Building 1 and 2 are office buildings (where 1 has installed PV). Consumer 3 is a walking bridge with an integrated system for snow melting. The grid tariffs consist of volumetric cost $C^{vol} = 0.00687\frac{EUR}{kWh}$, fixed cost $C^{fixed} = 881.78 EUR$, and peak cost $C^{peak} = 8.163\frac{EUR}{kWh/h}$. A conversion factor at 10.00 NOK/EUR has been used.

The goal of the analysis is to see how an existing BESS with $K^{max} = 200$ kW and $E^{max} = 500$ kWh can benefit the community by reducing the total electricity cost with both peak-shaving and load-shifting. As the current Norwegian regulations do not allow shared metering for a community of commercial buildings and facilities [10], the cases will not only involve looking into s-BESS, but also individual metering and ownership of the battery.

The analysis is conducted for January 2020 when power peaks are on their highest during the year. However, due to minimal irradiation in Norway in January, the total PV-production is merely 260.8kWh, limiting impact from PV-production with joint metering and a s-BESS. The CH and PH have a 1 and 8 hour horizon, respectively, with hourly resolution and actual measuring data. The scenario tree is made up of three scenarios from 100 generated scenarios for consumption and production for the buildings, which is updated for each operating hour. The number of scenarios were chosen to limit computational time. The presented optimization algorithm is programmed using the Python-based optimisation modeling language, Pyomo 5.7, with the GLPK solver. The simulations were run on a AMD Ryzen 5 4500 64-bit processor, with an average run time of 1 hour per case. The following cases are investigated:

3.1. Case 1: All buildings and the battery behind the meter
Case 1 consist of the community operating together behind a shared meter ($\delta^{joint} = 1$), with a s-BESS at their disposal ($\delta_b = 0, \quad \forall b \in B$). The peak grid tariff is paid based on the accumulated import from all participants. With free float of power behind the meter, this configuration can be seen as a microgrid depending on a strong connection to the distribution grid.

3.2. Case 2: Individual metering and no battery
Case 2 let all three consumers being metered individually($\delta^{joint} = 0$), and the BESS is not present in the system ($\delta_b = 0, \quad \forall b \in B$). Each consumer pays electricity imported and their own separate peak grid tariff.

3.3. Case 3: Individual battery and metering
Case 3 is divided into three different sub-cases, where it is looked into how the BESS can assist each individual consumer behind their individual meter ($\delta^{joint} = 0$). Case 3.X depicts where the BESS is connected to consumer X ($\delta_X = 1, \delta_{b \neq X} = 0 \quad \forall b \in B$). The BESS can assist in storing electricity to perform peak-shaving or load-shifting without extra costs only for consumer X.

4. Results and discussion
With the RHC optimization algorithm, the BESS can be operated to consider the short-term costs of operation, and the long-term effects of for instance peak-shaving. Based on the case depicting the location of the BESS, the value the BESS can offer to peak-shaving and load shifting changes. The performance of the three cases are presented in Table 1. The results show that the RHC model successfully manages to reduce total system costs and power peaks by considering the uncertainty of high power peaks even in the early stages of the SH.

With s-BESS, total system power peaks are reduced by 17.8%, while individual BESS power peaks are reduced by $0.4 - 12.4\%$ compared to having no battery. This shows that s-BESS reduces the power peaks with $6.2 - 17.5\%$ compared to individual batteries, resulting in a cost reduction of 19.2% and $13.9-18.3\%$ compared to no battery and individual batteries respectively. The cost reduction obtained here supports the results displayed in References [8, 9], finding the s-BESS beneficial for the community. In addition, the findings show that the s-BESS promote cost reduction for buildings with different production profiles and an MP grid tariff.

The system still experiences such high power peaks with individual batteries, because only one consumer will benefit from the peak shaving effect of battery operation. This causes one consumer's reduced power peaks to possibly have little effect on total system peak reduction, if the consumers experience coinciding peak hours. While the RHC model optimises the total system costs, case 3 highlights that for the consumers without an integrated BESS, there are no incentives for importing power from the local battery rather than the grid as costs will be exactly the same. Case 1 shows that even with low PV-production, there is great potential for consumer cost reductions with joint metering and s-BESS as well as reduced system power peaks which in turn will benefit the DSOs. Even though this configuration is not in line with current Norwegian regulations, the results indicate that the introduction of means such as local grid tariffs or a local energy or flexibility market to get closer to the realisation of case 1, should be of interest.

Table 1: Total cost and peak power for the 3(5) cases.

	Case 1			**Case 2**			**Case 3.1**			**Case 3.2**			**Case 3.3**		
Total Peak [kW]	769			936			910			932			820		
Total Cost [EUR]	14 927.6			18 463.8			18 091.4			18 260.5			17 337.0		
Buildings	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Building Peak [kW]	270	96	617	270	96	617	228	96	617	270	72	617	270	96	479

5. Conclusion

This paper presents a receding horizon control (RHC) model for optimal battery operation to minimise total system costs under a measured peak (MP) grid tariff. The MP tariff incentivises the reduction of power peaks to reduce costs, which is enabled by battery operation.

The RHC model is applied to a realistic case study in Norway to find the optimal placement of a 500kWh battery in an urban area. The case study shows that a shared battery energy storage system (s-BESS) can reduce total system costs by up to 17.8% and allow consumers to reduce their costs by not having to import all their power from the grid. s-BESS also reduce total power peaks more effectively than individually owned batteries, making the case for s-BESS for commercial buildings with varying consumption and production profiles.

An s-BESS where there is a free float of power behind the meter, is clearly the most energy efficient and monetary beneficial solution. However, as this is not in line with current Norwegian regulations, one should look at other shared storage solutions. As power peak and total system costs were significantly reduced, one can conclude that there are incentives for other solutions. Further work should investigate solutions such as implementing local grid tariffs or local energy and flexibility markets for s-BESS.

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