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Sizing electric storage system for atypical grid usage of industrial consumers

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Abstract

There are many applications for electric storage systems (*ESS*) in manufacturing systems. While applications for maintaining production in case of a blackout are already established and economical, applications for optimizing energy supply are becoming increasingly interesting for manufacturing companies. Atypical grid usage is one application for optimizing the energy supply which has the potential to reduce the grid fee of industrial consumers. The grid fee for industrial consumers depends on the characteristics of the energy consumption. The smoother the power is drawn from the grid, the less grid fee has to be paid. This goal can be achieved by integrating an electric storage system. Electric storage systems offer high power and capacity, making them the ideal solution for this application. The challenge is the sizing of the electric storage system and the resulting economic efficiency. In this article a sizing methodology for electric storage systems, aiming for atypical grid usage, is presented.

Keywords

Energy storage; energy flexibility; sizing methodology; atypical grid usage

1. Introduction

Electric storage systems (*ESS*) offer a wide range of applications within industrial companies. *ESS* have been established to ensure an uninterruptible power supply (*USP*) [1]. Overall, the applications for a short- to medium-term storage period can be categorized as shown in Table 1.

Table 1: Applications for ESS in manufacturing companies according to entrepreneurial benefit [2].

Maintaining production	Optimization of energy supply	Provision of system services
Security of supply	Self-consumption optimization	Switchable loads
Quality of supply	Recuperation	Provision of balancing energy
	Trading on power exchange market	
	Grid fee reduction	

The applications for maintaining production include security of supply as well as the maintenance of supply quality. *ESS* are available on the market for these applications and already in use [1]. The overriding benefit of these applications is the avoidance of production disruptions or rejects caused by voltage fluctuations or blackouts and the resulting quality deviations of the product [2].

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The applications in the category optimization of energy supply are becoming more important for companies due to the required increase in energy efficiency [2]. These applications include optimization of self-consumption, recuperation, peak load reduction in order to reduce grid fees and load shifting through trading on the power exchange market.

The overriding benefit of these applications is to reduce energy costs either by reducing energy consumption (increasing energy efficiency) or by adjusting power consumption in order to reduce grid fees [2].

In the third category of applications, the provision of system services, *ESS* are used to serve the grid. This means, a *ESS* is used in such a way that it contributes to the stabilization of the primary energy system [3]. The provision and actual retrieval of capacities is remunerated differently by the associated transmission system operator depending on the product. The system services include the provision of control energy, divided into primary control, secondary control and tertiary control, as well as the switchable loads. The overriding benefit of these applications is to generate revenue by providing system services. Another application in this category would be the provision of the current reserve, but there is currently no payment for this application [3].

According to a survey conducted by Zimmermann et al., manufacturing companies see a high potential in the applications of the second category optimization of energy supply [2]. 17 % of survey participants consider the grid fee reduction to be one of the most important applications. In the future, this potential will increase continuously, as average grid fees for industrial consumers in Germany rose by around 6,5 % per year between 2011 and 2018 [4]. According to Consentec and Fraunhofer ISI, the future grid fees for industrial customers are expected to rise by up to 71 % till 2030 [5]. Therefore, this paper describes the atypical grid usage as a part of grid fee reduction and shows a method for sizing an *ESS*.

2. Atypical grid usage

The goal of atypical grid usage is to reduce the grid fee (*GF*). In Germany, the framework for this is regulated by the electricity grid fees ordinance (*StromNEV*) [6] and the energy industry act (*EnWG*) [7]. The grid fee

$$GF = DR \cdot P_{con,max} + ER \cdot E_{con} \tag{1}$$

is calculated using the maximum annual peak load $P_{con,max}$, the corresponding demand rate (*DR*) and the annual energy consumption E_{con} with the corresponding energy rate (*ER*).Atypical grid usage is not the only option to reduce the grid fee. According to Rothacher et al., there are four options [8]:

- Reduction of the annual peak load
- Change of the annual utilization hours
- Atypical grid usage
- Power-intensive final consumer

Due to the mutual influence of atypical grid usage and the other three options, only atypical grid usage is considered in this paper. Atypical grid usage means that less energy is consumed when all other consumers require a lot of energy from the grid [9]. This time period is called peak load time window (*PLTW*). All grid operators annually publish the *PLTW*. An *ESS* offers the possibility of pushing the peak loads out of the *PLTW* [8]. However, two requirements must be fulfilled for this. On the one hand, a specific load transfer potential (*LTP*) and on the other hand, the materiality threshold (*MT*) have to be satisfied. For the calculation two peak loads are used, the maximal annual peak load $P_{con,max}$ and the maximum peak load in *PLTW* $P_{PLTW,max}$. The *LTP* must be at least 100 kW and is calculated by the difference between $P_{con,max}$ and $P_{PLTW,max}$ as described in formula 2 and 3 [8].

$$LTP = P_{con,max} - P_{PLTW,max} \tag{2}$$

$$LTP \geq 100\ kW \tag{3}$$

The MT is calculated by the ratio of LTP and $P_{con,max}$ (see formula 4) [8]. For industrial consumers at low- and medium-voltage level a MT of 30 % must be achieved (see formula 5) [10].

$$MT = \frac{LTP}{P_{con,max}} \tag{4}$$

$$MT \geq 30\% \tag{5}$$

If these requirements are met, the calculation of *GF* is not based on the $P_{con,max}$, but on the $P_{PLTW,max}$ (see formula 6) [10].

$$GF\ = DR \cdot P_{PLTW,max} + ER \cdot\ E_{con,new} \tag{6}$$

Since the *GF* can be reduced to a maximum of 20 % of the original *GF,* according to §19 Para. 2 p. 1 StromNEV, a maximum cost reduction of 80% is possible [6].

3. State of the art

In order to assess the utility of an *ESS* a load profile analysis of the consumer is required [8, 11]. The load profile, which represents the power consumption of a consumer over a year in 15 minutes average values, can either be recorded by measuring the power or can be estimated using a standard load profile [8]. The individual measurement of the load profile is required for consumers with an energy consumption over 100 MWh according to § 20 StromNEV [6]. Depending on the application, static, dynamic or optimization models are used for sizing an *ESS* [12]. Optimization models for different appliactions have already been implemented in [12–16]. In these optimization models, a business key figure is always defined as target function. In [12, 17] revenue maximization is used. The net present value (*NPV*) is evaluated in [18] and the biggest cost savings in [19]. General optimization models are suitable for applications that have a business focus [12]. This also includes the reduction of grid fees through atypical grid usage. This paper describes an optimization approach using the *NPV* as target function for sizing the *ESS* for atypical grid usage with a charging and discharging strategy.

4. Sizing an *ESS* for atypical grid usage

The proposed sizing method provides the optimized rated capacity and power of an *ESS* for the application of grid fee reduction. The method consists of four steps as shown in Figure 1.

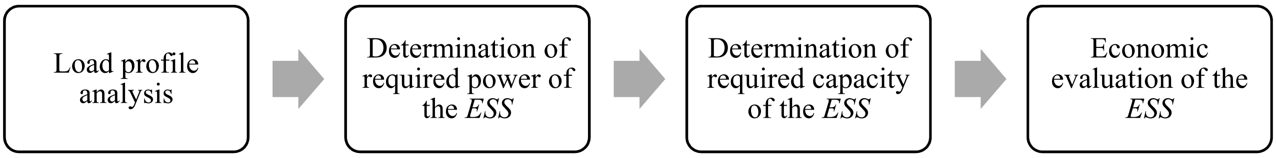

Figure 1: Four steps of sizing methodology

The four steps are explained in the following sections.

4.1 Load profile analysis

The aim of the load profile analysis is to identify key figures from the load profile P_{con} that are relevant for the application described above and for sizing the *ESS*. The annual peak load

$$P_{con,max} := max\{P_{con}(k)\} \tag{7}$$

is the maximum of the 15 minutes average values for one year.

An average power

$$P_{con,avg} = \frac{1}{35040} \sum_{k=1}^{35040} P_{con}(k) \tag{8}$$

can also be calculated from the 15 minutes average values of one year. The integral of the load profile shows the annual energy consumption

$$E_{con} = \int_{k=1}^{35040} P_{con}(k) \tag{9}$$

$P_{con,max}$ and E_{con} can be used to calculate the original *GF* (see formula 1). For atypical grid usage the maximum peak load in the time period of *PLTW*

$$P_{PLTW,max} := max\{P_{PLTW}(k)\} \quad for\ k \in PLTW \tag{10}$$

must be identified. By using this key figures in the next step the required power of the *ESS* can be limited.

4.2 Determination of required power of the *ESS*

The identified key figures from chapter 4.1 can be used to check the requirements *LTP* and *MT* for atypical grid usage. If these are not fulfilled, $P_{PLTW,max}$ is reduced step by step (see formula 11).

$$P_{PLTW,max,ESS,x} = P_{PLTW,max} - x \quad for\ x = [0, P_{con,avg}] \tag{11}$$

For each $P_{PLTW,max,ESS,x}$ an *ESS* is sized and economically valued. First, the requirements are checked (see formula 2 to 5). If the requirements are not yet fulfilled, the new $GF_{ESS,x}$ is calculated as shown in formula 1, otherwise $GF_{ESS,x}$ is calculated as shown in formula 6. For the calculation of the *ESS* power $P_{ESS,x}$, the following applies for the new $P_{PLTW,max,ESS,x}$ (see formula 12):

$$P_{ESS,x} = P_{PLTW,max} - P_{PLTW,max,ESS,x} \tag{12}$$

In formula 13 the required power $P_{ESS,x}$ is extended by the efficiecy factor for the interfacing AC converter η_{AC} and DC rectifier η_{DC} [1].

$$P_{ESS,real,x} = \frac{P_{ESS.x}}{\eta_{AC} \cdot \eta_{DC}} \tag{13}$$

The following third step for the determination of the *ESS* capacity is performed for each $P_{ESS,real,x}$.

4.3 Determination of the required capacity of the *ESS*

A requirement for determining the capacity is that the *ESS* has full forecasting capability. First, the energy demand per time step

$$\Delta E_x(k) = \left(P_{con}(k) - P_{PLTW,max,\mathrm{ESS},x}\right) \cdot 0.25h\ for\ k \in PLTW \tag{14}$$

is calculated. ΔE_x is negative if the energy storage can be charged. The following applies for the discharging capacity $E_{ESS,dch,x}$. If energy is required at the next time step (*k*+1), meaning $\Delta E_x(k+1) > 0$, $E_{ESS,dch,x}$ is increased by $|\Delta E_x(k+1)|$ plus the efficiency factors $(\eta_{AC}, \eta_{DC}, \eta_{ESS})$ at time step *k* (see formula 15). The efficiency factor η_{ESS} depends on the storage technology. $E_{ESS,dch,x}$ remains the same if there is no energy demand.

$$E_{ESS,dch,x}(k) = \frac{|\Delta E_x(k+1)|}{\eta_{AC} \cdot \eta_{DC} \cdot \eta_{ESS}} \tag{15}$$

In this paper, the charging strategy "charge as much energy as necessary as late as possible" according to Kaschub is used [20]. For this purpose it is checked, whether energy is needed (see formula 16).

$$E_{ESS,dch,x}(k+1) > 0 \tag{16}$$

In the next step the charging energy $E_{ESS,ch,x}$ must be defined. If the maximum possible charging energy within a quarter hour ($P_{ESS,real,x} \cdot 0.25h$) is less than the energy demand $\Delta E_x(k+1)$ reduced by the efficiency factors of the AC converter and DC rectifier, the maximum possible charging energy in a quarter hour limits the $E_{ESS,ch,x}$ (see formula 17 and 18).

$$P_{ESS,real,x} \cdot 0.25h < |(\Delta E_x(k+1) \cdot \eta_{AC} \cdot \eta_{DC})| \tag{17}$$

$$E_{ESS,ch,x}(k) = P_{ESS,real,x} \cdot 0{,}25h \tag{18}$$

If this is not the case, the charging energy $E_{ESS,ch,x}$ is limited by ΔE_x itself. Then $E_{ESS.ch,x}$ is calculated as shown in formula 19.

$$E_{ESS,ch,x}(k) = |\Delta E(k+1) \cdot \eta_{AC} \cdot \eta_{DC}| \tag{19}$$

Subsequently, it is checked, whether the charging energy $E_{ESS,ch,x}$ is sufficient for $E_{ESS,dch,x}$. If not, $E_{ESS,ch,x}(k-y\,) for\ y = [1{,}35040])$ is accumulated, with the steps of formula 14 to 19, until the discharging energy $E_{ESS,dch,x}(k+1)$ is covered. The required capacity $E_{ESS,max,x}$ is determined by using the maximum

$$E_{ESS,max,x} := max\{|E_{ESS,dch,x}(k)|, |E_{ESS,ch,x}(k)|\} \tag{20}$$

This capacity $E_{ESS,max,x}$ is increased according to Köhler et al. by the depth of discharge *DOD* which is different for each storage technology, ageing surcharges η_{EOL} and a general reserve capacity η_{res} (see formula 21) [1].

$$E_{ESS,\text{real,x}} = \frac{E_{ESS,max},x}{\left(\frac{1}{DOD}\right) + \eta_{EOL} + \eta_{res}} \tag{21}$$

With the completion of this step, for each possible $P_{ESS,real,x}$ an associated $E_{ESS,real,x}$ is identified. The optimum *ESS* size can be identified on the basis of the calculated economic efficiency.

4.4 Economic evaluation of the *ESS*

An economic evaluation is performed by calculating the *NPV*. Several input parameters are required to calculate these two key figures. The lifetime of the *ESS* depends on the number of full cycles. For this reason, according to Fuchs et al. equivalent full cycles per year

$$FC_x = \frac{\sum_{k=1}^{35{,}040} |E_{ESS,dch,x}(k))| - \sum_{k=1}^{35{,}040} |E_{ESS,ch,x}(k)|}{2 \cdot E_{ESS,real,x}} \tag{22}$$

are calculated [21]. Since each *ESS*, depending on the technology, has both a calendar T_{cal} and cyclic lifetime T_{cyc}, it must be determined which one is reached first. If the quotient of T_{cyc} and FC_x is greater than or equal to T_{cal}, then T_{cal} is the lifetime t_{ESS} of the ESS, otherwise T_{cyc} is equal to t_{ESS}. The lifetime t_{ESS} is also the planning horizon for the economic evaluation. The new grid fee $GF_{ESS,x}$ per year is equally relevant for the economic evaluation. This depends on the new $P_{PLTW,max,ESS,x}$ as shown in formula 11. Compared to the original load profile P_{con}, the new load profile

$$P_{con,new,x}(k) = P_{con}(k) + \frac{(E_{ESS,dch,x}(k) - E_{ESS,dch,x}(k-1)) \cdot \eta_{AC} \cdot \eta_{DC} \cdot \eta_{ESS}}{0{,}25h} \tag{23}$$

$$P_{con,new,x}(k) = P_{con}(k) + \frac{(E_{ESS,ch,x}(k) - E_{ESS,ch,x}(k-1))/(\eta_{AC} \cdot \eta_{DC})}{0{,}25h} \tag{24}$$

decreases for discharging processes (see formula 23) and increases for charging processes (see formula 24). This means that $E_{con,new,x}$ can also be calculated using formula 9. These parameters can be used to calculate $GF_{ESS,x}$ per year (see formula 4). The revenues

$$R_x = GF - GF_{ESS,x} \tag{25}$$

per year are the savings from the difference between *GF* and $GF_{ESS,x}$, including an annual increase of grid fee (see formula 25) [22].The investment costs C_0 for the *ESS* depend on $E_{ESS,real,x}$ and $P_{ESS,real,x}$ [23, 24]. $C_{0,x}$ is calculated as shown in formula 26. Specific investment costs c_P and c_E for power and capacity vary according to the storage technology.

$$C_{0,x} = P_{ESS,real,x} \cdot c_P + E_{ESS,real,x} \cdot c_E \tag{27}$$

The payments

$$A_x = C_{0,x} \cdot C_B + \left(E_{con,new,x} - E_{con}\right) \cdot C_S \tag{28}$$

consist of the operating costs C_B per year [24] and additional electricity costs C_S including an annual increase [25] (see formula 28). Using *R*, $C_{0,x}$ and *A*, the *NPV*

$$NPV_x = -C_{0,x} + \sum_{t=0}^{\mathrm{t}_{ESS,x}} \frac{-A_x(\mathrm{t}) + R_x(\mathrm{t})}{(1+i)^t} \tag{29}$$

can be calculated (see formula 29). For discounting an interest rate *i* is used. *NPV* can decide, whether the investment is economically viable. If the *NPV* is positive, the *ESS* is economical. This step is performed for each possible $P_{ESS,real,x}$ and associated $E_{ESS,real,x}$. The optimal *ESS* size can be identified from the maximum *NPV*.

5. Case study

For validation, the load profile of an automobile plant is analyzed and *DR*, *ER* and *PLTW* from Stuttgart Netze are used to calculate *GF* and $GF_{ESS,x}$ [26]. An annual increase of 4% after BNetzA is chosen for *GF* [22]. C_S is assumed to be 0.1844 €/kWh with an annual increase of 3.3% [25]. C_B per year is 3% of C_0 according to Sterner and Stadler [24]. The efficiency factors of the power electronic devices η_{AC} and η_{DC} are fixed at 95% [1]. For η_{EOL} 20% and for η_{res} 10% of the required capacity are assumed [1]. An interest rate *i* of 3 % is set for the calculation of the *NPV* [1]. For the analysis three storage technologies are considered: a lead-acid battery (*LAB*), a lithium-ion battery (*LIB*) and a redox-flow battery (*RFB*). The key figures taken into account are shown in Table 2.

Table 2: Average key figures of the considered storage technologies [24].

Key figure	Unity	LAB	LIB	RFB
η_{ESS}	[%]	81.5%	93.5%	74.5%
T_{cal}	[a]	10	15	17,5
T_{cyc}	[full cycles]	851	3,200	11,000
c_P	[€/kW]	345.00	385.00	1,250.00
c_E	[€/kWh]	222.50	385.00	475.00
DOD	[%]	60%	80%	100%

If the requirements are not met, the analysis shows that none of the considered storage technologies can achieve a positive *NPV*. Figure 2 shows the *NPV* via $P_{ESS,real,x}$ from the time when the requirements are fulfilled.

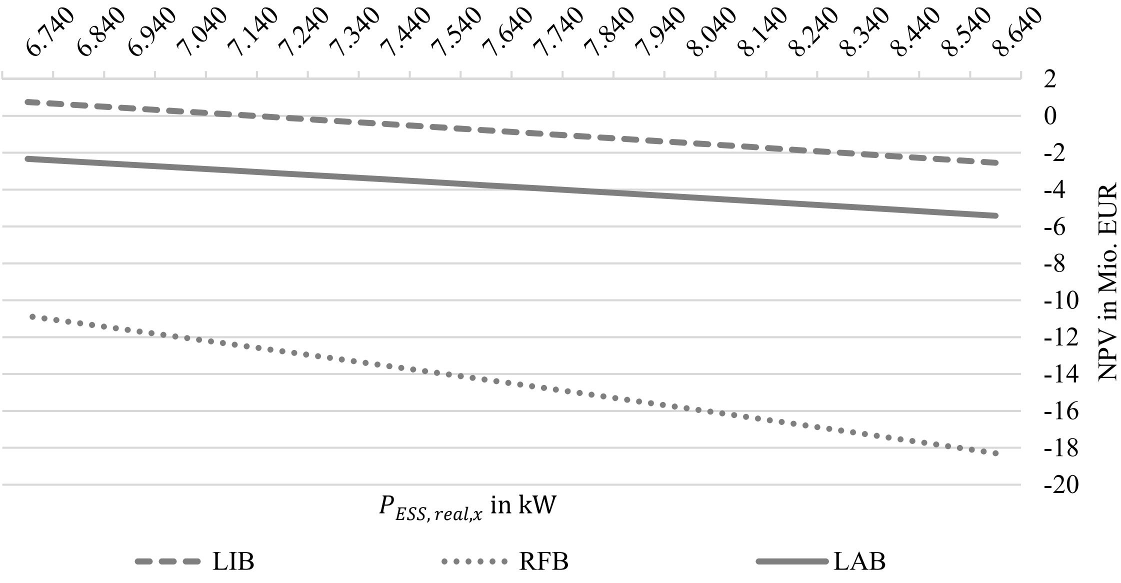

Figure 2: NPV of LAB, LIB and RFB for different sizes of $P_{ESS,real,x}$.

As soon as the requirements are fulfilled, only *LIB* achives a positiv *NPV* for the analyzed load profile. No economic result can be achieved for *LAB* and *RFB*. For *LIB* the smallest size that fulfills the requirements can achieve a positive *NPV*. The technical and economical key figures of the most economical *LIB* are shown in Table 3.

Table 3: Key figures for the most economical LIB.

Key Figures	Unity	LIB
$P_{ESS,real}$	[kW]	7,357
$E_{ESS,real}$	[kWh]	30,014
t_{ESS}	[a]	15
C_0	[€]	14,387,994
NPV	[€]	916,506
Grid fee reduction	[%]	18,85

A positive *NPV* can be achieved over the lifetime of 15 years. However, C_0 are very high compared to the *NPV*. But a reduction of 18 % for *GF* could be achieved. $E_{ESS,real}$ of *LIB* is large for the analyzed load profile, since $P_{PLTW,max}$ is drastically reduced to meet the requirements that the *LIB* has to discharge over the complete *PLTW* (four hours). A load profile with a larger fluctuation range or other *PLTW* could lead to more economic results.

6. Conclusion

It can be seen that the atypical grid usage has great economic potential. However, the economic efficiency of an *ESS* is strongly dependent on the individual load profile. *LIB* can be economically sized for the analyzed load profile. For the economic efficiency of *LAB* and *RFB*, other load profiles should be analyzed. The method could also be transferred to other applications and thus offers the possibility to combine applications, since a multifunctional storage operation ensures a higher utilization of the *ESS* and an associated increase in revenue [12]. In addition, the interest rate *i* has a significant impact on the *NPV*. The influence can be checked by a sensitivity analysis.

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