Comparison of peak shaving and atypical grid usage application for energy storage systems in the german industrial sector

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Abstract:
With a higher fluctuation in the electricity supply and the reduction of investment costs for energy storage systems in recent years, energy storage systems could become a possibility to make industrial consumers more flexible. By utilizing the incentives set by the electricity grid charge regulation ordinance (StromNEV), this paper describes a sizing method that identifies the most economic size for an energy storage system for the applications of peak shaving and atypical grid usage to reduce the grid charge.

Keywords: grid charge reduction, energy storage, energy flexibility

1 Introduction

Within rising electricity prices, the industrial sector is searching for solutions to save energy costs and to be more energy efficient [1]. In regards to the continuous investment cost reduction of energy storage systems (*ESS*) [2], the implementation of *ESS* applications are becoming feasible.

ESS are already established in the industrial sector, the most prominent usage of *ESS* can be found in the applications of protection of production [3]. As it is shown in table 1, besides the protection of production, there are two more categories of applications for *ESS* in industrial companies [4].

Table 1 Applications for ESS in industrial companies according to entrepreneurial benefit [4]

Protection of production	Optimization of energy supply	Provision of system services
Security of supply	Self-consumption optimization	Interruptible loads
Quality of supply	Recuperation	Provision of balancing energy
	Trading on electricity exchange	
	Grid charge reduction	

The applications in the category optimization of energy supply are becoming more important for companies due to the required increase in efficiency. 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 charges [4].

In the third category of applications, the provision of system services, *ESS* are used to stabilze the primary energy system [5]. 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 [5].

The results of a survey by Zimmermann et al. show, that more than half of the survey respondents from the industrial sector occupied themselves with the integration of *ESS* in their organization [4]. 17% of survey participants consider grid charge reduction to be one of the most important applications [4]. Furthermore, it is expected that in the future the grid charges for industrial consumers rise by up to 71% [6]. Therefore, this paper shows a method for sizing *ESS* and compares the applications of grid charge reduction, peak shaving and atypical grid usage.

2 Applications of grid charge reduction

With more than half the cost of the industrial electricity price, the grid charge has a great effect on the total costs of electricity [1]. In Germany the grid charge (*GC*) is the fee charged for the transmission of electricity from the producer to the consumer [7] . It is regulated by the Electricity Network Charges Ordinance (StromNEV) [8] and the Energy Industry Act (EnWG) [9], and is calculated every year on the basis of a standardized calculation method. The general calculation of the *GC* is derived from the annual peak load (P_{max}) multiplied by the power rate (*PR*) and the annual energy consumption (E_a) multiplied by the energy rate (*ER*), as seen in formula 1.

$$GC = DR \cdot P_{max} + E_a \cdot ER \qquad (1)$$

According to the regulations in StromNEV and EnWG, either the application peak shaving or atypical grid usage can accomplish a grid charge reduction [10].

2.1 Peak shaving application

Peak shaving describes the smoothing of P_{max} using *ESS* and resulting in a minor annual peak load $P_{max,ESS}$. Reducing P_{max} results in a more balanced load profile, which in turn leads to an increase in another important indicator - the usage hours (*UH*). The higher the ratio, the more evenly the energy is consumed [10]. It is calculated as shown in formula 2:

$$UH = \frac{E_a}{P_{max}} \qquad (2)$$

Besides the reduction of P_{max}, *UH* of more than 2500 usage hours leads to a different rate category for calculation of *GC* [7]. An exception occurs if the E_a exceeds 10 GWh per year and the *UH* of 7000 usage hours is surpassed [10]. In that case, the consumer can register according to § 19 StromNEV as a power-intensive consumer and is entitled to minimize *GC* [8]. With at least 7000 usage hours a reduction of up to 80% of *GC* is possible, with over 7500 usage hours a reduction of up to 85% is possible and with *UH* of more than 8000 usage hours a reduction of up to 90% is possible [10].

2.2 Atypical grid usage application

Atypical grid usage means that less energy is consumed when all other consumers require a lot of energy from the grid [11]. Atypical grid usage involves a reduction of peak loads in the peak load time windows (PLTW). The PLTWs are predefined by the distribution system operator and are designated windows in which a lot of electricity is drawn from the grid [12]. Consumers who meet the requirements and who register are awarded with individual *GC*. The requirements for being able to profit are on the one hand, a minimum load transfer potential (*LTP*) of 100 kW and, on the other hand, a materiality threshold (*MT*). The *LTP* is calculated by the difference between P_{max} and the peak load in the PLTW ($P_{PLTW,max}$) as described in formula 3 and 4.

$$LTP = P_{max} - P_{PLTW,max} \quad \text{for } P_{PLTW,max} \in PLTW \tag{3}$$

$$LTP \geq 100\ kW \tag{4}$$

The *MT* is calculated by the ratio of *LTP* and P_{max} (see formula 5) [10]. For industrial consumers at low- and medium-voltage level a *MT* of 30 % must be achieved (see formula 6) [13]

$$MT = \frac{LTP}{P_{max}} \tag{5}$$

$$MT \geq 30\% \tag{6}$$

If these requirements are met, the *GC* can be reduced to a maximum of 20 % of the original *GC*, according to §19 Para. 2 p. 1 StromNEV, that means a maximum cost reduction of 80% is possible [8].

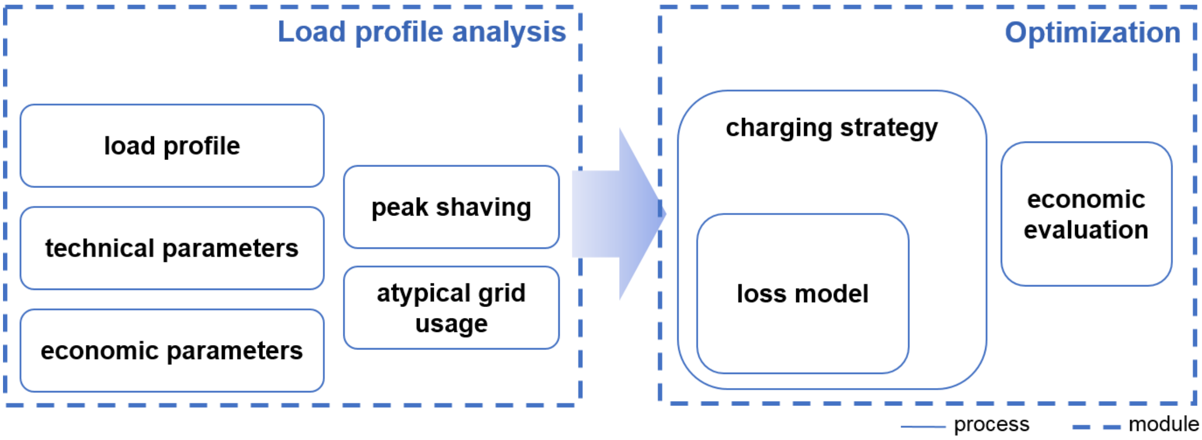
3 State of art

In recent years an increasing amount of studies about *ESS*, their applications and their feasibility have been part of the scientific discourse [14]. Of those studies, which determine the optimal size of an *ESS*, can be three types of a modelling approach categorized. Static, dynamic and optimization modelling account used to determine the economic value of *ESS* [15]. Optimization models for different applications have already been implemented in [15–19]. In these optimization models, a economic key figure is always defined as a target function. In [15, 20] revenue maximization is used. The net present value (*NPV*) is evaluated in [21] and the biggest cost savings in [22]. General optimization models are suitable for applications that have a business focus [15]. This also includes the reduction of grid charge through peak shaving or atypical grid usage. This paper describes an optimization approach using the maximum of *NPV* over all possible power sizes as a target function for sizing *ESS* for peak shaving and atypical grid usage.

4 Sizing ESS for peak shaving and atypical grid usage

The proposed sizing method provides the optimized rated capacity and power of an *ESS* to reduce *GC*. The method consists of two superordinate modules as shown in figure 1.

Figure 1 Two modules of sizing methodology



The model, built in a modular structure, is formulated as a linear optimization problem. It consists of a load profile analysis and an optimization module. With the economic evaluation, the maximum *NPV* of the observed optimization space (I) is presented (see formula 7).

$$ESS_{optimal} = max\left(NPV(i)\right) \quad \forall i \in I \qquad (7)$$

The objective of the model is to assess *ESS* with several technologies on a comparable technical and economic basis. The saving potentials are determined by potential of the grid charge reduction. The subsequent optimization consists of a load scheduling strategy combined with a loss model and results in the economic evaluation. This procedure identifies the optimum *NPV* and delivers it as the final result.

4.1 Load profile analysis module

In the load profile analysis essential key figures for the subsequent calculation are identified. The aforementioned high accuracy of the load profile is needed so that temporary fluctuations are reflected its display. The load profile $P(t)$ is analyzed to identify P_{max} (see formula 8). The load profile has a time resolution of 15 minutes average values over one year ($t = [1; 35040]$. In addition, the E_a is calculated (see formula 9) as well as the *UH* (see formula 2).

$$P_{max} = max(P(t)) \qquad (8)$$

$$E_a = \sum_t^{35040} P(t) \cdot \frac{1}{4} \qquad (9)$$

These key figures are used to determine the initial *GC* using formula 1. The initial *GC* serve as a reference for a later reduction.

In the next step, the power of the *ESS* is initialized in conjunction with power losses according to [3] and resulting in the variable $P_{ESS,real}$. The *ESS* sizing is an iterative process with the iteration step *i*. When the application of peak shaving is chosen, the increasing $P_{ESS,real}$ is accompanied by a decrease of P_{max} (see formula 10).

$$P_{max,ESS}(i) = P_{max,ESS}(i-1) - P_{ESS,real}(i) \qquad (10)$$

When the application of atypical grid usage is chosen, the increasing $P_{ESS,real}$ is accompanied by a decrease of $P_{PLTW,max}$ (formula 11). The load outside *PLTW* remains the same.

$$P_{PLTW,max,ESS} = P_{PLTW,max,ESS}(i-1) - P_{ESS,real}(i) \tag{11}$$

In the first step of the iteration *i* the values P_{max} and $P_{PLTW,max}$ are used as starting point. In both applications, for each iteration an optimization with a charging strategy in combination with the loss model is implemented.

4.2 Optimization module

To estimate the capacity of the *ESS* E_{ESS}, a charging strategy 'charge as much energy as necessary as late as possible' according to [23] is applied. Therefore a full forecasting capability for the load profile is assumed. The procedure is explained for the peak shaving application and applies to all iteration steps *i*. However, the procedure also applies to atypical grid usage with the difference that $P_{PLTW,max,ESS}$ is used for the calculations.

According to the charging strategy, the load profile is traversed from back to front. For any time step *t*, the load profile is checked whether the current load $P(t)$ is above or below $P_{max,ESS}$. For each step, the power for reducing the peak has to be determined (see formula 12).

$$P_{pot}(t) = \left|P(t) - P_{max,ESS}\right| \tag{12}$$

If $P(t) \geq P_{max,ESS}$, $P_{pot}(t)$ is the required power $P_{req}(t)$. In that case the required capacity $E_{req}(t)$ is calculated and accumulated with previous values (see formula 13).

$$E_{req}(t) = (P_{req}(t) \cdot \tfrac{1}{4}) + E_{req}(t+1) \tag{13}$$

In case that $P(t) < P_{max,ESS}$, it is possible to charge the *ESS*. If $E_{req}(t)$ is 0, since no peak has been reduced, the *ESS* will not be charged. In those cases where $E_{req}(t) > 0$, *ESS* has to be charged. This is done under the restriction that the charging capacity $E_{ch}(t)$ cannot be higher than the maximum possible energy given by $P_{ESS,real} \cdot \frac{1}{4}$. A further limitation not to exceed $P_{max,ESS}$ is shown in formula 14.

$$P(t) + P_{req}(t) < P_{max,ESS} \tag{14}$$

As results of the charging strategy, the necessary capacity of *ESS* E_{ESS} is determined as shown in formula 15.

$$E_{ESS} = max\left(E_{req}(t)\right) \tag{15}$$

E_{ESS} is further over-sized justified by the depth of discharge, aging surcharges and a reserve capacity and becomes the real capacity of ESS $E_{ESS,real}$ according to [3].

The lifetime of the *ESS* T_{ESS} is an important indicator for the economic evaluation. For this purpose the equivalent full cycles *FC* according to [24] are calculated to identify the annual full cycles of the *ESS* (see formula 16).

$$FC = \frac{\sum_{t=1}^{35040} E_{req}(t)}{E_{ESS,real}} \tag{16}$$

The quotient of the cyclic lifetime of the respective *ESS* technology and *FC* are used to estimate the lifetime after cycles of the ESS. In a comparison with the calendrical lifetime of the *ESS* technology, the minimum of the comparison is used for the lifetime of *ESS* T_{ESS}.

The new grid charge GC_{ESS} is calculated by using $P_{max,ESS}$ which is depending on the application case either $P_{PLTW,max,ESS}(i)$ (see formula 17).

$$GC_{ESS} = DR \cdot P_{max,ESS} + E_a \cdot ER \tag{17}$$

Accompanying the investment costs (CAPEX = capital expenditure) and operating costs (OPEX = operational expenditure) are calculated (see formula 18 and 19). For CAPEX and OPEX each ESS technology has economic key figures related to power and a value related to energy.

$$CAPEX = max(CAPEX_{kWh} \cdot E_{ESS,real} \wedge CAPEX_{kW} \cdot P_{ESS,real}) \tag{18}$$

$$OPEX = OPEX_{kWh} \cdot E_{ESS,real} \tag{19}$$

The payments are the savings from the reduction of grid charge ΔGC (see formula 20).

$$\Delta GC = GC - GC_{ESS} \tag{20}$$

With these parameters and the interest rate *z* the *NPV* can be calculated (see formula 21).

$$NPV = -CAPEX + \sum_{t}^{T_{ESS}} \frac{\Delta GC - OPEX}{(1+z)^t} \tag{21}$$

$ESS_{optimal}$ is selected based on the maximum *NPV* (see formula 7).

5 Case Study

A case study was conducted to evaluate the objective function of the optimization model. In this case study, a load profile of a medium-sized automobile supplier serves as an input for the comparison of four electrochemical ESS technologies. For the electrochemical *ESS* technologies the lithium battery, the lead-acid battery, the sodium battery and the redox-flow battery were parameterized with key figures to reflect the technical and economic values (see table 2).

Table 2 Average key figures of the considered ESS technologies [25]

Technical parameters	**Lead-acid battery**	**Sodium battery**	**Lithium battery**	**Redox-flow battery**
Cycle life [cycles]	852	11750	5375	11000
Service life over time [years]	10.0	15.0	17.0	17.5
Depth of discharge [%]	60	80	80	100
Efficiency [%]	81.5	76.5	93.5	74.5
Self-discharge [%/day]	0.170	0.025	0.050	0.300

Table 2 Average key figures of the considered ESS technologies [25]

Economic parameters	Lead-acid battery	Lithium battery	Sodium battery	Redox-flow battery
$CAPEX_{kWh}$ [€/kW]	222.50	465.00	160.00	475.00
$CAPEX_{kW}$ [€/kW]	345.00	680.00	150.00	1250.00
$OPEX_{kWh}$ [€/kWh]	0.46	0.42	0.45	0.46

The considered *DR*, *ER* and *PLTW* are taken from NetzeBW as it is the regional distribution system operator [26]. The industrial electricity price is set to 0.19 euros per kWh [1] and the interest rate *z* is fixed at 3% according to [3]. The most economic *ESS* technology for peak shaving and atypical grid usage is analyzed. Finally a comparison of both applications is done.

5.1 Peak shaving

For peak shaving three of four *ESS* technologies achieve a positive result. Only for the redox-flow battery no economic result can be achieved. Figure 2 shows the *NPV* of the *ESS* technologies for different ESS power sizes, which is equal to the reduction of P_{max}.

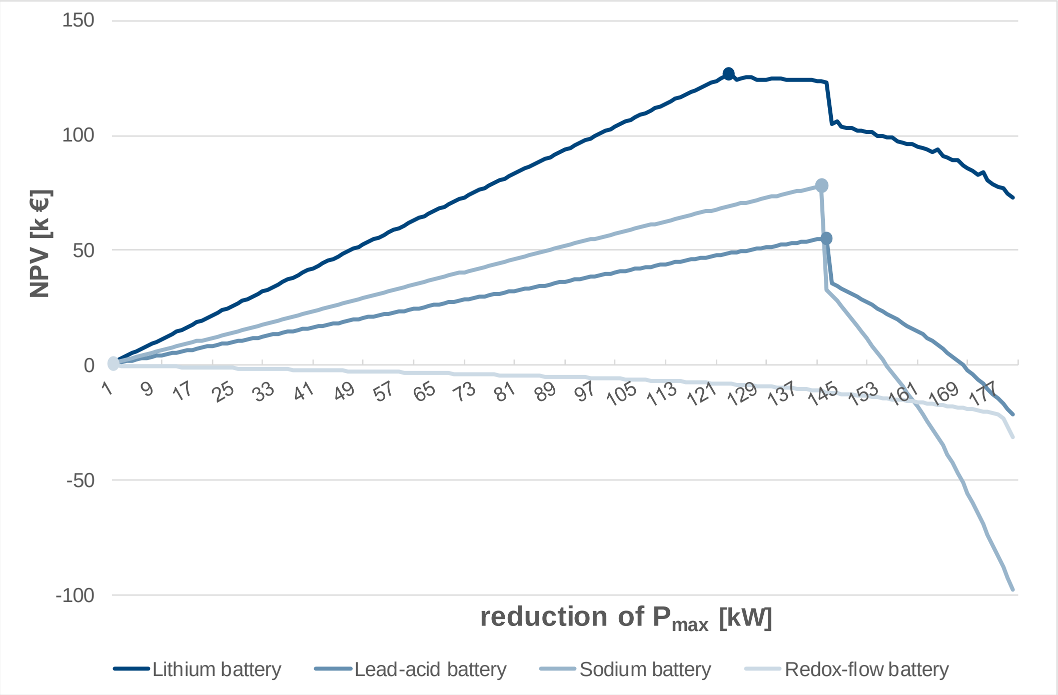


Figure 2 NPV of the energy storage technologies for the reduction of P_{max} for peak shaving

It can be seen that the *NPV* rises for the lithium, lead-acid and sodium battery to just 100 kW. The lithium battery is the most economic technology in comparison, with a maximum *NPV* at a reduction of P_{max} of 124 kW. However, it needs to be considered, that the lifetime of the *ESS* technology was used for the investment period and has an effect on the *NPV*.

5.2 Atypical grid usage

In the application of atypical grid usage, all *ESS* technologies initially have an increasing negative *NPV*. Only at a reduction of the peak in *PLTW* of 158 kW all *ESS* technologies jump into a positive *NPV* (see figure 3**Fehler! Verweisquelle konnte nicht gefunden werden.**).

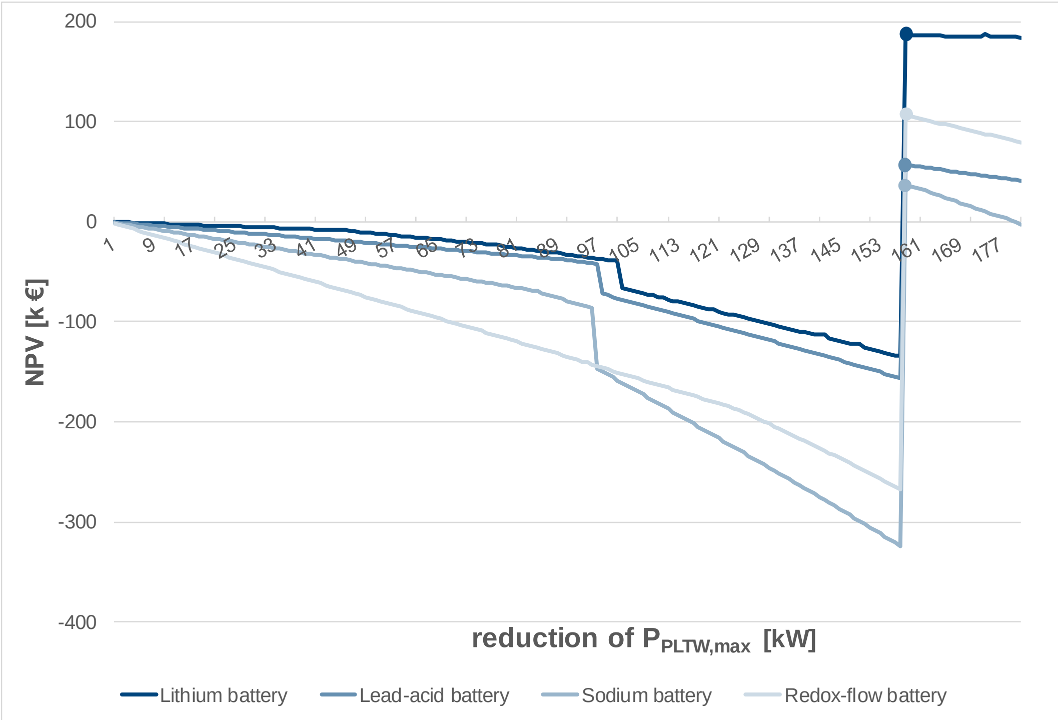


Figure 3 NPV of the energy storage technologies for the reduction of $P_{PLTW,max}$ for atypical grid usage

The *ESS* technologies has the highest *NPV* with lithium battery, followed by redox-flow battery with and lead-acid battery. This development can be explained by the previously described mechanism of atypical grid usage. Up to reducing $P_{PLTW,max}$ by 157 kW, either the requirements were not met in order to be eligible for individual *GC*. However, at 158 kW both requirements were met with all considered *ESS* technologies. Furthermore, the smallest possible *ESS* size is the economic optimum after meeting the requirements. Further savings do not compensate for the investment cost of a larger *ESS* size.

5.3 Comparison of results

In the case study for both applications the lithium battery was the most economic *ESS* technology. Table 3 compares the key figures for the most economic lithium battery.

Table 3 Comparison of the most economic lithium-battery

Results	**Peak Shaving**	**Atypcial grid usage**
Power of ESS (kW)	145.03	184.79
Capacity of ESS (kWh)	135.92	789.57
Lifetime ESS (a)	15	15
Investment costs of ESS (€)	21754.39	126331.39
Grid charge savings (%)	13.07	28.03
Net present value (€)	126798.59	188668.27

Considering the power of *ESS*, the difference between the two is relatively small. For peak shaving an *ESS* with 145.03 kW is required. For atypical grid usage the optimum is achieved with a reduction of 158 kW, which requires an *ESS* capable of 184.79 kW. When examining the capacity, larger differences between the applications can be found. For peak shaving a lithium battery with a capacity of 135.92 kWh is required. In contrast, for atypical grid usage an lithium battery with a capacity of 789.57 kWh is required. The much larger capacity can be explained as a result of the fact that the *ESS* in the *PLTW* has to bridge considerably longer periods of time to reduce peaks, because only then the requirements are met. A larger amount of energy has to be stored to compensate for all peaks in the PLTW. This larger capacity also has a distinct effect on the size of the lithium battery and the associated investment costs. However, the savings in *GC* are also more than twice as great.

According to the economic evaluation, the *NPV* for atypical grid usage is significantly higher than that for peak shaving. Over the project duration, which corresponds to the lifetime of the lithium battery, an investment in a larger *ESS* is more appropriate and the strategy of atypical grid usage should be pursued.

6 Outlook

This sizing method displays the possible optimum *ESS* size for an individual load profile with a certain scheduling strategy for different *ESS* technologies. The optimum within the model is sought by examining a static load profile with predefined prices. This profile is applied as a foundation for a consideration over the period of the lifetime of the applied *ESS* technology. For a more realistic analysis, a time series of consecutive years with different *PLTW* and varying prices should be considered. The application of reducing grid charges by peak shaving or atypical grid usage is only one application for industrial consumers. Further research can be conducted by extending the existing model with e.g. the implementation of renewable energy sources. In addition, the interest rate z has a significant impact on the *NPV*. The influence can be checked by a sensitivity analysis.

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