Specification and Assessment of Electric Energy Storage Systems based on Generic Storage Load Profile

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Abstract: Due to the increasing amount of renewable generation, storage capacities are needed. Important dimensions of every Electric Energy Storage System (EESS) that have to be determined before the installation are its nominal power and storage capacity. This contribution proposes a standardized method to specify those properties and to analyze the needs of the storage operator. In order to clarify the process the method is applied to an exemplary application. For a small industrial plant the storage dimensions are determined and important storage characteristics are calculated.

Keywords: Specification process, Storage characteristics, Sizing, Assessment, Industrial application

1 Introduction

Many countries plan to change their energy supply to a more sustainable one. Most concepts are based on renewable energies such as wind and solar. These energy sources, however, come with a major disadvantage. Their power output shows high fluctuations and is thus difficult to project. In combination with a stochastic demand for electrical energy there is a need for storage capacity. Depending on the situation or location where the Electric Energy Storage System (EESS) is installed and depending on the task it has to accomplish different storage properties are necessary. These properties, such as capacity, maximum charge and discharge power, cycle-life and energetic losses are crucial for its profitability in the field of application. Consequently these properties must be carefully determined during the project planning process. In order to determine the influences of these properties on the behavior of the system, and hence its profitability in the field of application, the standardized SDA-Methodology has been introduced [1]. It enables the ‘Specification’, the ‘Design’ and the ‘Assessment’ of different energy storage systems based on detailed performance indicators, such as self-consumption and self-supply, and combined performance indicators, such as lifecycle costs or the global-warming potential.

This contribution provides a closer look at the suggested specification process of an EESS as part of the overall SDA-Methodology. In order to demonstrate the methodology, the load profile of an industrial plant is used. The goal is to limit the maximum power consumption of the plant by smoothing the load profile. The work closes with discussion and conclusion.

2 SDA-Methodology

In [1] a general method for the development of energy storage systems is described. The exact process is displayed in Fig. 1. It consists of the three meta-steps: ‘Specification’, ‘Design’ and ‘Assessment’. Every meta-step can be divided into several sections. The specification process starts with the load profile synthesis. Here the necessary storage power profile is derived from the application load profile. Based on this the energy storage system can be dimensioned. The storage dimensions are forwarded to the design process that starts with a decision for a certain storage technology or a combination of several different storage technologies to a hybrid system. Within the block ‘Energy Storage’ the technology is designed and optimized. In order to ensure a correct and efficient operation of the system, a suitable operational strategy has to be developed. The designed storage technology is then forwarded to the step ‘Assessment’. Here the technology can be tested and evaluated based on simulations. Necessary iterations and optimization steps can then be initiated.

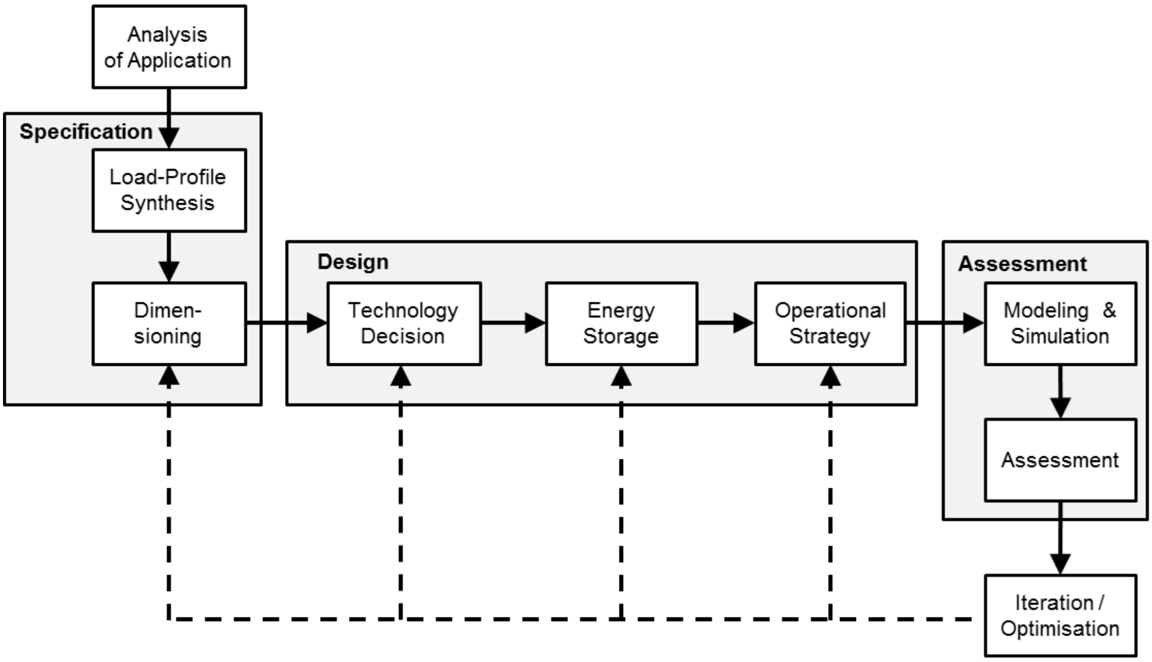

Figure 1: Process diagram of SDA-Methodology [1]

3 Specification Process

The ‘Specification’ step can be broken down into several sub-steps, as displayed in Fig. 2. The procedure starts with the measurement or simulation of the load profile of the future application. In order to reduce uncertainties within the load profile, such as high peak loads or feed-in periods, a detailed knowledge of the underlying electrical processes is necessary.

An important step within the process is to define the aim of the EESS. This can be done by defining parameters that describe the desired load profile. Combining the storage aim and the application profile leads to the synthesis of a generic application load profile that should be achieved with the EESS. It serves as a set point for the operational strategy.

The difference between the application load profile and the generic application load profile gives the generic storage profile. Most probable this profile is unbalanced meaning that the amount of chargeable energy and dischargeable energy is not equal. Without any control strategy the EESS would have to generate or dissipate energy to follow the signal. As a consequence a suitable operational strategy is needed to balance the storage profile. This rudimentary operational strategy must not be confused with the meta-step within the SDA methodology. It is just a first draft of the future operational strategy that is necessary to successfully complete the 'Specification' process.

Mathematically the process of storing energy correlates to the integration of the charge and discharge power over time. Since the energy content of an EESS cannot be less than zero, the energy content at the start of the study can distort the results dramatically. To overcome this influence a boundary free EESS is simulated for the specification process, its energy content can be positive as well as negative.

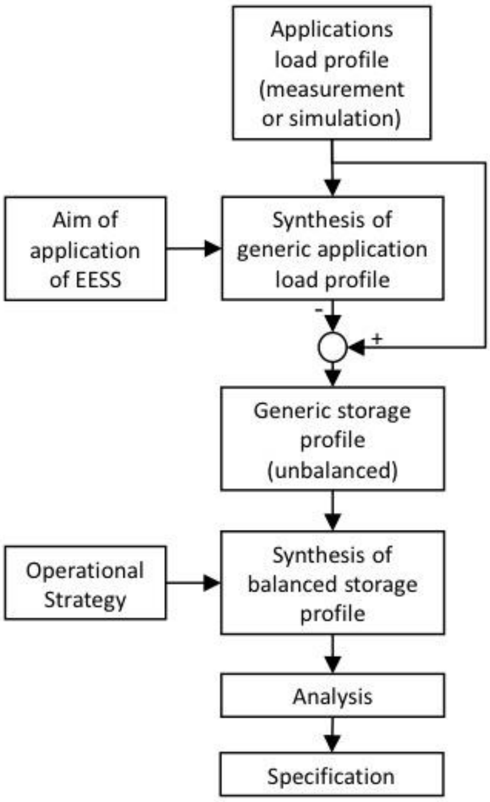

Figure 2: Specifictaion process within the SDA-Methodology

Depending on the field of application of the energy storage system different requirements can result from the 'Specification'. Indispensable for the design process, however, is the nominal electrical power and the usable storage capacity. Other requirements such as certain efficiencies, cycle life, safety, total costs or specific energy and power densities can be defined by the process and have to be fulfilled in the design process. These criteria also serve as basis for the 'Assessment'.

The 'Specification' can be seen as an in-depth analysis of the field of application and the needs of the future storage operator. It should thus be conducted very thoroughly. In many academic discussions and practical applications this step is insufficiently considered leading to inefficient as well as over- or undersized EESS.

4 Application Example: Industrial Plant

The described ‘Specification’ method is applied to an exemplary small industrial plant. The sub-steps described in Fig. 2 are applied to this example and the results are analyzed. As mentioned before the main goal is to find suitable storage dimensions and to define optimization and assessment criteria.

4.1 Description of the field of application

An industrial plant consisting of a process chain with four different steps is analyzed. The goal of the process is to manufacture one metal component part of a system. Such a plant is currently planned and constructed within the research project ‘ETA-Fabrik’ at TU Darmstadt.[1]

The underlying process chain consists of the four steps:

- lathing,
- grinding,
- cleaning,
- tempering.

Every machine shows a typical load profile as one part or several parts at a time (cleaning, tempering) is/are processed. As the production is designed as a flow process the electrical load profiles of the different machines superimpose to a plant load profile. Depending on the set-up time of the different machines the plant load profile can vary. On the one hand extremely high power peaks are possible when several machine peaks occur at the same time. On the other hand very low power consumption can be measured when several set-up times coincide.

With the application of an EESS this plant load profile shall be smoothened in order to reach two goals. One goal is to relive the electricity grid to which the industrial plant is connected to. The other is to reduce the power connection cost.

The application load profile (here the plant load profile) was synthesized from measured machine load profiles. As can be seen in Fig. 3 the machine load profiles of one machine are connected by normally distributed set-up times ($t_{set\text{-}up}$) where only the stand-by power of the machines has to be provided.

[1] For more information visit: www.eta-fabrik.tu-darmstadt.de.

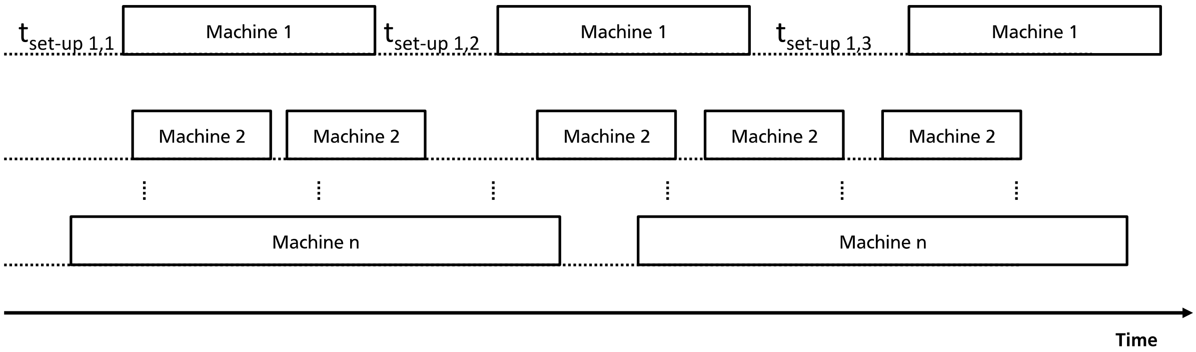

Figure 3: Synthesis of the plant load profile from machine load profiles with random set-up times

One resulting plant load profile is shown in Fig. 4. The length of the profile is determined by the length of one shift of about 8 hours. As mentioned before the aim of the EESS is to smoothen the load profile and thus reduce the volatility of the profile. A low-pass filter can perform this task but leads to a phase delay of the filtered signal. The field of digital signal processing provides methods to overcome this drawback. One possibility is to use a zero-phase digital filter to generate the generic load profile. Such filters process the input data in both, the forward and reverse direction [2]. Since the full load profile has to be known at the time of filtering this method cannot be used for real time applications. For the suggested procedure no online capabilities are necessary because the 'Specification' process is performed offline and before installing the EESS. Moreover the simulated EESS is assumed to be ideal without any energetic losses or phase delay. This approach allows for a technology neutral specification of necessary storage characteristics.

Fig. 4 also shows the generic load profile resulting from the low-pass filtering process. A first-order filter (PT1) with a time constant of T=120 min is used. Caused by double filter process double the slope compared to a normal PT1 filter is obtained.

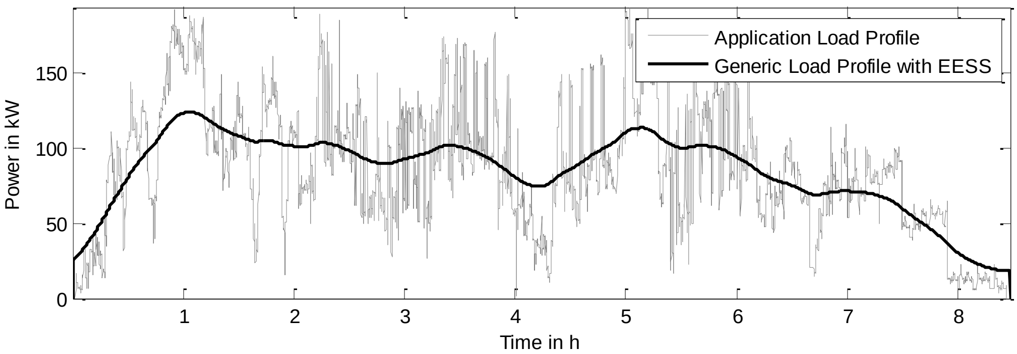

Figure 4: Application load profile and generic load profile with EESS

4.2 Unbalanced and balanced storage profile

With both, the application and genric load profile defined the unbalanced storage profile is calculated. The task of the EESS is to manipulate the application load profile (P_{app}) in a way that the generic load profile ($P_{load,gen}$) results. In order to achieve this goal the EESS has to provide the positive and negative power difference between the two profiles. The generic storage profile ($P_{st,gen,ub}$) can thus be described by the following relation:

$$P_{st,gen,ub} = P_{load,gen} - P_{app} \quad (1)$$

The resulting generic storage profile for the industrial plant is displayed in Fig. 5. As mentioned before, the process of storing energy can be described as integrating the charge and discharge storage power over time. For a discrete power signal P_t with a power information every time step delta_t the stored energy E_st can be calculated as follows:

$$E_{st}(\tau) = \sum_{t=1}^{\tau} P_t \cdot \Delta t \quad (2)$$

In order to eliminate the influence of the stored energy at t=0, the EESS is simulated as a boundary free storage meaning that the energy content can be positive as well as negative. Fig. 5 shows the generic storage profile as well as the unbalanced energy profile resulting from the relation in Equation 2.

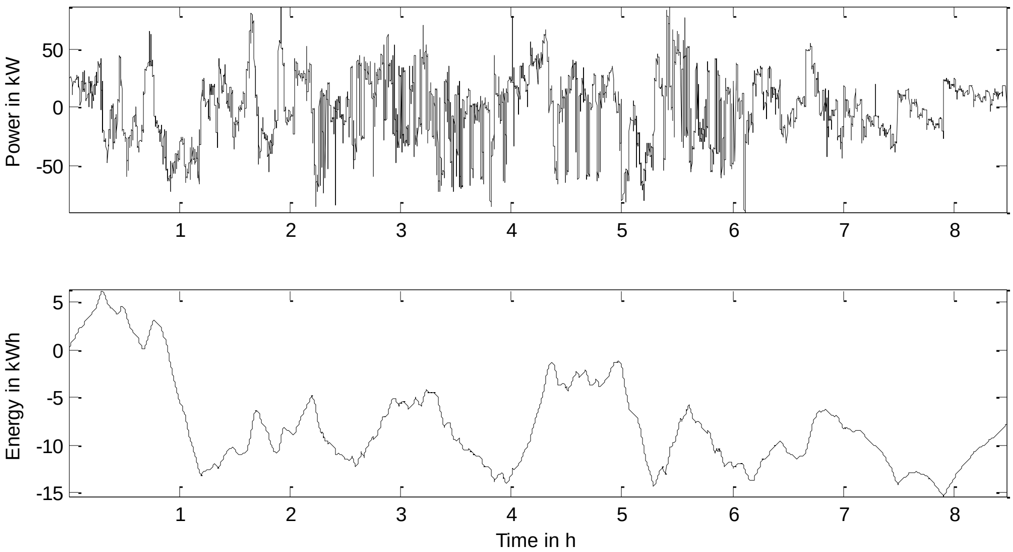

Figure 5: Generic storage profile (top) and resulting unbalanced storage energy profile (bottom)

When analyzing the unbalanced energy profile one observes that most of the time the energy lies below zero. This is caused by the fact that at the beginning the profile shows an energy deficit (around 0.8 and 1.5 h). This leads to discharge of the EESS. The rest of the profile is relatively steady with a mean energy level of around -10 kWh. If one would specify an EESS based on this information a large storage capacity of about 20 kWh would be necessary. Depending on the field of application and the load profile the energy could theoretically alternate between positive and negative infinity.

The next step in the ‘Specification’ (Fig. 2) is to determine the rudimentary operational strategy. An operational strategy can be set up using a cascaded controller. The inner cascade controls the power of the EESS, the outer cascade controls its state of charge (SoC) [3]. In this step especially the SoC controller is necessary to influence the stored energy. For this example a linear SoC controller with a small proportional gain is used. Fig. 6 shows the comparison of the energy profiles with (balanced) and without (unbalanced) operational strategy.

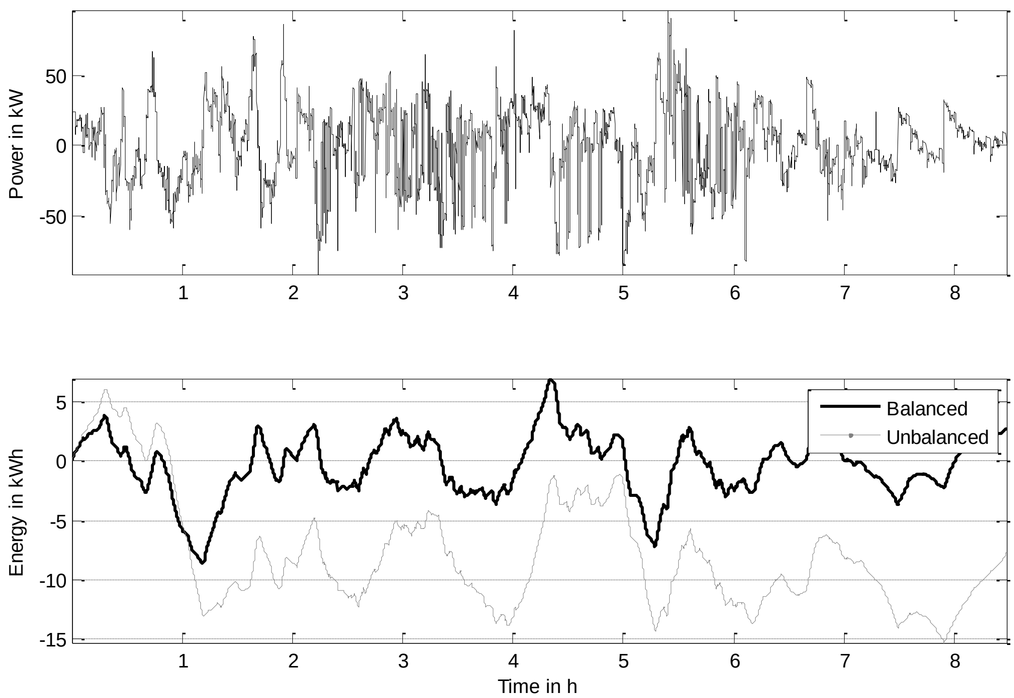

Figure 6: Balanced storage power profile (top) and
comparison of the balanced and unbalanced storage energy profile (bottom)

Comparing the balanced and unbalanced energy profile one observes that the characteristic shape of the two profiles is the same. What changes is the mean stored energy. Whereas the energy of the unbalanced EESS drops to -10 kWh after approx. one hour, the energy of the balanced EESS alternates around zero. It is immediately visible that the balanced EESS requires significantly less storage capacity as the energy profile ranges between +7 and -8 kWh.

4.3 Analysis and Specification

The last two steps of the 'Specification' consist of a detailed analysis and the actual specification, thus the determination of the nominal power and maximum capacity of the EESS. Moreover additional storage requirements can be gained from the analysis such as information about the type of storage necessary or expected savings.

The main part of the analysis consists of a frequency analysis. In this regard the power or energy profile is plotted as histogram. Fig. 7 shows the power distribution of the balanced storage profile.

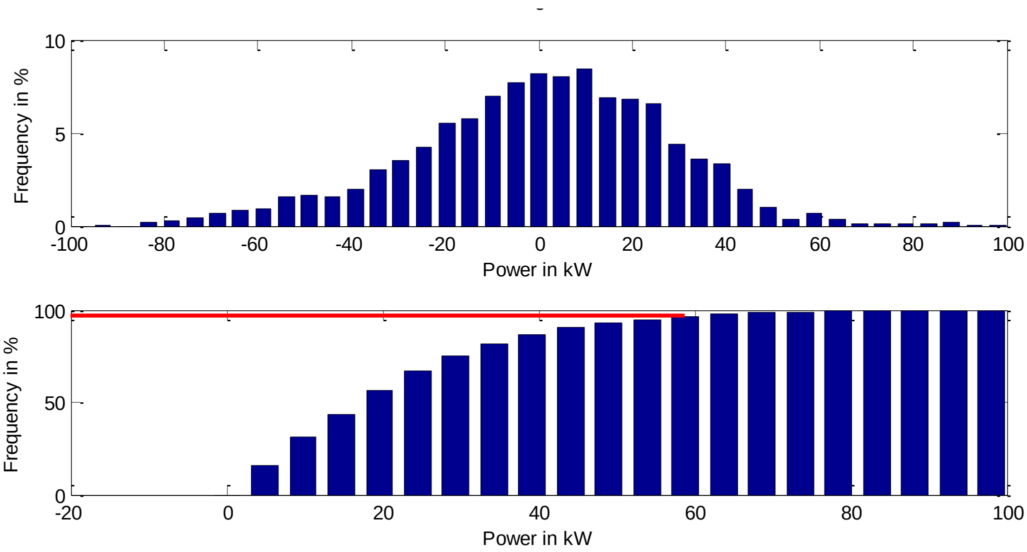

Figure 7: Power distribution of the balanced storage profile
(top: relative frequency, bottom: cumulated absolut relative frequency)

The top graph shows the relative frequencies of the power of the EESS within the simulated profile. Positive and negative values can be observed corresponding to charging and discharging processes respectively. The bottom graph shows the unsigned cumulated relative frequencies adjusted for the zero power interval. This illustration can serve as dimensioning tool for the power dimension. If for example 96% of the power states should be fully compensated, a nominal power of the EESS of 59 kW is necessary (red line).

A similar approach is used to determine the capacity of the EESS. Fig. 8 shows the frequencies of the balanced energy profile. The relative frequencies (top) and the cumulated relative frequencies for positive and negative energies (bottom) are displayed.

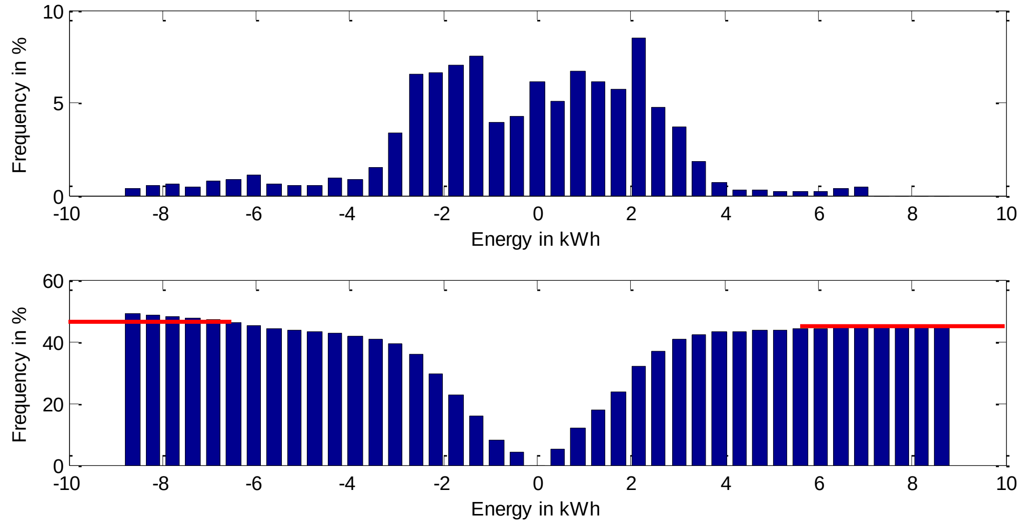

Figure 8: Energy distribution of the balanced storage profile
(top: relative frequency, bottom: cumulated relative frequency)

The cumulated relative frequencies can be used as a tool to find the necessary storage capacity of the EESS. In order to determine the capacity the positive and negative frequencies and the magnitudes of the energies have to be aggregated. 90.2% of the energy demand can be satisfied with an EESS of 12.1 kWh. These numbers are obtained when summing up the magnitudes of the positive (5.62 kWh) and negative (6.48 kWh) energies as well as their frequencies (positive: 44 %, negative: 46.2 %). For a 100% coverage a storage capacity of 17.28 kWh would be necessary. The decision has to be made based on cost-benefit calculations. Depending on the field of application the incremental cost for one additional unit of storage capacity has to be compensated by its benefits.

Besides the main properties other information can be obtained from the balanced storage profile, such as the power ramp rate, the number of load reversals or the number of load cycles (see Table 1).

Table 1: Balanced storage profile characteristics for 8 h and a whole year

	Per Profile (≈8 h)	**Per Year (200 workdays)**
Power ramp rate	71.8 kW/s	71.8 kW/s
Number of load reversals	17,415	3,483,000
Number of load cycles (100% DoD and 100 % Capacity)	10.7	2,133

From these selected values indications of the suitable storage technology can be derived. For the described industrial plant the calculated power ramp rate of 71.8 indicates that this application is highly dynamic. Also the number of load reversals of 17,415 within one shift of 8 h shows that many partial cycles are required. The number of full load cycles at full capacity (17.28 kWh) within the profile lies at 10.7. For a full year with 200 workdays this leads to more than 2,100 cycles per year. Most currently available chemical energy storage systems cannot fulfill these requirements. For this application kinetic energy storage systems or a combination of different storage technologies (hybrid energy storage) would be suitable.

5 Discussion and Conclusion

At the beginning of this contribution the SDA methodology has been described. One part of this method is the ‘Specification’ process. Within this process the necessary electrical power, the capacity as well as other properties of the EESS are determined from the application load profile. Further the projection of the energetic losses resulting from the generic storage load profile, allows for the estimation of the energy costs resulting from the operation of the EESS. Together with the asset costs this enables the calculation of the lifecycle costs. Different kinds of EESSs can be compared on this basis. Accordingly the presented analytical method for the specification of EESS allows for a technology neutral definition and assessment of the requirements of a projected EESS. It gives a distinct path and makes the specification process reproducible.

In order to apply this method a detailed knowledge of the field of application and of the intended goals is necessary. Moreover extensive load measurements or verified simulation models of the application are crucial in order to have a reliable data basis for the calculations. A generic storage profile can only be derived from the application profile if the goals of the storage installation are distinct in detail. The generic storage profile is the basis for all further steps.

Every measurement or simulation of application data is subjected to uncertainties. These uncertainties can be reduced by very long measurements or simulation times but they can never be completely eliminated. Therefore methods to cope with those risks have to be implemented in the 'Specification' process but also in future operational strategies. Suitable methods could be model-based approaches or robust control.

Not only uncertainties in the field of application influence the results of the design process for an EESS. Also the method itself dramatically affects the results. Therefore standardized specification and design as well as assessment methods should be introduced. Another step towards comparable results between different fields of application or between different storage alternatives would be to agree on standardized load profiles for energy storage systems. These could evaluate storage technologies on a standardized basis and would make technology decisions understandable and reproducible.

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