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Battery Storage Systems in Various Types of Non-Residential Buildings for Peak Shaving Application

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***Abstract*—Battery Energy Storage Systems (BESS) are becoming increasingly attractive for German households together with photovoltaic (PV) systems to increase the PV self-consumption and reduce electricity costs. For large and power-intensive consumers, for instance, in the industrial sector, peak shaving with BESS can be an attractive option to reduce the consumer's network charges as well. This study focuses on the potential of BESS for peak shaving application in the non-residential sector in Germany, considering four types of non-residential buildings: office, fire station, hotel and sports center. Results provide an overview of profitable BESS sizes depending on specific installation costs and grid demand limit. Additionally, PV systems could help to reduce the necessary storage capacity for maintaining the maximum demand within the desired grid demand limit. Furthermore, peak shaving with BESS could enhance the grid support characteristics of the buildings, although the corresponding BESS sizes would not be economically feasible under current pricing conditions. However, the enhancement of the grid support characteristics could become an incentive, if consumers would get the opportunity to exploit wholesale market price signals.**

Keywords*—battery energy storage system, lithium-ion battery, peak shaving, electric load profile, photovoltaic (PV) power systems, non-residential buildings, network charges, financial analysis, sensitivity analysis

I. Introduction

Steadily increasing share of volatile renewable power generation in the German electricity mix continues posing a challenge to grid operation. Hence, flexibility measures are becoming essential to support the power grid stability in Germany [1], as in other countries. The German electricity pricing schemes provide some opportunities to benefit from flexibilization of electricity consumer behavior. Particularly, reduced network charges stimulate non-domestic consumers for shifting electricity consumption to off-peak times and/or reducing of maximum grid demand by peak shaving. Battery energy storage systems (BESS) pose one solution to such issues [2]. Due to expected reduction of BESS prices in future [3], they could become attractive for a wide range of non-domestic customers in industry, retail and public sector. However, each customer is different in terms of load profile shape and electricity consumption, consequently, to meet feasibility constraints, the BESS sizing is usually conducted individually.

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This work aims to define a scope for economic use of BESS for peak shaving application in various types of non-residential buildings. Additionally, we investigate the extent to which peak shaving with a BESS would impact consumer behavior in terms of grid support, i.e. better utilizing of renewables in electricity mix. For this purpose, we analyze peak demand shaving by a BESS in four non-residential buildings concerning (cp. Table I):

- Sizing and feasibility of a BESS under the current technological and economic parameters
- Impact of PV onsite generation on the BESS size
- Impact of the capacity installation cost on the economic feasibility of the BESS (sensitivity analysis)

TABLE I. Range of Scenarios Considered for each of the Buildings

Availability of a BESS	**Load Profile**	
	Building	***Building + PV***
Without BESS	*Basic:* The baseline scenario considers the building coupled neither to BESS nor PV system	*Basic + PV:* The scenario considers the building coupled to a grid-connected PV system. The size of the PV system is determined for each building individually, according to the available space.
With BESS	*Basic + BESS:* The scenario considers the building coupled to a grid-connected BESS for peak shaving.	*Basic + PV + BESS:* The scenario considers the building coupled to a grid-connected PV system and BESS for peak shaving.

- Impact on the grid support, i.e. coincidence of the electricity demand with the availability of the electricity in the corresponding market zone.

This paper is structured as follows: Section II presents the data input and the methodology, including the energy storage model and its mathematical formulation that was used to perform the analysis on BESS sizing for peak shaving. Section III evaluates the potential of peak shaving with a BESS and its viability. Besides, the analysis on grid support characteristics of the considered buildings with and without PV system and BESS is conducted. Concluding remarks and future work are presented in Section IV.

II. Methodology and Data

A. Electricity load profiles

In this work, four non-residential building types are explored: full service hotel, fire station, sports center and office. A sports center and an office are existing buildings. A hotel and a fire station are currently being under construction.

To generate the electricity load profiles of the buildings, TRNSYS 18 [4] simulation environment is used to simulate the buildings, their equipment and appliances: TRNBuild is used to create a multi-zone building model for each building individually; the simulation of the building services (lighting, heating, cooling, HVAC, etc.) is performed in TRNSYS Simulation Studio (cp. Table II). The models of the buildings are built according to plans and documentation from the detailed design stage of the analyzed buildings, which were obtained directly from the responsible building services engineering firm. Additionally, occupancy profiles are taken from [5, 6], according to the building type. The weather datasets for respective locations (required anonymizing) were obtained from the Climate Data Center (CDC) of the German Meteorological Service (DWD) [7]. One of the models (sports center) could be successfully validated using the real time series data of electricity consumption of the building over a 12-month period. Table III provides the results from statistical analysis of the simulated load profiles. Boxplots of the daily electricity consumption of the analyzed buildings and annual load duration curves can be seen in Fig. 1 and Fig. 2.

B. PV generation data

The time series data on PV generation used in this work were obtained by a simulation of the solar PV systems in TRNSYS 18 [4, 8]. The simulation was carried out for each building individually. The detailed design documentation of the hotel, fire station and sports center provides the plans of a rooftop solar PV. Additionally, a further suitable area for both on roof and façade mounted PV panels was calculated using floor, roof, elevation and section plans of the buildings. The area that would be shaded by any neighboring buildings or due to geography of the site or self-shading were excluded using, where appropriate, the online application [9] and site plans. The façade area facing an inappropriate direction was excluded as well. To calculate the module area, the suitable area was subsequently multiplied by factors 0.5 [10] for a rooftop and 0.9 for a façade PV system, respectively. For a 1 kWp system, approx. 7m^2 module area was assumed to be

TABLE II. BASIC BUILDING DATA

	Building type			
	7-story full service hotel	***7-story fire station***	***4-story sports center***	***3-story office***
Construction year	2019	2019	2013	2010
Location, anonymized	Western Germany	Southern Germany	Northern Germany	Western Germany
Heating system	District heat supply	District heat supply Brine-to-water reversible heat pump	District heat supply	Brine-to-water reversible heat pump
Cooling system	Air cooled liquid chiller	Brine-to-water reversible heat pump	Geothermal energy pile system	
Heating ventilation and air conditioning system (HVAC)	Central air conditioning system with 10 air handling units (AHUs) and variable air volume (VAV) multiple-zone system	Central air conditioning system with 6 AHUs and VAV multiple-zone system	Central air conditioning system with an AHU and VAV multiple-zone system	Natural ventilation Central air conditioning system with an AHU and VAV multiple-zone system
Heat Distribution System	Thermally Activated concrete slabs Underfloor heating (UFH) Radiant heating and cooling ceiling	Thermally Activated concrete slabs UFH Radiant heating and cooling ceiling	Radiators UFH	Thermally Activated concrete slabs Radiators UFH

TABLE III. STATISTICAL ANALYSIS OF THE ELECTRICITY LOAD PROFILES OF THE BUILDINGS

	Building type			
	Hotel	***Fire station***	***Sports center***	***Office***
Annual electricity consumption (MWh/yr)	610	1065	340	540
Maximum demand (kW)	156	200	159	267
Average electricity load (kW)	70	116	39	62
Mean daily consumption (MWh)	1.676	2.779	0.937	1.479
Coefficient of variation (CV) of demand within a year (as percent of the annual mean)	+/- 38%	+/- 16 %	+/- 102 %	+/- 83 %
Coefficient of variation (CV) of daily consumption within a year (as percent of the annual mean)	+/- 10%	+/- 6 %	+/- 32 %	+/- 30 %

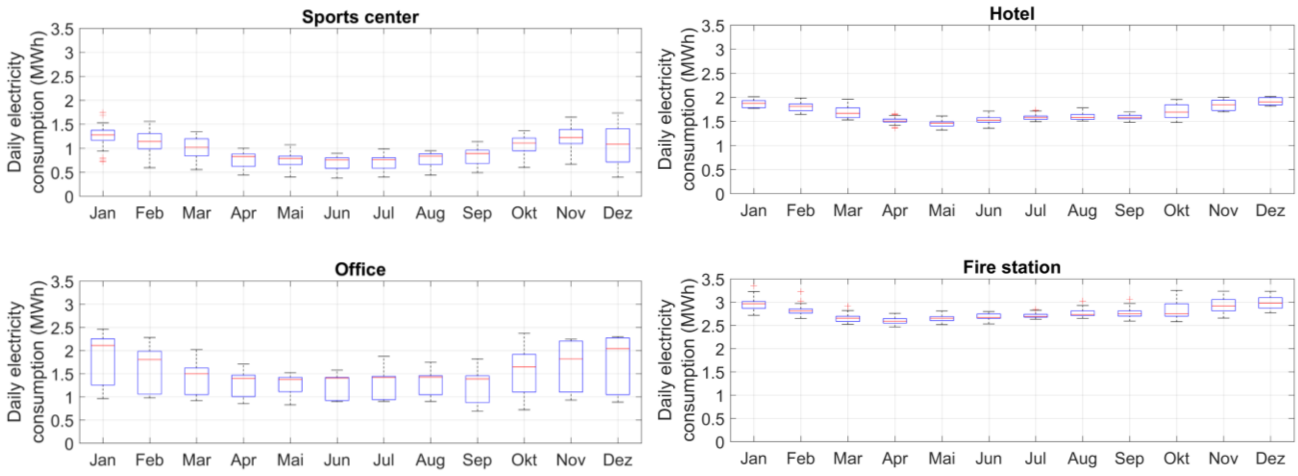

Fig. 1. Boxplots of the daily electricity consumption of the analyzed buildings over a 12-month period.

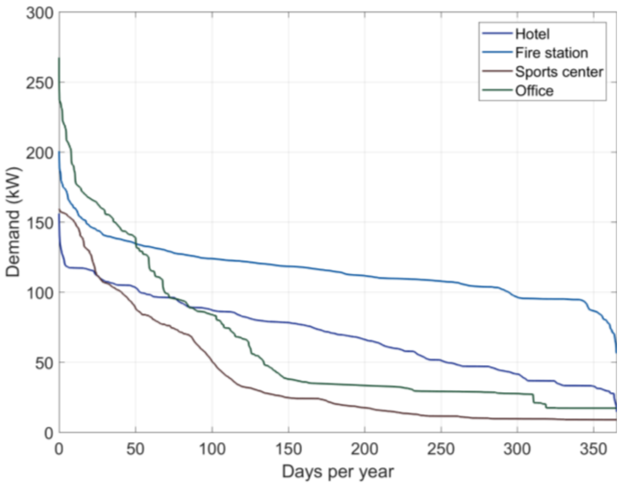

Fig. 2. Annual load duration curves of electricity demand for the analyzed buildings.

necessary [11]. The weather datasets, as mentioned in Section II.A, were obtained from DWD [7]. Production duration curves of PV systems and an example of the daily electricity generation over a 12-month period can be seen in Fig. 3 and Fig. 4. Table IV provides description of the simulated PV systems.

In order to validate the PV models, their output was compared with the output of a corresponding system estimated using the PVGIS interactive tool [12]. The percentage error between the simulated (TRNSYS) and estimated (PVGIS) annual solar energy output amounted to 3.93%, -6.95%, -0.15%, -3.55% for the hotel, fire station, sports center and office PV systems respectively. In order to reduce the difference between the simulated and estimated annual solar energy output for the fire station PV system, the simulation was performed with the Meteonorm weather dataset [13] instead of the DWD dataset. Consequently, the percentage error for the fire station PV system could be reduced to -5.4%.

C. Energy storage model

In the present analysis, a storage model is used for optimal sizing such that the grid demand limit $P_{\mathrm{grid}}^{\mathrm{max}}$ is not exceeded at any time. The method has been described in [15] before and will be summarized briefly in the following. The grid demand is computed via the demand profile P_{l}, the generation profile P_{PV} and the storage power P_{s}.

$$P_{grid} = P_l - P_{PV} + P_s \tag{1}$$

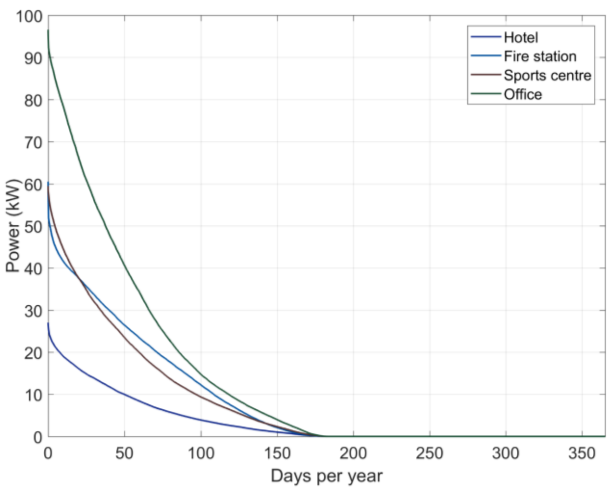

Fig. 3. Production duration curves for the analyzed PV systems.

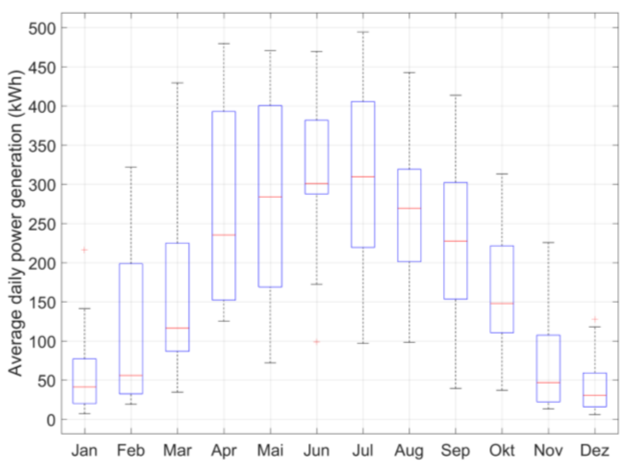

Fig. 4. Boxplot of the daily electricity generation over a 12-month period for the PV system of the sports center.

TABLE IV. PV SYSTEM DESCRIPTION

Specifications	Building type			
	Hotel	*Fire station*	*Sports center*	*Office*
Yearly global horizontal irradiance GHI (kWh/m^2/yr) [14]	1021 - 1040	1121 - 1140	1001 - 1020	1021 - 1040
Rooftop PV system				
PV technology / panel nominal power (W_p)	Poly-Si / 260	Poly-Si / 290	Poly-Si / 280	Poly-Si / 290
Array nominal power (kW_p) by orientation of collector (azimuth)	23.9 (-95°) 9.4 (85°)	12.2 (-90°) 11.6 (90°)	49.2 (32°)	92.8 (-28°)
Number of panels by orientation of collector	92 (-95°) 36 (85°)	42 (-90°) 40 (90°)	176 (32°)	320 (-28°)
Tilt of collector	10°	15°	15°	30°
Façade PV system				
PV technology / panel nominal power (W_p)	-	Mono PERC / 305	Mono PERC / 305	Mono PERC / 305
Array nominal power (kW_p) by orientation of collector (azimuth)	-	36.6 (61°) 33.6 (-29°)	33.6 (-58°)	18.3 (62°) 12.2 (-28°)
Number of panels by orientation of collector	-	120 (61°) 110 (-29°)	110 (-58°)	60 (62°) 40 (-28°)
Tilt of collector	-	90°	90°	90°
PV system summary				
Total nominal power (kW_p)	33.3	94.0	82.8	123.3
Annual energy output (kWh/yr)	29,559	74,733	69,402	118,514
Ratio of the total nominal power of a PV system to the maximum demand (%)	21	47	52	46
Self-consumption ratio (%)	100	100	66.9	96.9
Electricity self-sufficiency (%)	4.8	7.0	13.7	21.1

Therein, the storage power is computed with the help of a storage model. It consists of an energy balance to determine the state of energy F.

$$C_E \frac{dF(t)}{dt} = -k_{sd} \cdot C_E \cdot F(t) + P_s(t) \cdot \begin{cases} \eta_{ch} & \text{if } P_s(t) \geq 0 \quad \text{(charging)} \\ 1/\eta_{dis} & \text{if } P_s(t) < 0 \quad \text{(discharging)} \end{cases} \tag{2}$$

Where C_E is the usable energy capacity, k_{sd} the self-discharge rate constant and η_{ch} the charge and η_{dis} discharge efficiency. The storage power $P_s(t)$, where t is a time step (every 15 minutes), results from the storage management system. It makes sure to keep the physical limitations.

$$P_s(t) = \begin{cases} P_{s,ch}^{max} & \text{if} \quad P_{s,ch}^{max} < P_s^{set} \quad \wedge \quad 0 \leq F(t) < 1 \\ P_s^{set} & \text{if} \quad 0 < P_s^{set} \leq P_{s,ch}^{max} \quad \wedge \quad 0 \leq F(t) < 1 \\ P_s^{set} & \text{if} \quad -P_{s,dis}^{max} \leq P_s^{set} < 0 \quad \wedge \quad 0 < F(t) \leq 1 \\ -P_{s,dis}^{max} & \text{if} \quad P_s^{set} < -P_{s,dis}^{max} \quad \wedge \quad 0 < F(t) \leq 1 \\ 0 & \text{else} \end{cases} \tag{3}$$

Therein, $P_{s,ch}^{max}$ is the maximum charge power and $P_{s,dis}^{max}$ the maximum discharge power. Both are determined by the technology specific parameter π_{ch} resp. π_{dis} as follows.

$$P_{s,ch}^{max} = \pi_{ch} \cdot C_E \tag{4}$$

$$P_{s,dis}^{max} = \pi_{dis} \cdot C_E \tag{5}$$

The set point for the storage operation P_s^{set} is given through the storage objective. It is in the present case keeping the desired grid demand limit $P_{grid}^{max,set}$.

$$P_s^{set} = P_{grid}^{max,set} - P_l + P_{PV} \tag{6}$$

In the analysis, the smallest energy capacity C_E is determined, such that a given $P_{grid}^{max,set}$ is kept. It can be formulated in an optimization problem as follows:

$$\min C_E$$

$$\text{w.r.t. } \max\left(P_{grid}(t)\right) \leq P_{grid}^{max,set} \tag{7}$$

Additionally, the discussed storage model equations (1) – (6) are taken as constraints.

In a second step, the savings and expenses resulting from the storage are compared. The annual cost savings directly result from the reduced grid demand power and the power price of the grid fee k_p.

$$S_a = \left(\max(P_l - P_{PV}) - P_{grid}^{max,set}\right) \cdot k_p \tag{8}$$

Regarding the expenses of the storage a linear cost model for the installation is assumed.

$$I = c_E \cdot C_E + c_p \cdot P_{s,ch/dis}^{max} \tag{9}$$

Whereas, the first term considers the storage system itself and the second one the inverter installation costs. With the help of a simple lifetime model, equivalent annual costs are derived from the installation costs.

$$C_a = I \cdot \frac{(1+i)^{T_L} \cdot i}{(1+i)^{T_L} - 1} + C_{loss} \tag{10}$$

Therein, i is the interest rate and T_L the expected useful life. It results from the calendrical lifetime T_L^{cal} and the number of performed equivalent cycles N_{cyc}^{max}.

$$T_L = \min\left(T_L^{cal}, \frac{N_{cyc}^{max} \cdot C_E}{\int -P_S \cdot H(-P_S)\, dt}\right) \tag{11}$$

H stands for the Heaviside function, which makes sure to count only the discharged energy in the denominator. The losses of the storage have to be priced appropriately. Taking into account, that the losses either reduce the feed-in of surplus PV power or increase the energy demand from the grid, it is computed as follows:

$$C_{\mathrm{loss}} = k_e \left(E_{grid}^{\mathrm{imp}} - E_{\mathrm{grid}}^{\mathrm{imp,wos}}\right) - k_{\mathrm{FiT}} \left(E_{\mathrm{grid}}^{\mathrm{exp}} - E_{\mathrm{grid}}^{\mathrm{exp,wos}}\right) \quad (12)$$

Therein, $E_{\mathrm{grid}}^{\mathrm{imp}}$ is the imported energy from the electricity grid with energy storage and $E_{\mathrm{grid}}^{\mathrm{imp,wos}}$ without an energy storage, k_{e} is the corresponding price for energy consumption from the grid. Analogously, $E_{\mathrm{grid}}^{\mathrm{exp}}$ and $E_{\mathrm{grid}}^{\mathrm{exp,wos}}$ is the surplus energy that is exported to the grid with and without the energy storage. The feed-in tariff is considered with k_{FiT}. These energies are computed with (13) and (14) as follows:

$$E_{\mathrm{grid}}^{\mathrm{imp}} = \int P_{\mathrm{grid}} \cdot H\left(P_{\mathrm{grid}}\right) \mathrm{d}t \quad (13)$$

$$E_{\mathrm{grid}}^{\mathrm{imp}} = \int - P_{\mathrm{grid}} \cdot H\left(-P_{\mathrm{grid}}\right) \mathrm{d}t \quad (14)$$

In the cases, that no PV plant is installed, the load profile P_{PV} is set to zero and the given set of equations holds true as well. The parameter used for the following analyses (cp. Section III.A - B) are given in Table V and Table VI.

TABLE V. ASSUMED PARAMETERS FOR SIMULATION

Parameter		Value	Unit	Source
η_{cyc}	Roundtrip efficiency of the battery $\eta_{\mathrm{ch}} = \eta_{\mathrm{dis}} = \sqrt{\eta_{\mathrm{cyc}}}$	94	%	[16]
k_{sd}	Self-discharge rate	0.0245	%/day	[16]
$\pi_{\mathrm{ch}} = \pi_{\mathrm{dis}}$	Specific charge and discharge power	1	kW/kWh	
$N_{\mathrm{cyc}}^{\mathrm{max}}$	Maximum equivalent cycle number	6000		[17]
$T_{\mathrm{L}}^{\mathrm{cal}}$	Calendrical lifetime	15	years	[16]
c_{E}	Capacity installation cost	900	€/kWh	
c_{P}	Inverter installation cost	150	€/kW	[18,19]
k_{p}	Electricity price - the demand rate for the maximum annual demand	95	€/kW	
k_{e}	Electricity price - the energy rate for industrial customers	17.17	ct/kWh	[20]
i	Interest rate	5	%	

TABLE VI. FEED-IN TARIFF (k_{FiT}) CALCULATED DEPENDING ON THE TOTAL NOMINAL POWER OF PV SYSTEM IN ACCORDANCE WITH [21], YEAR OF CONSTRUCTION ASSUMED TO BE 2019

Building Type	Value k_{FiT}	Unit
Hotel	11.25	ct/kWh
Fire station	10.50	ct/kWh
Sports center	10.57	ct/kWh
Office	10.37	ct/kWh

D. Grid support

With increasing share of fluctuating renewable power generation in the energy system, flexibilisation of the demands becomes important in terms of grid support [22]. However, the current energy market mechanisms and the corresponding legal framework conditions do not provide an opportunity for a large-scale integration of a "grid-supportive" behavior into the energy market.

The authors of [23, 24] propose of metrics for the grid support characteristics of a demand profile. The absolute Grid Support Coefficient (GSC) characterizes the interaction of building's electricity demand with the availability of the electricity in the grid. The electricity availability can be represented by the following reference quantities (G): market electricity price, share of renewable electricity in the gross electricity generation, residual load, etc. Which of these values is an appropriate reference quantity G depends on the objective of a particular customer's operating strategy. For instance, if the market efficiency of the power supply should be maximized, reference quantities that characterize the supply-demand balance in the electricity market would be appropriate, e.g. market electricity price [22].

GSC can be calculated for various evaluation periods, e.g. a day, month, heating or cooling period, year. The demand and reference quantity profiles should be collected for the chosen evaluation period and have the same temporal resolution. The GSC is defined for "consumers" and "prosumers" separately as follows:

$$GSC(G) = \left(\sum_{t=1}^{n} W_{el}^{t} \cdot G^{t}\right) / \left(W_{el} \cdot \bar{G}\right) \quad (15)$$

$$\text{where } \mathrm{W_{el}} = \sum_{\mathrm{i=t}}^{\mathrm{n}} \mathrm{W_{el}^{t}} \text{ and } \overline{\mathrm{G}} = \frac{1}{\mathrm{n}} \sum_{\mathrm{t=1}}^{\mathrm{n}} \mathrm{G^{t}} \quad (16)$$

where W_{el}^{t} is the electricity consumption and G^{t} is the value of the reference quantity at the time step *t* (assumed every 15 minutes) and *n* is the total number of time steps (in this study, *n* equals to 35,040 for a one-year period).

The Grid Support Coefficients for "prosumers" are first calculated separately for the periods of electricity consumption $GSC_{load}(G)$ and generation $GSC_{gen}(G)$ and then summarized in a single value $GSC_{tot}(G)$ in accordance to [23]:

$$GSC_{tot}(G) = \left(GSC_{load}(G) \cdot W_{el}^{load} + \left(2 - GSC_{gen}(G)\right) \cdot W_{el}^{gen}\right) / \left(W_{el}^{load} + W_{el}^{gen}\right) \quad (17)$$

where W_{el}^{load} and W_{el}^{gen} characterize the amount of imported electricity and of the surplus PV electricity, respectively. It is calculated for a given time period, here one

TABLE VII. EEX DAY-AHEAD-PRICE STATISTICS OF 2017

	Value	Unit
Mean	34.19	€/MWh
Coefficient of variation (CV)	+/- 51.65	%
Min	- 83.06	€/MWh
Max	163.52	€/MWh

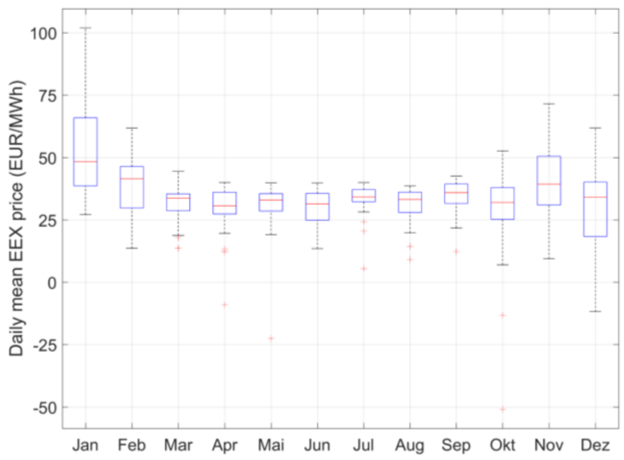

Fig. 5. Boxplot displaying the distribution of the daily mean EEX price during 2017

year. For the present study, the day-ahead-price at the European Energy Exchange (EEX) was chosen as the grid reference quantity (cp. Table VII and Fig. 5). This is beneficial, since it is a consistent, site-independent and energy market related quantity. Thus, the different consumer behaviors can be more easily compared. Furthermore, using the price the resulting GSC is equivalent to the well studied market value of the energy and allows to estimate possible economic benefits and potential of utilizing fluctuations in electricity prices. In addition, the EEX day-ahead-price is a good indicator of the availability of renewables in the electricity mix in Germany. If the $GSC > 1$, it means that the electricity is consumed at an above average or a high price (e.g. $GSC = 1.2$ means the electricity consumed at 120% of the average price of the corresponding period).

The EEX price profile for the corresponding bidding zone (Germany, BZN|DE-AT-LU) over 2017 was obtained from the ENTSO-E Transparency Platform [25].

III. Results and Discussion

A. *Demand peak shaving with a BESS: System sizing and financial analysis*

The analysis on sizing and feasibility of a BESS for peak shaving for scenarios *Basic + BESS* und *Basic + PV + BESS* is carried out with the parameters represented in Table V and Table VI according to the energy storage model presented in Section II.C. Fig. 6 (a) shows the necessary battery capacity depending on the desired grid demand limit. To present the results of all cases, it is normalized by the maximum grid demand without an energy storage. Fig. 6 (b) shows the corresponding annual profit computed as difference between the annual cost savings (8), equivalent annual costs (10) and losses of the storage (12). All analyzed cases lead to negative profits and therefore no storage system is financially feasible. The maximum possible reduction of the maximum peak in scenario *Basic + BESS* varies between approximately 80% and 45%. Due to more volatile grid demand, in case of sports center and office (CV of +/- 102 and +/- 83 % respectively, cp. Table III) a BESS obtains greater peak shaving capability. A PV system enhances this capability by a few percent (cp. *Basic + PV + BESS*). Fig. 7 shows a zoom into the results of Fig. 6. Therein it is evident, in all scenarios the necessary storage capacity increases first linearly with the rising demand reduction and then at the breaking point begins to increase exponentially. Hence, the breaking point characterizes the point of optimum balance between maximum grid demand limit and respective cost. This point is characterized by the specific charge discharge power (cp. (3) - (5)).

B. *Sensitivity analysis of installation costs*

The parameters used in the financial analysis reflect usual market conditions. Such an approach is useful to assess the potential of peak shaving with a BESS in terms of cost-benefit balance and system sizing. Since installation cost of a BESS can vary widely [16], depending on diverse factors such as system type, size, service and product competition, project requirements, etc. and tend to decrease [26], a sensitivity analysis was carried out to assess the impact of the capacity installation cost on the economic feasibility of the BESS.

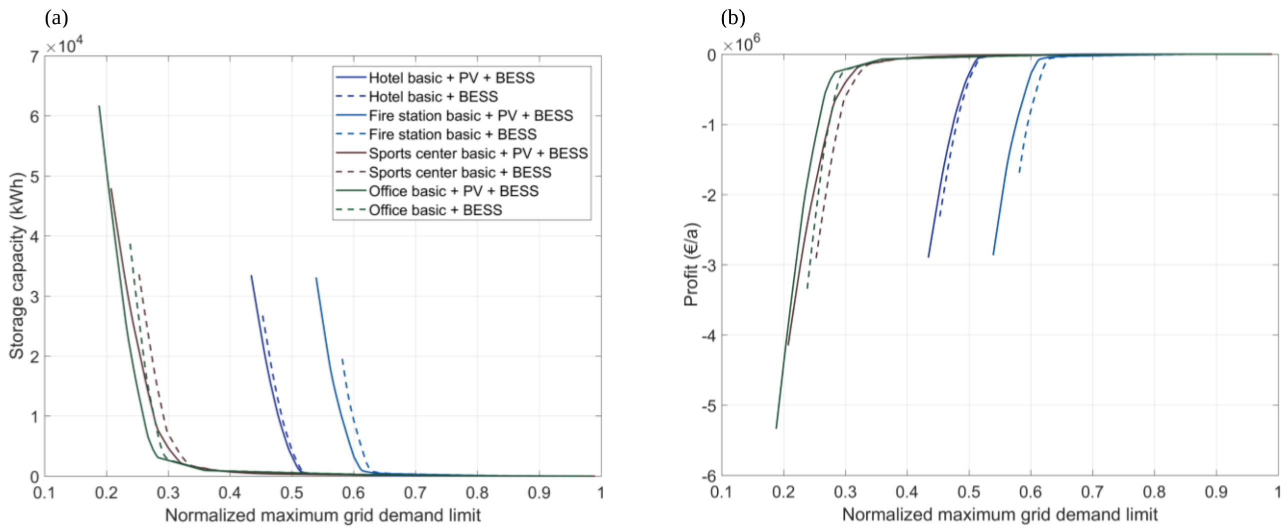

Fig. 6. Necessary battery capacity (a) and corresponding annual profit (b) associated with maximum grid demand limit (normalized to the corresponding maximum demand value) provided by a BESS

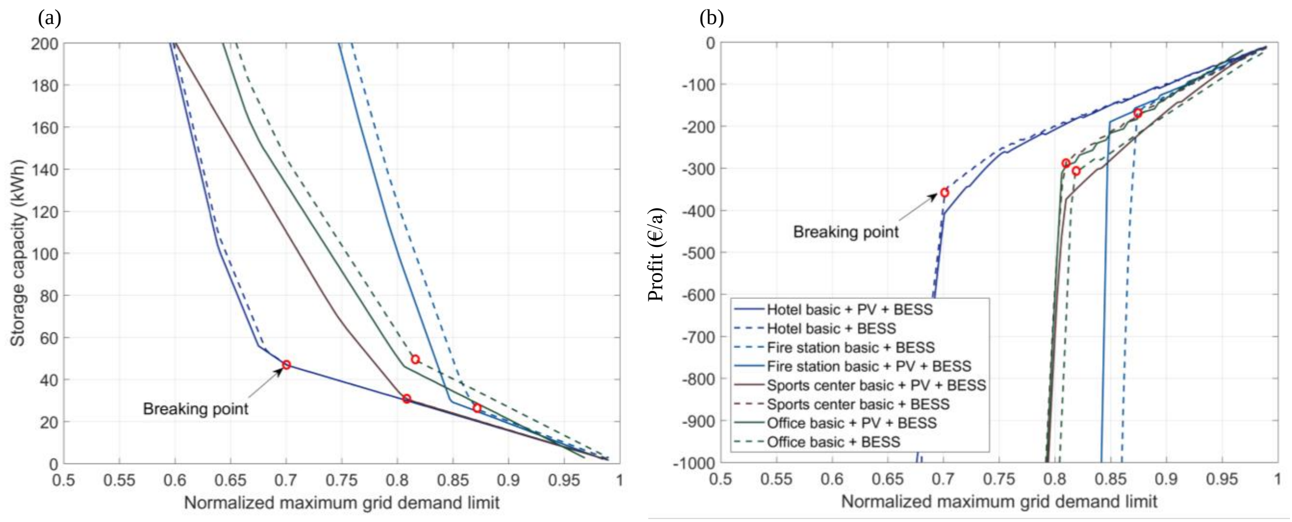

Fig. 7. A magnification of Fig. 6: Storage capacity (a), profit (b) and normalized maximum grid demand are limited to 200 kWh, –1000€/a and 0.5 respectively

The following analysis is performed for the case *Basic+BESS*. Fig. 8 (a) shows the maximum profit at the breaking point (cp. Fig. 7) for varying the capacity installation cost parameter between 600 and 900 €/kWh. In all cases, demand peak shaving with a BESS becomes economically feasible when capacity installation cost drops below 850 €/kWh threshold. The lower the capacity installation cost, the higher the profit generated by maintaining the maximum grid demand within the optimal grid demand limit. For example, peak shaving with a BESS purchased for 700 €/kWh (assuming the other parameters remain unchanged) generates the maximum profit at the grid demand limit of 0.7, 0.88 and 0.81 for the hotel, fire station and both office and sports center respectively (see Fig. 8 (b)). The corresponding net annual income ranges from approximately 300 € to about 625 € (cp. Fig. 8 (a)) depending on characteristics of the electricity load profile of the particular building.

The case of hotel represents the most effective peak shaving among the considered cases in terms of better reduction of demand peaks and higher expected earnings. In all cases, the optimal maximum grid demand limit is constant for specific capacity cost below 800 €/kWh or 750 €/kWh respectively (see Fig. 8 (b)). Once this threshold is reached, reducing capacity cost further gives higher maximum profit, while corresponding optimal storage capacity and maximum grid demand limit (Fig. 8 (c)) remain the same.

The optimal storage capacity in kWh (Fig. 8 (c)) divided by the mean daily consumption of the corresponding building in MWh (see Table III) equals the optimal specific storage capacity in kWh/MWh for each specific investment cost. I.e. the optimal specific storage capacity expresses the sufficient capacity in kWh per 1 MWh of daily electricity consumption to meet any electricity demand beyond the optimal maximum grid demand limit. As shown in Fig. 9 , the optimal specific storage capacity ranges about 30 kWh per 1 MWh daily consumption for the hotel, sports center and office, whereas for the fire station it estimated to be approximately 10 kWh per 1 MWh electricity consumed daily. However, the peak shaving capability for the maximum net income at the fire station is the lowest among the considered cases (the maximum peak is reduced only by 10%). It is worth noting, that the electricity demand of the fire station varies slightly throughout the year with the lowest CV of demand and CV of daily consumption within a year (see Table III).

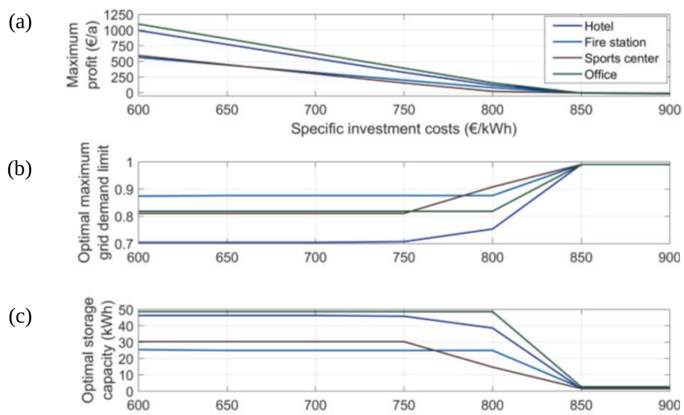

Fig. 8. Showing the estimated maximum profit earned due to peak shaving against the capacity installation cost of a BESS (a) by maintaining the maximum grid demand at the optimal maximum grid demand limit (b). The optimal storage capacity, i.e. the BESS capacity, necessary to maintain the maximum grid demand at the optimal maximum grid demand limit (c)

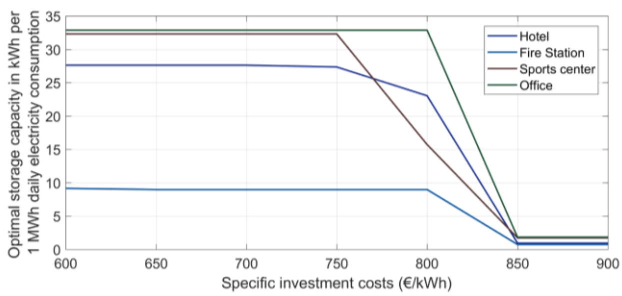

Fig. 9. Optimal (in terms of profit maximization) specific storage capacity against specific investment cost

C. Analysis on the grid support

The analysis on the grid support due to consumer behavior of the considered buildings in terms of utilizing electricity was carried out using Grid Support Coefficient (GSC) and EEX day-ahead-price as reference quantity (G) as described in Section II.D. Thereby, in the "consumer" case a $GSC < 1$ characterizes favorable consumer behavior, hence it indicates that electricity is consumed mainly at below average prices. A $GSC > 1$ indicates electricity consumption at above average price and therefore is unfavorable, i.e. such a behavior assumed to be grid-adverse in terms of EEX price. If GSC equals to 1, the consumer behavior is expected to be grid-neutral.

Grid Support Coefficients for hotel and fire station were calculated according to (15) and (16) for "consumers", since there was no excess PV electricity exported into the grid. The demand profiles used in the *Basic* scenario (see Fig. 10) are the original electricity load profiles P_l of the corresponding buildings, simulated with TRNSYS as mentioned in Section II.A. In the scenario *Basic + PV*, the residual demand profiles are used, as given by:

$$P_{\text{grid}} = P_{\text{l}} - P_{\text{PV}} \quad (18)$$

Demand profiles used in scenarios *Basic + BESS* and *Basic+BESS+PV* were generated according to (1) for each grid demand limit $P_{\text{grid}}^{\text{max,set}}$ of peak shaving and then evaluated according to (15) and (16).

Fig. 10 (a) shows that the consumer behavior of the hotel tends to be slightly grid-adverse, i.e. unfavorable with respect to EEX prices for the corresponding time period (year 2017). Reducing of maximum grid demand by peak shaving with a BESS does not improve or influence the consumer behavior characteristic, until the maximum grid demand limit of about 106 kW is reached, i.e. below this threshold GSC begins to decrease towards one. Table VIII illustrates threshold values for reduction of maximum grid demand, beyond which a gradual enhancement of GSC with decreasing maximum grid demand limit is identified.

It is evident, that onsite PV generation affects slightly the GSC, since due to onsite generation less electricity is imported during low-priced hours. Consumption behavior of the fire station (cp. Fig. 10 (b)) is considered to be less volatile and hence close to grid-neutral per se. Consequently, peak shaving with a BESS does not improve the GSC significantly (see Table VIII).

Since PV Systems of sports center and office generate surplus electricity to the grid, the Grid Support Coefficients were calculated according to (17) for "prosumers". GSC_{load}, GSC_{gen}, GSC_{tot} for considered scenarios are illustrated in Fig. 11. In *Basic* and *Basic + PV* scenarios, electricity is imported grid-adversely (see GSC_{tot}). In scenarios *Basic + PV + BESS* and *Basic + BESS*, the consumer behavior becomes more favorable due to leveling off demand peaks. Onsite PV generation affects GSC_{tot} in both cases below even more than in cases hotel and fire station due to higher self-sufficiency ratio (see Table IV). GSC_{gen} equal to 0.88 (see Fig. 11 (a)) means that PV electricity is generated at prices on average 12% lower than the mean EEX price of the corresponding time period (see Table VII). Consequently, PV generation is assumed to be grid-adverse with respect to EEX prices. The similar situation can be seen in case of office (see Fig. 11 (b)). As seen in Fig. 11, GSC_{tot} has been generally improved through peak shaving with a BESS. Nevertheless, it can also undergo a slight temporary increase.

Fig. 12 provides insights about extend to which a demand profile can be transformed by peak shaving and how does it correspond with a price profile. Fig. 12 illustrates daily grid

TABLE VIII. GRID DEMAND REDUCTION THRESHOLD, BEYOND WHICH GSC DECREASES AND MAXIMUM PERCENT ENHANCEMENT OF GSC FOR THE CONSIDERED SCENARIOS

Building type	**Necessary percent reduction in maximum grid demand**	**Maximum percent enhancement of *GSC* achieved by peak shaving with a BESS**	
		Scenario Basic + BESS	***Scenario Basic + PV + BESS***
Hotel	32%	6%	7%
Fire station	26%	2%	2%
Sports center	17%	17%	21%
Office	49%	8%	12%

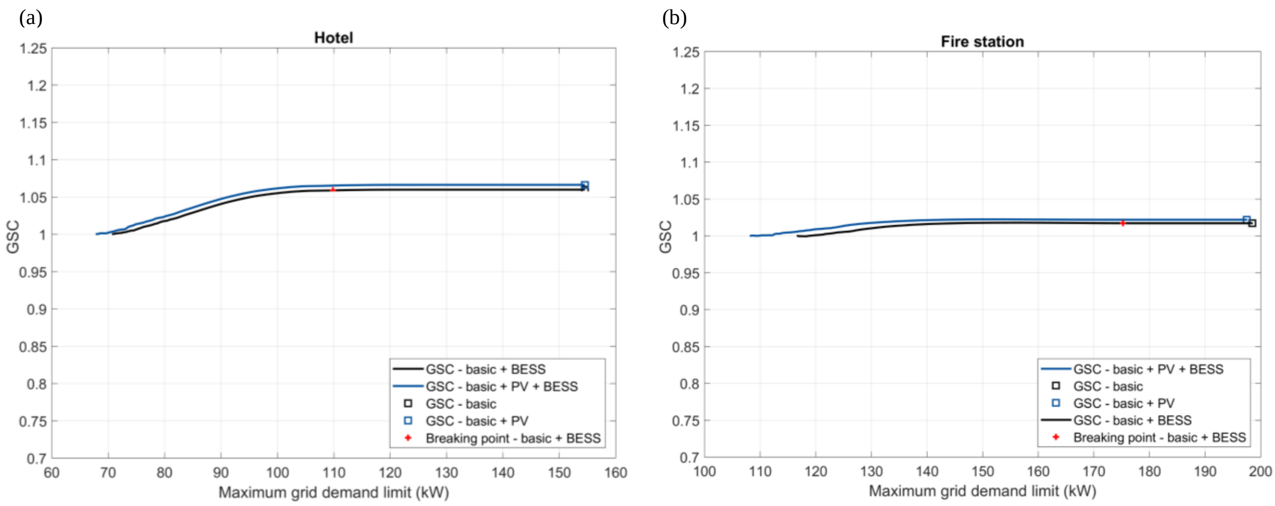

Fig. 10. Showing GSC estimated for the considered scenarios for hotel (a) and fire station (b) against maximum grid demand limit

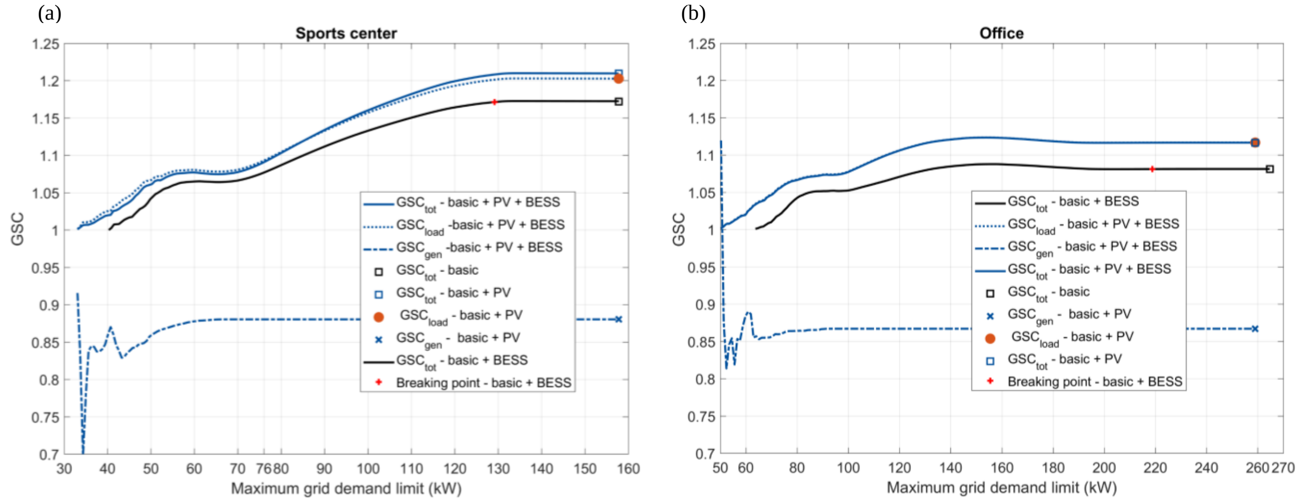

Fig. 11. Showing GSC estimated for the considered scenarios for sports center (a) and office (b) against maximum grid demand limit

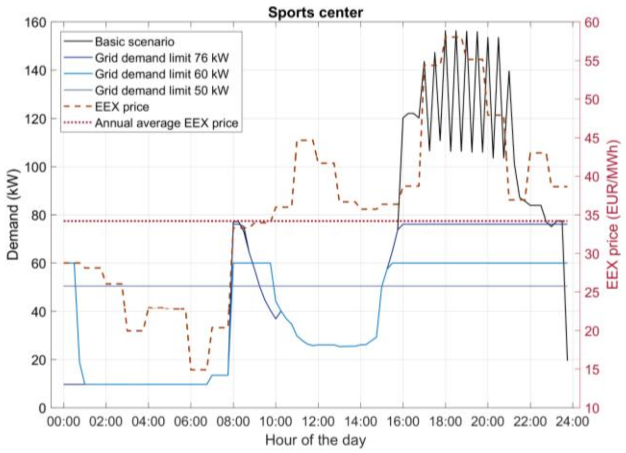

Fig. 12. Showing grid demand profiles of sports center after peak shaving with the maximum grid demand limit 76 kW, 60 kW and 50 kW and corresponding EEX price profile

demand profiles for sports center in *Basic* scenario (bevor starting any peak shaving) and after peak shaving (*Basic + BESS*) at the grid demand limit of 76 kW, 60 kW and 50 kW respectively and corresponding daily EEX price profile. The load profile leveled at the demand limit of 50 kW is characterized by a higher demand during low-priced hours (in the figure between 00:00 and 09:00) and reduced electricity demand during high-priced hours (from 09:00 to 24:00) than the load profiles limited by 60 kW and 76 kW respectively. Hence, the load profile limited by 60 kW is more grid-supportive than the profile limited by 76 kW and less grid-supportive than the profile leveled at 50 kW. Consequently, the GSC calculated for the daily profiles equal to 1.216, 1.163, 1.128 and 1.000 respectively.

Besides, both Fig. 11 and Fig. 12 show positions of the breaking points (as discussed in Section III.A), that characterize the optimal percent reduction in maximum grid demand in terms of maximum annual profit (or the optimum balance between maximum grid demand limit and respective cost, if a BESS is not feasible). It could be observed, that peak shaving at the optimal maximum grid demand limit does not impact the grid support characteristic of the building.

IV. CONCLUSION

The study has shown that:

- Maximum possible peak demand reduction achieved in considered buildings varies between approximately 45% and 80% and depends on the volatility of the origin load profile. When adopting a PV system, a smaller battery capacity may be necessary to achieve the same relative percent peak reduction than without any PV System.

- Peak shaving with a Li-ion BESS can be economically viable at capacity installation cost below 850 €/kWh. According to [16], BESS at these prices are already commercially available. Beside the capacity cost, the maximum grid demand limit impacts significantly the feasibility of a BESS. The greatest feasible reduction of the demand peaks achieved in the considered cases amounts between 12% and 30% and requires that capacity price decreases below 750 €/kWh. Annual net income earned under these circumstances varies from 150 € to 390 € and increases linearly with decreasing capacity costs. Sufficient battery capacity ranges hereby between 10 kWh and 30 kWh per 1 MWh daily electricity consumption. Another important factor that impacts peak shaving efficiency (in terms of feasible demand peak reduction) is the load profile shape, e.g. volatility, peak load duration.

- Maintaining the maximum grid demand within the optimal grid demand limit (in terms of maximum annual profit) has no impact on the examined grid support characteristic of the considered buildings, i.e. the electricity consumption behavior does not become more favorable in terms of utilizing fluctuations in EEX price. For an enhancement of the grid support characteristic (i.e. to benefit from price fluctuations) a moderate to significant reduction in peak demand is essential. Additionally, peak shaving with a BESS does not result in grid-supportive behavior per se, at best, it becomes grid-neutral.

Although this paper has defined a scope for a feasible peak shaving with a BESS in diverse non-residential buildings, an extended research with additional building types and a greater number of buildings could provide statistically more valid results that cover German non-residential building stock more accurately. A research on impact of electricity price (both the demand and energy rates) on viability of BESS for peak shaving would complement the conducted sensitivity analysis in order to take the variety of national pricing schemes into account.

Reference [26] expects an enhancement in calendar and cycle aging of a li-ion battery. Hence, in future research, it would be worthwhile to perform an appropriate analysis to assess the impact of these particular parameters on the economic feasibility of a BESS for peak shaving. The cost-benefit analysis performed in this study can also be modified with regard to revenues from improved grid support characteristic. It would illustrate, whether the improvement of grid support characteristics could additionally incentivize the usage of BESS for peak shaving.

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