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Main characteristics to consider in a BESS during the design process.

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***Abstract*—This paper presents the most important characteristics and dimensional criteria when specifying a Battery Energy Storage System (BESS). Rated energy and power capacity values and their meaning in different measurement points are discussed. Both system and individual subsystem efficiency in different operation points is considered. Battery lifetime definitions are presented and their relationship to the above characteristics discussed. Finally, an example design process with a specification is presented.**

Keywords—BESS, dimensioning, sizing, battery, lithium-ion, li-ion, energy storage system, ESS, battery economics, degradation, energy capacity, efficiency, Round-Trip Efficiency

NOMENCLATURE

BESS	Battery Energy Storage System
BMS	Battery Management System
BoL	Beginning of Life
BoP	Balance of Plant
DoD	Depth of Discharge
EoL	End of Life
HVAC	Heating, Ventilation and Air Conditioning
RFQ	Request for Quote
PCS	Power Conversion System
PoC	Point of Connection
SoC	State of Charge
SoH	State of Health
RTE	Round-Trip Efficiency

I. INTRODUCTION

In recent years the lithium-ion -based Battery Energy Storage System (BESS) market has grown fast globally and expected to grow increasingly fast [1], especially in countries with existing incentive structures in line with the technical benefits of such systems.

The purchasing process for BESS often includes technical specifications, outlined in the Request for Quote (RFQ) that the tenderer must respond to so that the buyer can compare offers from various tenderers in how well the tenderers meet said specifications. The present paper discusses BESSs with the focus on lithium-ion technology.

BESS design for a certain application is an iterative process. The physical design of the system is interconnected to financial benefits that may be gained from a system of specific characteristics, especially energy capacity and output power. The lifetime of the battery, for example, is directly in relation to the investment period. Since the lifetime of a battery with a specific use profile depends on its energy capacity, which directly correlates with the investment cost, it is reasonable to consider all these variables holistically.

The authors of this paper have been party to various purchasing processes globally and seen different ways of specifying characteristic values for BESSs, and the objective of this paper is to draw from this experience to help the readers – and actors in this business - to understand the sizing process of a BESS and its related terminology.

II. TYPICAL COMPOSITION OF A BESS

The BESS is built from the components and subsystems listed in Table I. Each of these components influence the discussion in later chapters.

Table I. MAIN COMPONENTS AND SUBSYSTEMS OF A BESS

Component or subsystem	Notes
Battery	Batteries are usually built by stacking hermetically sealed battery cells to modules which are then stacked into series-connected battery “racks” which form an individual mechanical building block. A complete battery system is built by installing these racks in parallel in several DC circuits.
Power Conversion System (PCS)	Consists of one or more bidirectional AC/DC converters capable of managing the charging and discharging processes. The converters are controlled by a centralized control system. The inverters are connected to a low voltage AC bus and directly to the same DC bus with the batteries.
Transformer	Step-up transformers are required to connect the PCS converters to medium voltage, which is typical in installations of various megawatts. The PCS converters’ contractual connection point can also be on low voltage, where the transformer is not needed.
Cooling system	HVAC or liquid-cooling chiller system is cooling the batteries and/or PCS converters. During high charge/discharge powers (when batteries have their maximum heat emissions), the auxiliary power consumption especially to convey the heat away from the batteries can be the dominating auxiliary power consumer.
Switchgear and fusing	Depending on the protective requirements and the design, fusing can be found from individual battery racks, DC buses, individual converters and AC low voltage buses. The step-up transformers are connected to a medium voltage switchgear, which can provide one incoming feeder for the whole

	system.
Battery Management System (BMS)	The battery management system is usually distributed into various subsystems: there is monitoring logic in the battery cell level, battery module level and typically on the rack level. These subsystems are coordinated by a main BMS which typically acts as the single communication interface for other systems.
Main control system	The main control system, sometimes referred to as Balance of Plant (BoP) system is the highest level of hierarchy in the local control. It controls the array of PCS converters, carries out all operation algorithms and works as an interface to the BMS (Battery Management System).

The most important thing to understand in the above table is that these components each consume electricity either in the main circuit or as an auxiliary system which affects the later definitions for efficiency, energy capacity etc.

Specifying rated values for a BESS cannot be done generically, as the composition of a specific system affects the possible ranges for the rated values, as we will see in later Chapters.

III. BESS RATED VALUES

A. *The importance of the definitions*

The definitions used in the present paper are based on the IEC standard [1], later referred to as *IEC standard*, which has made an effort to standardize the definitions of the most important performance characteristics related to BESS specifications.

The measurement methods defined in the IEC standard are designed in a manner that BESSs of different compositions (made by different manufacturers or integrators) can be compared with each other on equal grounds, because the point of measurement, operation point of the system etc. are all fixed part of the definitions.

For comparability between different solutions, the definition of the rated values and the measurement methods by which they are verified must be explicit and leave no room for interpretation.

B. *Energy capacity*

The energy capacity of a BESS is typically defined in MWh, but without defining the measurement point, and moreover, the stage of the lifecycle of the battery at the time of the measurement for the energy capacity, the interpretation can be somewhat arbitrary. This creates confusion in tender processes, as it is common knowledge that the proportionally biggest cost component in a given BESS are the lithium-ion batteries, and therefore different BESS offers' pricing is often compared with a price / MWh ratio. To do this kind of comparison, the measurement point and time need to be fixed as explained in the following.

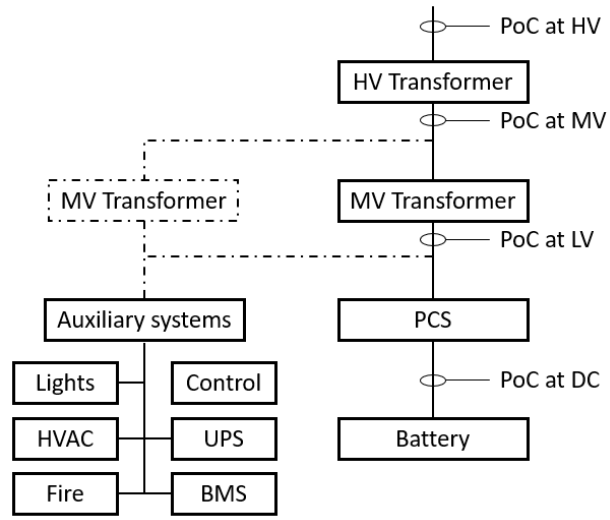

Fig. 1. BESS main circuit (right side of the Figure) and auxiliary circuit (left side of the Figure). The measurement points discussed below are marked in the above Figure.

Fig. 1 depicts the typical components connected in series and parallel between the AC network Point of Connection (PoC) of a BESS. The components on the right side of the Figure can be considered the main circuit of the BESS, whereas the subcomponents on the left side can be considered auxiliary systems. The definition of the PoC can be in various points of the network depending on the connection voltage, utility requirements and the agreement between the supplier and buyer of the BESS; therefore, there is no single PoC applicable to every project and it needs to be specified per system.

Depending on the PoC, there are various components that draw electrical losses or auxiliary power between the battery terminals in the DC system and the PoC. From the battery user's point of view, if a certain energy capacity needs to be dischargeable at the PoC in AC network, the capacity in the batteries measured from the DC terminals needs to be higher to both feed the required energy to the PoC and said losses and auxiliary power use.

In another words, if the PoC and the measurement point are not clearly defined, there is room for interpretation in the energy capacity of the BESS. The highest energy capacity that can be measured in any given BESS is the *nameplate energy capacity* of the batteries; this value is not affected by the composition of the components between the battery terminals and the PoC.

If the energy capacity is measured from the batteries terminals when the battery is discharged from full to empty in a closed circuit, the measurement is referred to as *installed energy capacity* in this paper and is slightly lower than the nameplate capacity, more specifically by a coefficient that is typically between 0.90 to 0.98. The reduction in capacity by this factor can be considered as the internal resistive losses of the battery and are dependent on the charging/discharging current magnitude. This energy is dischargeable from the battery terminals in DC, but not yet usable for the customer as it needs to be transformed to AC.

The energy capacity available in the PoC, after all the losses in the discharging path, is referred to as *usable energy capacity* or *actual energy capacity* (terminology used by the IEC standard). Confusing the above-mentioned values, measured at distinctly different points, can cause comparability issues and also lead to a false sizing of the system. In practice this can mean up to 10 % difference in sizing and cost.

All energy capacities should be defined within a given State of Charge (SoC) range, which can sometimes be limited either due to guarantee-related reasons, batteries' technical properties or to adhere to certain limitations that the PCS converters have. From a practical point of view, if there are limitations to the use of the nameplate energy capacity, they should be clearly stated in the BESS description.

C. Power rating

Similarly to the energy capacity, the power rating of a BESS depends on the measurement point. In discharging the battery, some of the total available DC power, measured from the batteries' terminals, is used to feed the losses discussed above in discharge direction. On the other hand, the rated AC charge power may be higher than the rated DC charge power because some of the power measured at the charging point will depend on the losses on the way to the battery terminals.

The most clear terminology would be to define the power simply by its measurement point and to use terminology such as *rated DC power at the battery terminals.* There is no standard term for the above known to the authors.

The equivalent term for the AC power would be *the rated AC power at the PoC* or *input and output power*, respectively, as defined in the IEC standard.

The power rating for charge and discharge directions may be different in the DC circuit, but because of the losses in between the AC and DC circuits, the theoretical charge and discharge powers are always different, if not limited by the converter rated power or current. The discharge power can always be assumed to be lower, and therefore, if a symmetrical charge and discharge power is desired, it should be the dimensioning limiting rating. The IEC standard uses separate definitions for *input power* and *output power* to allow for the asymmetry, but this paper considers this power as a symmetrical characteristic.

It is important to note that the available power is not necessarily limited by the batteries' rated power. Since all of the power flows through the PCS, it can effectively limit the available power regardless of what is the battery's rating, and this can be intentional, depending on the desired relation of the power and energy of the system and how well available battery components can be directly designed based on such relation criterion.

The power rating of a BESS can also be defined in different timescales, and this is recognized in the IEC standard by the opportunity to specify a duration for the specific output or input power. For most of the components in the power path from batteries to the PoC, the underlying reason for limiting the power flow is based on thermal restrictions, but different subsystems have different thermal time constants (consider the difference between the batteries, IGBTs in the PCS converters and transformers, for example).

This might mean that even if the same batteries could be rated for a momentary short time charging and discharging power that is higher than the rated continuous power, the PCS might have to be designed for higher rating to actually take advantage of this. Often the battery applications are such that the system is designed for a continuous and symmetrical rating, but in some applications the possibility to use shorter power can yield an economical advantage in terms of the available power per price.

D. Power-energy relationship

The power-to-energy ratio is important to be considered with the design. The requirements for this ratio typically arise from the actual use case of a BESS, for example due to economical utility.

Typical measure for the power-to-energy ratio is C or P-rate that is referred to battery energy capacity vs. discharge/charge rate.

C-rate refers to battery's rate in constant current charge/discharge rate vs. its capacity whereas P-rate, a term commonly used by battery manufacturers, is the battery's rate in constant power charge/discharge rate vs. its capacity. Both are used commonly and often mixed with each other, even though they are not exactly interchangeable. C-rate is defined in Ampere-hours and therefore when used when discussing energy and power, it contains a dimensional error. Regardless, it is worthwhile to note that in practice in BESS markets, C-rate is often interpreted as the relationship of energy and power. In this paper they are used interchangeably.

Mostly used batteries for BESS applications available are rated at between 0.5…2 C or P (30-minute to 2-hour storage duration). While other ratings may also be available, they are mostly marginal. The choices made during the design and manufacturing of the battery result in the desired rating of the storage device.

As an example of the rate of the battery, 1 P means that the power and energy are equal and are typically referred to as 1-hour battery. This kind of battery can be used at 1-hour rate (i.e. 1 MW power and 1 MWh energy) or lower, but not any higher power.

Similarly, 0.5 P means that the maximum power is half of the battery capacity, and such battery can be used at 2-hour rate (i.e. 0.5 MW power and 1 MWh energy) but not any higher.

Essentially this means that selecting a correct rated battery for the application is crucial. Using non-optimal battery rating may lead to oversizing of energy or power and to additional cost, because the price per MWh is different for different C-rates.

For example, the battery selection for 1 MW of power and 1 MWh of capacity should normally lead to using 1 P-rated battery. If one, however, would choose to use 0.5 P-rated battery, the design of the battery size should be doubled to fulfill the required power rating (2 x 0.5 MW/1 MWh = 1 MW/2 MWh). By this the battery would meet the design criterion of the power but would have double the nameplate energy capacity and nearly double the cost.

It is equally important to understand that in the power-energy relationship, the specifications may not be made with an arbitrary precision. A system of an output power of 1000 kW and defined energy capacity of 50 kWh cannot be built exactly to specification because batteries with such a C-rate are not commercially available.

The commercially available batteries have a defined C-rate and power and energy characteristics within a specific mechanical integration (battery rack). For example, let's consider having a specification of a battery system of 1000 kW output power and 900 kWh of energy (measured from the DC bus only). If we are building the system from battery racks of 300 kWh nameplate capacity and 300 kW available power (1 C-rate), respectively, the practical solution would consist of four racks and therefore have specified values of 1200 kW of output power and 1200 kWh of energy capacity, and therefore exceed the specified values.

Lower C-rates for a complete system can be achieved without changing the battery (that has a higher C-rate itself), since ultimately the power available at the PoC is limited by the PCS rated power. Therefore, if the power available at the batteries is not required, the rating of the complete system can be reached simply by limiting the PCS rated power.

E. *Efficiency and Round-Trip Efficiency*

From considerations above, it can be deduced that the efficiency of a BESS is not only dependent on the used components' efficiency, but also the composition and design of the components between the batteries' terminals and the PoC.

Above we used the terms *nameplate energy capacity* and *usable energy capacity* which are related to this chain of components. Fig. 2 illustrates on how the nameplate energy capacity is broken down into usable energy and unusable energy that is feeding the system losses.

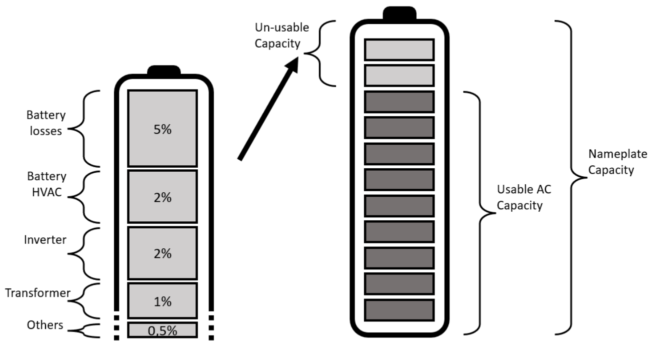

Fig. 2. BESS energy capacity loss composition with typical percentages, when the system is used at the rated power of the batteries. The percentages would be different in a different operation point.

The efficiency of a BESS is always operation point dependent and a design question, because not all of the components in the main circuit (or the auxiliary circuit) are necessarily designed to be used at their fully rated power, where efficiency is defined based on the IEC standard. Moreover, some losses (such as the transformer no-load losses) are fixed regardless of the power used by the battery, and therefore even at 0 power some losses are present. Table II. breaks down the most important components and subsystems that affect the system efficiency and their behavior in relation to the loading.

Table II. TYPICAL LOSSES FOR DIFFERENT SUBSYSTEMS

Component or subsystem	Typical efficiency range at the rated power	Behavior of losses as a function of the output power
Battery	Typical 93-98%	Losses are mostly resistive and thus exponential. Batteries' losses are considerable smaller if measured at lower than the rated power. Adding more batteries in parallel than necessary can improve the efficiency due to more parallel resistance paths, but adds to the overall cost of the system.
PCS converters	Typical 97-98%	Nearly linear losses with <0,5% fixed losses (no-load losses).
Transformer	99%	Nearly linear losses with ~0,1% fixed losses (no-load losses).
Cooling systems	Coefficient of performance typically 2.5-3.5.	Nearly linear. There is however delay in when these losses materialize compared to when a higher output power is switched on because of different thermal time constants of the cooling media or the cooled material (for example PCS IGBTs vs. battery structure).
Other auxiliary loads	Typically 0.5%	Consists of auxiliary power use that can be assumed to be a fixed load.

Fig. 3 illustrates how the operation point affects the total losses as a function of the rated power of a BESS in an example system.

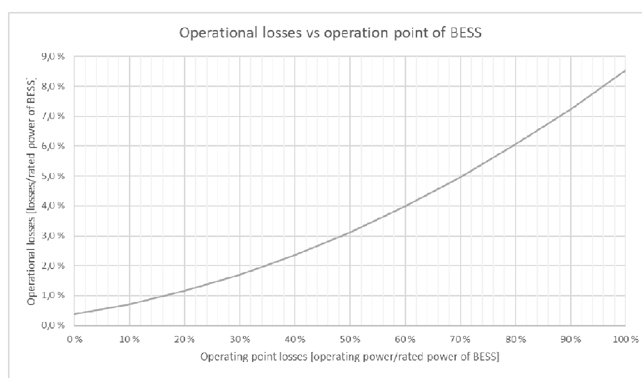

Fig. 3. BESS operational system modeled for an example system. The nature of the curve would depend on the design of a given system and needs to be modeled separately considering the components' characteristics.

Considering the above, it can be deduced that the efficiency can be affected by design, because each component could be sized according to the desired efficiency. For example, if we consider that the internal losses of the batteries can be modeled as resistive losses and therefore have a quadratic relation to the output power, the efficiency of the system can be improved by installing more batteries to the BESS of the same power rating, because the proportional power that each battery rack experiences would be smaller. At the same time, more parallel batteries mean more parallel resistance paths in the DC circuit, lowering the total resistance and therefore also improving the efficiency.

Often BESS efficiency is measured by *Round-Trip Efficiency* (RTE). The authors have noted that often this term is used (and a target for it has been given) without a specific definition. This is problematic, because without a clear definition of how it is measured, it leaves room for interpretation.

The IEC standard defines RTE to be measured in a specific PoC by at least two repeated energy measurements of which the average is considered as the result.

The test is carried out with the rated power of the system – so that for example all auxiliary power losses and other losses are at their maximum and thus give a comparable result. The test is carried out so that before starting, the system is discharged and charged once full. This is important for comparability - the temperature in the batteries and other components has stabilized to an operational level so that, for example, the cooling system will consume its maximum power at the rated system power instead of kicking in later in the measurement period.

After the initial discharge-charge cycle, the energy measurement recording starts at the PoC, and the system is fully charged and discharged in two or more cycles. The difference between the total charged and discharged energy at the PoC defines the roundtrip efficiency, the idea simplified by the below formula:

$$RTE(\%) = \frac{Total\ discharged\ energy\ at\ the\ Po}{Total\ charged\ energy\ at\ the\ PoC} \quad (1)$$

where *RTE* is the Round-Trip Efficiency of the system over one charge-discharge cycle.

Even though the measurement point is defined only in one place for the main power circuit only and the auxiliary power feeder might be elsewhere, it is explicitly stated in the standard that the auxiliary power energy consumption during the charge and discharge cycle must be taken into account in the result for comparability – if it has a separate physical feeder, it has to be measured separately and subtracted from the discharged energy and added to the charged energy (which are measured at the main power circuit feeder, respectively).

The above definition has some important implications. When the charge and discharge cycles have to be done with the rated power of the system, the results are comparable with different design choices because all the losses in the system and auxiliary energy use have same conservative value. If the measurement could be taken with an arbitrary power, the RTE results would be different for previously considered reasons.

When the measurement method is defined in the above manner, it is not possible to start the measurement in a situation where the batteries and other components are in an idle temperature, in which situation it would be possible to make the cooling system power use look better than in practice.

In general, defining the efficiency in terms of energy instead of instantaneous power gives a more realistic albeit conservative account of the losses within a complete charge and discharge cycle with the rated power. As seen in the previous analysis, the efficiency of the system is operation point dependent, and therefore instantaneous efficiency would possibly give the wrong idea.

Even though RTE is a good measure for comparability – when standard definitions and measurement methodology are used – it has limited practical value in evaluating actual losses in a business case for an ESS. The RTE test is based on the idea of charging and discharging the ESS continuously with the rated power, but when using the ESS in a realistic application, this rarely is the case.

For example, in a frequency regulation application, as exemplified by Fig. 4, the output power is on average much lower than the rated power, which means that the losses on average are lower as well.

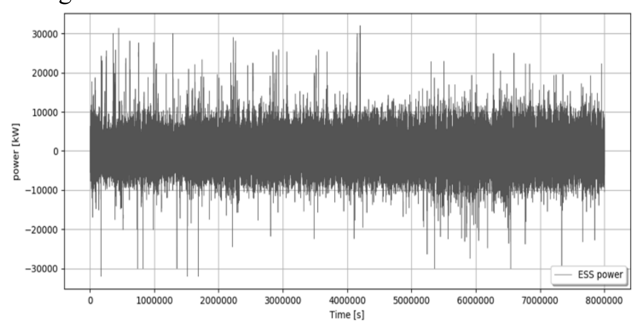

Fig. 4. Example power profile (positive active power denoting charging power and negative discharging power) in a typical frequency regulation application. The rated power in this example would be 30000kW, but on average the power is much lower.

Therefore, to reach a realistic estimation of the ESS losses for a particular business case, the losses should be simulated by using the case specific power profile. RTE would give too conservative an estimation for losses, as it implies that the system is used at the rated power. Moreover, if a specific target for RTE is given without considering the specifications holistically, it can lead to nonoptimal designs. As discussed before, increasing the number of parallel battery racks can improve efficiency, but at a very high cost compared to the achievable gains.

Regardless, RTE is a useful measure to compare the efficiencies of different BESS designs with the same criteria, if only one number is desired to use for the comparison for simplicity's sake.

IV. LIFETIME CONSIDERATIONS

The previous chapters defined the importance of the definition of the electrical measurement points to be able to devise a clear specification. The efficiency of the system was also examined carefully. This chapter is concerned with the definition of the above characteristics during the lifetime of the system.

A. Lithium-ion battery degradation

Lithium-ion battery degradation happens essentially with two modes: calendar degradation and cyclical degradation. Calendar degradation is passive and happens simply over time because of passive chemical reactions inside the battery cells.

The key factors affecting a lithium-ion battery's calendar life are the temperature and the SoC. Both factors are speeding the passive chemical processes taking place inside the battery that degrade the battery over time. Controlling the ambient temperature well both during storage and transportation and with cooling systems in operational use both are important to achieve long battery life. The significance of the SoC is through its dependence on the battery terminal voltage. On higher SoC, the terminal voltage of the battery is higher which means a higher potential between the battery anode and cathode in the cell itself. Higher potential boosts passive side reactions inside the battery that cause it to degrade over time. This implies that when the battery is not in use but in idle or storage conditions, maintaining it at a lower SoC, e.g. around 20%, helps optimize the lifetime. [3]

Of these two modes of degradation, the cyclical degradation is typically more dominant in practical use and therefore the use of the battery correlates to its useful lifetime stronger than simply calendar aging [4]. The mechanisms by which the battery degrades during the charge and discharge cycles are complex. The aging is correlated to the C-rate by which the battery is used, the average Depth of Discharge (DoD) during cycling and the temperature generated in the charging or discharging process [3]. The DoD's influence The DoD's influence is especially complex and nonlinear; the depth of a discharge cycle itself (for example a discharge from 80% SoC to 20% SoC means 60% DoD), but the absolute levels of the state of charge affect as well [4].

Although the aging mechanisms are complex, the discharge and charge -cycles themselves physically mean energy flow (through charge and discharge current) between the battery and the network it is connected to, and therefore we can correlate this flow of energy to its aging. If we conclude that the cycling has a dominant effect on the battery aging and that even though the specific conditions of charging and discharging the battery have an effect to how rapidly the degradation happens, we can also conclude that the charging and discharging itself, i.e. the energy flow is the root cause of ageing.

Therefore, one useful way to analyze battery degrading is the *cumulative energy flow* through the battery in MWh during its utility life. This method of analysis omits the effect of the exact C-rate and specific DoD during the battery use, and therefore has limited accuracy. Regardless, it is especially useful considering practical ESS applications where the planned power profile of a BESS in a specific type of application (such as in Fig. 4) needs to be interpreted as battery charge and discharge cycles to evaluate the battery life according to the desired investment period.

Often the battery lifetime is considered to consist of a specific number of charge-discharge cycles. This requires these cycles to have a clear definition. If a battery of a specific nameplate capacity is charged completely full and discharged completely empty, the meaning of a cycle is easy to conceptualize, but in practical applications this is rarely how the battery is used. An example of a practical SoC profile in a frequency regulation application of a battery is shown in Fig. 5.

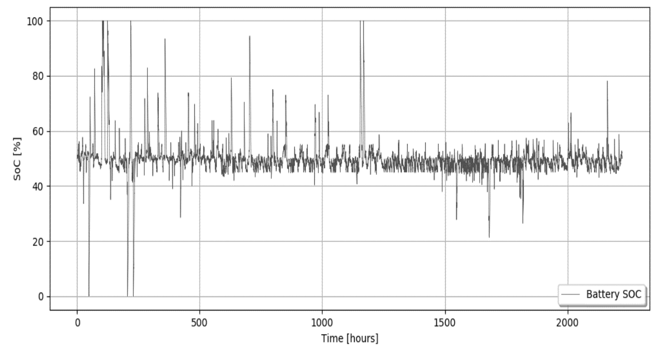

Fig. 5. Example SoC profile in a typical frequency regulation application that corresponds to the power profile in Fig. 4 with an energy capacity of 30 MWh of nameplate energy.

To use the concept of cycles to analyze the stress that the battery experiences from use, there must be a way of interpreting various use profiles as cycles with a standard definition. The proposed definition is an *equivalent full cycle*, which is the energy flow through a given battery proportional to its nameplate capacity in a given time period:

$$no. of\ cycles = \frac{cumulative\ energy\ flow}{2\ x\ nameplate\ energy\ capacity} \quad (2)$$

The above definition makes it possible to interpret varying power profiles as energy flows by integrating the charge or discharge power that the battery is experiencing over a specific time period. When this is proportional to the battery nameplate energy capacity, this *equivalent full cycle* always has a clearly defined physical meaning.

B. Battery degradation effect on the BESS rated values

The degradation of the battery has an effect on its characteristics. Due to known degradation mechanisms, the elevated internal resistance in the battery causes the heat losses to be higher (and therefore the RTE to be lower). An even bigger effect is the degradation of the battery energy capacity. [5]

The degradation of the battery over its lifetime is dependent on its use as discussed before. Fig. 6 shows an example of how a battery's energy capacity degradation profile changes with a different number of charge and discharge cycles.

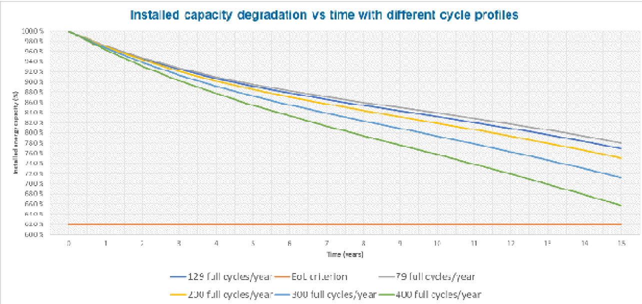

Fig. 6. Example of energy capacity degradation curves with different number of charge and discharge cycles. The energy capacity fade is shown as a function of the capacity in the Beginning of Life. This example should not be generalized to all lithium-ion batteries but instead are the result of a case-specific analysis made by the authors together with battery manufacturers.

The energy capacity at the start of the utility life of the system is referred to as the Beginning of Life (BoL) capacity of the battery. The energy capacity at the end of the utility life is referred to as the End of Life (EoL) capacity. The energy capacity evolution is shown in the above Figure as the proportion of the energy capacity left on a given year compared to the BoL capacity (100%). This terminology is necessary for the design process. If a specific application for example needs 10 MWh of energy throughout its planned investment period, this stems a requirement to have this energy capacity *at minimum* throughout the lifetime, meaning that this BESS should be specified to have 10 MWh energy capacity EoL. This implies that the BoL capacity of the energy storage needs to be higher. The definition of how much higher is dependent on the number of cycles that the BESS experiences during this lifetime.

It is important to note that the EoL capacity does not necessarily mean that the battery cannot be operated anymore – it is a term associated with the *planned* utility life which typically corresponds with the investment period. There, however, is a physical limit on the operational life of the BESS as well. The energy capacity in relationship to the BoL capacity is also often referred to as the State of Health (SoH) of the BESS.

The physical meaning of the SoH is the available energy capacity compared to BoL capacity, but it is also an indicator of how much utility lifetime the battery has left. The limit of when the battery cannot be used anymore is typically stated as a numerical limit to the SoH. This limit is stated by the battery manufacturer based on their proprietary designed life, but in the authors' experience it is typically between 60-65% SoH.

V. EXAMPLE DESIGN PROCESS

With the terminology and definitions that were discussed above, it is possible to define a design process for a real energy storage system based on specific input data as a basis for the sizing. The required information to get started is:

1. The desired lifetime of the system (investment period)
2. Definition of the PoC
3. Required energy capacity BoL and EoL (measured at the PoC)
4. Rated charge and discharge power (measured at the PoC)
5. Use profile of the BESS (for example number of full charge-discharge cycles or the cumulative energy flow).

Using the information defined above, a physical system can be designed, and its physical design can be optimized. The proposed design process is shown in Fig. 7.

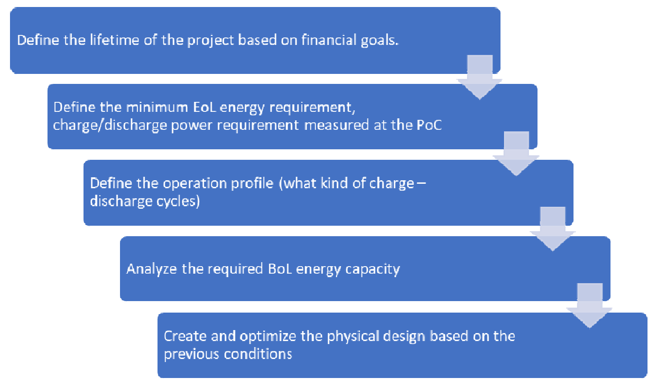

Fig. 7. The proposed design process for a BESS.

The design process starts from the definition of the financial investment period of the project. The investment period and selecting the application in which the BESS is operating, will ultimately determine the power profile of the BESS, which determines its SoC profile, which in turn determines the consequent capacity degradation. On the other hand, the projected degradation needs to be understood to know the required BoL capacity in relationship to the EoL capacity. is necessary is dependent on the number of cycles that the BESS experiences during this lifetime. As an example, for the sake of analysis, the investment period for the BESS is decided to be 10 years.

The application of the BESS typically sets practical requirements for the energy capacity and the charge and discharge power, and since the application is in the electrical grid, these characteristics need to be defined in the measurement point agreed with the utility, i.e. the PoC. Let's consider the minimum required energy capacity for a given application to be 20 MWh, measured from the PoC. In addition, let's consider the discharge power requirement to be 20 MW and the PoC to be on a medium voltage network (33 kV as an example). Reflecting on Fig. 1 and Table II. we can surmise that in order to deliver 20 MWh of energy and 20 MW of discharge power at the PoC, we need to feed the losses in the power train for the transformer, PCS and the internal losses of the batteries.

Let's assume the respective efficiencies for these components to be (according to the ranges presented in Table II.) 99 % for the transformer, 98% for the PCS and 97% for the battery at the rated power. This yields a total one-way efficiency of 94% between the battery terminals and the PoC, which means that to reach 20 MW of discharge power and 20 MWh of energy capacity at the PoC, there needs to be at least 20 MW / 0.94 ≈ 21.3 MWh of nameplate energy capacity that has a rated DC power of 21.3 MW.

Considering that the investment period is 10 years, and we need to be able to deliver the same energy defined above throughout the lifetime, we can consider the above definition of 21.3 MWh nameplate energy an EoL value. To find the required BoL energy, we need to take into account the degradation during the lifetime of the system, and in order to do that, analyze the cycles that the BESS experiences. In practice, this may be the most rigorous part of the design process where the intended use of the BESS is simulated iteratively with given power profile, such as in Fig. 4, to determine the SoC evolution during the use period, such as in Fig. 5.

Through this analysis we can find the number of charge-discharge cycles during the evaluation period. Let's assume that we have found the operation profile of the BESS to be 200 full equivalent cycles/year and the capacity degradation follows the respective degradation curve shown in Fig. 6. According to this we can see that the energy capacity drops by approximately 18 % in the 10 years of operation. Therefore, the BoL nameplate energy capacity needs to be at least 21.3 MWh / 0.82 ≈ 26 MWh.

At this point, we have reached a theoretical sizing for the BESS. The summary of the specifications of this BESS is shown in Table III. It is important to note that these specifications imply specific efficiencies as discussed above, which are specific to the actual design.

Table III. MAIN SPECIFICATIONS OF THE EXAMPLE BESS DESIGN

Characteristic	Value
Rated power measured at the PoC	20 MW
Rated power measured at the battery terminals	21.3 MW
Energy capacity at the PoC, EoL	20 MWh
Energy capacity measured from the DC circuit, EoL	21.3 MWh
Nameplate energy capacity, BoL	26 MWh
Connection voltage at the PoC	33 kV
Investment period / planned lifetime	10 years

The above analysis does not include the losses for auxiliary power use, and this is simply because it is assumed that the auxiliary power feeder is not in the main circuit. If the feeder for the auxiliary power was part of the low voltage circuit, it would have to be considered as well. In the IEC standard RTE measurement it needs to be taken into account regardless of the feeder connection point. Omitting the auxiliary power losses from an efficiency examination would not give a complete image of the system.

After creating the above theoretical specification, it now needs to be applied to engineer a physical system. The BESS needs to be designed based on commercially available components of specific characteristics. An example of such characteristics is shown in Table IV.

Table IV. RATED VALUES OF AVAILABLE COMPONENTS FOR THE EXAMPLE DESIGN.

Component / Subsystem	Characteristic	Rated value
Battery rack	Nameplate energy capacity	370 kWh
	Continuous charge and discharge power (C-rate)	370 kW (1C)
	DC voltage range	1000…1200 V
	Maximum number of battery racks per DC circuit	18
PCS converter	Power at a defined voltage level	1.1 MW of power at 690 V

The building of the physical system starts from the DC voltage range of the battery, as it dictates the AC voltage. Theoretically setting the AC voltage as high as possible is desirable, because the current would be lower at the same power, and this makes for a more efficient system (because of smaller I^2R losses). and smaller cable sizes. To be able to control the charge and discharge current, the PCS converter's AC voltage peak value needs to be higher than the lowest DC voltage (so that the current can be controlled also at the lowest SoC). According to the above Table and considering a sinusoidal waveform, the maximum AC voltage that we can set would be 1000 V / $\sqrt{2}$ ≈ 707 V. We select 690 V for some margin for a possible voltage drop in the converter power stage.

To connect to the PoC at 33 kV, a step-up transformer is required. Furthermore, in a larger BESS, multiple step-up transformers are required, because the batteries and PCS converters need to be sectionalized to various separate circuits. The short-circuit level of an individual battery rack is so high that there are practical limitations due to short circuit protection coordination, such as the busbar/cabling design and the availability of DC fuses or circuit breakers. Another aspect is the physical distance to a common coupling point (variable resistance between the battery terminals and inverters) that should be designed symmetrical. In the above Table the maximum number of battery racks in one DC circuit has been defined to be 18 pcs.

Apart from this practical limitation, sectionalizing the system in various transformer groups helps achieve modularity and redundancy in the system. Considering the above information, we can design the complete BESS with the following steps:

1. Required BoL nameplate energy capacity according is 26 MWh. To exceed this requirement, 72 battery racks are selected, which totals 72 x 370 kWh = 26640 kWh. 71 racks would suffice to reach the energy requirement, but the BESS would be asymmetrical physically and electrically.
2. According to the limitation for the battery racks in the same DC circuit, 18 pcs, these 72 battery

racks need to be divided into four different DC circuits. In practice this also means four LV AC circuits, step-up transformers, and medium voltage feeders (assuming two-winding transformers are used). This means that these four DC circuits will have nameplate energy capacity of 6660 kWh and accordingly DC charge/discharge power of 6660 kW.

3. The required number of PCS converters per DC circuit is found by first considering the required charge and discharge power at the PoC, which has been defined to be 20 MW, which would mean 5 MW for each separate circuit. Considering that previously the transformer efficiency has been defined to be 99 %, the required power at each LV AC circuit would be 5 MW / 0.99 ≈ 5.05 MW. Each PCS converter is to be 1.1 MW at 690V AC according to Table IV. , so by selecting 5 PCS converters, totaling 5.5 MW per circuit the rating can be met and exceeded.
4. Finally, the transformer for each circuit needs to be selected according to the power rating of 5 MVA to meet the required power at the PoC. It is assumed that the transformer rated power can be selected with this accuracy.

This example design is shown in a single-line diagram form in Fig. 8. The Figure shows the four designed circuits with the rated values in each connection point that meet the required specifications in Table III.

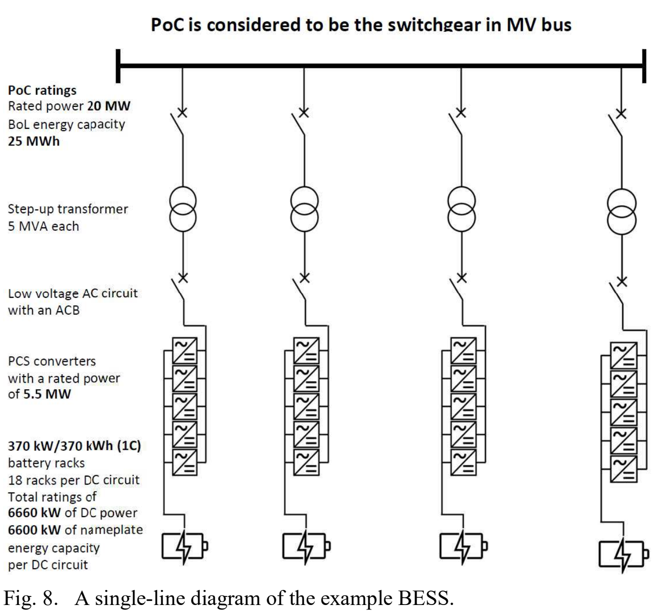

Fig. 8. A single-line diagram of the example BESS.

Important to note in the design is that the available DC power from exceeds the required power but is necessary to meet the EoL requirement for the batteries with the defined user profile. Likewise, the total power available from the PCS converters is higher than required, but the same number of converters is needed to meet the requirement.

Although the auxiliary power requirements are omitted in the scope of examination in the present paper, it is meaningful to note that if the auxiliary power for different subsystems was fed from the same medium voltage switchgear through an auxiliary power transformer, their losses would have to be considered in the design so that the required power and energy could be fed to the feeder upstream from the switchgear. Even if the auxiliary power feeder was from an external feeder, they need to be taken into account in the RTE and efficiency calculations according to the IEC standard.

VI. CONCLUSIONS

This paper has presented a comprehensive overview of the physical meaning of commonly used terminology in BESS design processes with the aim to establish a common understanding of these terms. As an example, the energy capacity of the battery was analyzed in different measurement points of a BESS with the purpose of emphasizing the importance of the exact measurement point definition.

Based on this terminology, this paper also proposed a practical design process for a BESS to arrive at a specific sizing based on the project requirements. The process is simplified in the paper and omits detailed design but should give an overview of what information is required to arrive to clear specifications for a BESS. Even more importantly, understanding the practical design process makes it possible to evaluate a proposed design by a BESS supplied against the original specification.

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