Definitions and reference values for battery systems in electrical power grids

Hubert Rubenbauer[1*] and Stefan Henninger[2]

[1]Siemens AG, Freyeslebenstraße 1, 91058 Erlangen, Germany

[2] Chair of Electrical Energy Systems, University Erlangen-Nuremberg, Cauerstraße 4,

91058 Erlangen, Germany

[*]Corresponding author: hubert.rubenbauer@siemens.com

Abstract:

Since more and more large battery based energy storage systems get integrated in electrical power grids, it is necessary to harmonize the wording of the battery world and of power system world, in order to reach a common understanding. In this regard this article presents different battery content values and their relation to each other. Battery operations typically lead to a change of the battery content. Based on a simplified battery model the basic values necessary to describe battery operations are clarified. Then the reference values and some acceptance criteria for batteries and secondary cells are defined. Also values describing limited usable energy content caused by operational restrictions are provided. In order to be as close as possible to existing definitions and practical applications, care is taken to be conform to current standards wherever possible in this article. The given set of consistent battery definitions can be used for an agreed design of battery storage systems and provides options for battery performance criteria.

Keywords: ‘state of energy’, ‘energy storage capacity’, ‘usable energy storage capacity’, ‘CP-rate’, ‘constant power time’, ‘usable constant power time’

Highlights:

- Harmonization of performance values of battery systems for a better understanding between battery manufacturers and power system integrators
- Presentation of a suitable definition for battery energy storage capacity and designation of state of energy (SOE)
- Definition of an appropriate reference (test) power value and explanation of the term ‘CP-rate’
- Introduction of the usable energy storage capacity value for description of limited usable battery content caused by operational restrictions
- Clarification of time values regarding constant power battery charging or discharging

Abstract

Since more and more large battery based energy storage systems get integrated in electrical power grids, it is necessary to harmonize the wording of the battery world and of power system world, in order to reach a common understanding. In this regard this article presents different battery content values and their relation to each other. Battery operations typically lead to a change of the battery content. Based on a simplified battery model the basic values necessary to describe battery operations are clarified. Then the reference values and some acceptance criteria for batteries and secondary cells are defined. Also values describing limited usable energy content caused by operational restrictions are provided. In order to be as close as possible to existing definitions and practical applications, care is taken to be conform to current standards wherever possible in this article. The given set of consistent battery definitions can be used for an agreed design of battery storage systems and provides options for battery performance criteria.

Keywords: 'state of energy', 'energy storage capacity', 'usable energy storage capacity', 'CP-rate', 'constant power time', 'usable constant power time'

1 Introduction

Although batteries are a quite old and principally well known technology there is still not always a common understanding about characteristic and reference values of primary and secondary cells, batteries and battery systems. Especially since huge battery systems get more and more interesting as stationary storage solutions for electrical power systems besides well known values like capacity in ampere-hours and C-rate also typical electrical values like energy and power shall be provided by the system integrator. Therefore this article gives an overview about some characteristic and reference values of battery systems, primary and secondary cells.

Battery model

For all definitions in this document the simplified battery model with the circuit diagram in Figure 1 is used ([1], [2]). The battery open-circuit voltage $v_{Bat,OCV}(t)$ describes the source voltage of the battery ($v_{Bat,OCV}(t) > 0$).

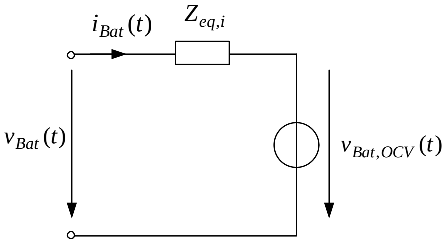

Figure 1: Simplified battery model with open circuit voltage

The equivalent, internal impedance $Z_{eq,i}$ is typically specified by manufacturer and summarizes all internal resistances of the battery. Besides ohmic parts also the diffusion resistance and the charge-transfer resistance have an influence on the internal resistance of a battery. The internal resistance also depends on battery's temperature and state of charge. If for simplification a constant resistance with only ohmic influences is taken into account, the internal impedance $Z_{eq,i}$ is equal to internal ohmic battery resistance $Z_{eq,i} = R_i$. The battery current $i_{Bat}(t)$ flows through the internal battery resistance. In this article the index '*Bat*' signalizes that the dedicated value is present at the battery terminals.

In no-load operation ($i_{Bat}(t)=0$) it follows $v_{Bat}(t) = v_{Bat,OCV}(t)$. As reference system of the battery current $i_{Bat}(t)$ the consumer reference system (Figure 2, left side) is used in this article. Therefore $i_{Bat}(t) > 0$ signalizes battery charging and $i_{Bat}(t) < 0$ battery discharging. The battery voltage $v_{Bat}(t)$ at the battery terminals can be calculated by

$$v_{Bat}(t) = v_{Bat,OCV}(t) + Z_{eq,i} \cdot i_{Bat}(t) \ . \qquad (1)$$

With battery current and battery voltage ($v_{Bat}(t) \geq 0$) the battery power $p_{Bat}(t)$ at the battery terminals can be derived

$$p_{Bat}(t) = v_{Bat}(t) \cdot i_{Bat}(t) \ . \qquad (2)$$

In consumer reference system the sign of the battery power also specifies, if the battery is charged ($p_{Bat}(t) > 0$) or discharged ($p_{Bat}(t) < 0$). Optionally the generator reference system may be used (Figure 2, right side), in which the opposite signs of battery current and battery power specify, if the battery is charged ($i_{Bat}(t) < 0$, $p_{Bat}(t) < 0$) or discharged ($i_{Bat}(t) > 0$, $p_{Bat}(t) > 0$).

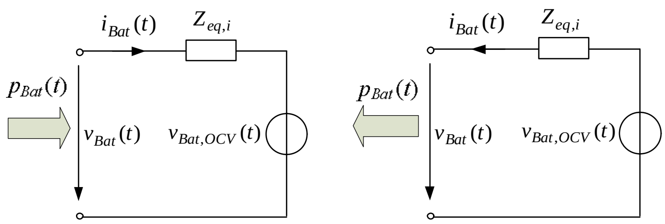

Figure 2: Consumer and generator reference system

After explanation of different battery content values in the following the basic values which are important, to describe the battery operation are presented. Then battery reference values and possible acceptance criteria are provided. Finally values for constricted battery operating ranges are characterized.

2 Battery content values

2.1 Electric charge

One main characteristic of a battery is the ability to store electric charge. Therefore '*stored electric charge*' *q(t)*, which is usable for applications, is an important value.

Stored electric charge *q(t)*

The electric charge which a battery can deliver under specified discharge conditions between its present electric charge content and its empty state is called '*stored electric charge*'. For stored electric charge which is expressed in ampere hours (Ah) the sign *q(t)* is used.

'*Full state*' of a battery is the state of charge wherein the battery has been completely charged in accordance with the manufacturer's recommended charging conditions (see also *SOC* value below). Accordingly '*empty state*' of a battery is usually defined by the battery supplier.

With q_{Start} and q_{End} as stored electric charge at the beginning and at the end of a charging or discharging process the change of stored electric charge ΔQ can be calculated by:

$$\Delta Q = \int_{q_{Start}}^{q_{End}} dq \qquad (3)$$

In consumer reference system a negative sign of ΔQ signalizes that at the end of the time period the battery contains less electric charge than at the beginning (‘*discharged*’); a positive sign of ΔQ signalizes that at the end of the time period the battery has got more electric charge than at the beginning (‘*charged*’).

Furthermore battery current $i_{Bat}(t)$ (charge or discharge), the start time t_{Start} and the end time t_{End} of the current flow can be used to derive the change of stored electric charge ΔQ (‘*Coulomb Counting*’):

$$\Delta Q = \int_{t_{Start}}^{t_{End}} i_{Bat}(t) \cdot dt \qquad (4)$$

In regard to ‘*Coulomb Counting*’ also time values can be used to describe battery’s electric charge content. See also ‘*constant current discharge time*’ and ‘*constant current charge time*’ below.

Capacity C

The (actual) capacity C of a battery is the electric charge which a fully charged cell or battery can deliver under specified discharge conditions, between its full state and its empty state. During lifetime of a battery the capacity decreases in comparison to the capacity at ‘*beginning of life*’ (BOL). Therefore an index can be added to the capacity C which specifies the battery aging. For example C_{EOL} expresses that the given capacity is valid at the ‘*end of life*’ (EOL). As for electric charge the SI unit for capacity C is coulomb (1C=1As) but in practice, capacity is usually expressed in ampere hours (Ah).

State of charge SOC

State of charge SOC of a battery is the amount of stored electric charge $q(t)$ related to the actual capacity C:

$$SOC = SOC(t) = \frac{\text{stored electric charge}}{\text{(actual) capacity}} = \frac{q(t)}{C} \qquad (5)$$

$(0\% \le SOC \le 100\%)$

‘*Full state*’ (SOC = 100%) is the reference value for stored electric charge $q(t)$ and means $q(t) = C$. ‘*Empty state*’ (SOC = 0%) means $q(t)$ = 0Ah. The other way round stored electric charge of a battery can be expressed by using the SOC value:

$$q(SOC) = SOC \cdot C \qquad (6)$$

Since the value of capacity changes during lifetime due to battery aging, an index of SOC can specify the capacity C, which is the reference for SOC value. For example SOC_{BOL} means that the capacity C at beginning of life (BOL) is used as SOC reference value ($C = C_{BOL}$). SOC_{EOL} means that the capacity C at end of life (EOL) is used as SOC reference value ($C = C_{EOL}$).

2.2 Battery open-circuit voltage

Since battery open-circuit voltage $v_{Bat,OCV}(q)$ mainly[1] depends on stored electric charge, the open-circuit voltage of a battery is well suited to be used in definitions of battery content.

[1] However in reality slightly different values for $v_{Bat,OCV}(q)$ result at the same stored electric charge q depending on whether the battery was charged or discharged before determination of $v_{Bat,OCV}(q)$.

Battery open-circuit voltage $v_{Bat,OCV}(q)$ or $v_{Bat,OCV}(t)$

The battery open-circuit voltage $v_{Bat,OCV}(q)$ shown in Figure 1 is the terminal voltage of a battery when the battery current is zero (according to [3]). Since typically stored electric charge $q(t)$ is a function of time also battery open-circuit voltage $v_{Bat,OCV}(t)$ can be seen as time dependent. For battery open-circuit voltage, which generally expresses the electrical potential of the d.c. source in a battery circuit, also the terms ‘*source voltage*’ and ‘*electromotive force*’ (EMF) can be used.

In Figure 3 battery open-circuit voltage is shown in dependence on the stored electric charge $q(t)$ and in dependence on SOC respectively. (The voltage values $V_{Bat,EOC}$ and $V_{Bat,EOD}$ in Figure 3 are explained in section 3.2 and rated capacity C_n is given in section 4.) Battery open-circuit voltage is usually defined at specified environmental conditions (e.g. 25°C ± 5°C). Due to aging the curve of open-circuit voltage related to stored electric charge of the battery can change during lifetime (see Figure 4).

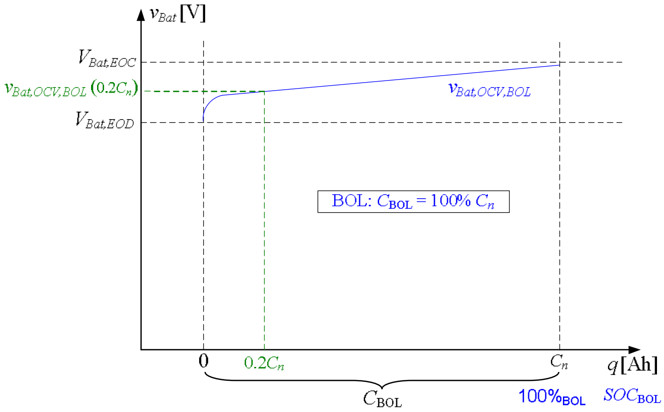

Figure 3: Typical battery open-circuit voltage $v_{Bat,OCV}$ curve related to SOC and q at BOL

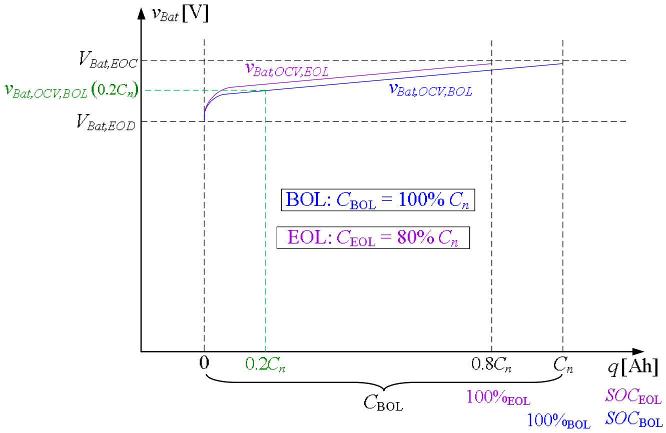

Figure 4: Typical change of battery open-circuit voltage $v_{Bat,OCV}$ due to change of capacity from BOL to EOL

2.3 Electrochemical energy

Stored (electrochemical) energy $E_{stored}(q)$ or $E_{stored}(t)$

Stored energy $E_{stored}(q)$ (of cells or batteries) is the electrochemical energy which is currently stored in the cell or battery referred to manufacturer’s reference point. Since typically stored electric charge $q(t)$ is a function of time also stored energy $E_{stored}(t)$ can be seen as time dependent. For specified conditions it can be calculated by using stored electric charge and battery open-circuit voltage $v_{Bat,OCV}(t)$ between its actual electric charge content and its empty state (see Figure 5 and Figure 6):

$$E_{stored}(q) = \int_{q(SOC=0\%)}^{q(SOC)} v_{Bat,OCV}(q) \cdot dq \qquad (7)$$

Stored energy is for high energy applications often expressed in kilo watt hours (kWh) or by using *SOE* value (see below).

The advantage of this energy definition derived from stored electric charge and open-circuit voltage only is that the resulting energy value is independent of internal resistance and battery current. For each stored electric charge value a definite stored energy value is given - independent of previous or current battery operation.

With q_{Start} and q_{End} as stored electric charge at the beginning and at the end of charging or discharging operation the change of stored energy ΔE_{stored} can be calculated by

$$\Delta E_{stored} = \int_{q_{Start}}^{q_{End}} v_{Bat,OCV}(q) \cdot dq = \int_{E_{stored,Start}}^{E_{stored,End}} dE_{stored} \quad (8)$$

In the consumer reference system a negative sign of ΔE_{stored} signalizes that at the end of the time period the battery has got less stored electrochemical energy than at the beginning (the battery was discharged); a positive sign of ΔE_{stored} signalizes that at the end of the time period the battery has got more stored electrochemical energy than at the beginning (the battery was charged).

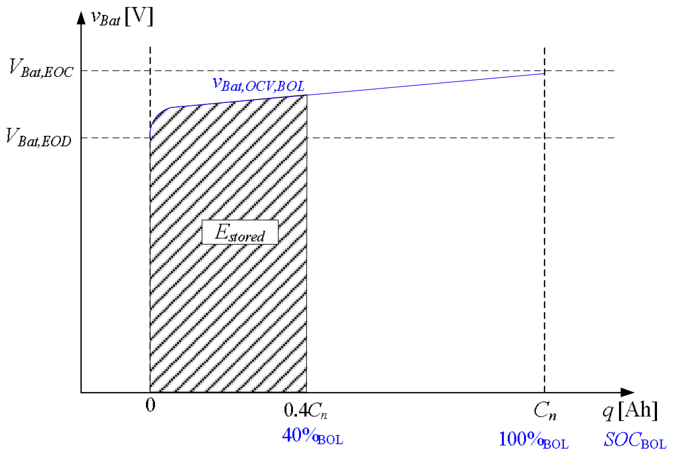

Figure 5: Stored energy $E_{stored}(q)$ derived from open-circuit voltage at BOL

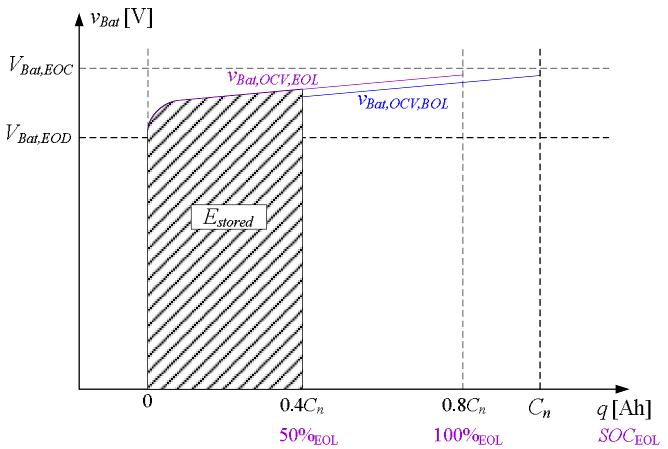

Figure 6: Stored energy $E_{stored}(t)$ derived from open-circuit voltage at EOL

Furthermore battery current $i_{Bat}(t)$ (charge or discharge), battery open-circuit voltage $v_{Bat,OCV}(t)$, the start time t_{Start} and the end time t_{End} of the current flow can be used to calculate the change of stored energy ΔE_{stored}:

$$\Delta E_{stored} = \int_{t_{Start}}^{t_{End}} v_{Bat,OCV}(t) \cdot i_{Bat}(t) \cdot dt \quad (9)$$

Using the definition of stored energy the '*energy storage capacity*' can be specified.

Energy (storage) capacity *EC*

According to [4] the (actual) energy storage capacity *EC* is the amount of (electrochemical) energy a cell or battery can store and deliver, within established design limits and maintenance interval conditions. Energy storage capacity of a cell or battery can be calculated by using (actual charge) capacity *C* and battery open-circuit voltage $v_{Bat,OCV}(t)$ between full and empty state:

$$EC = \int_{q(SOC=0\%)}^{q(SOC=100\%)} v_{Bat,OCV}(q) \cdot dq \quad (10)$$

Energy storage capacity is usually expressed in kilo watt hours (kWh). For energy storage capacity also the terms '*energy capacity*', '*actual energy capacity*', '*actual maximum energy content*' or '*(actual) electrochemical energy capacity*' can be used.

The (actual) energy storage capacity can be lower than the rated energy storage capacity (see EC_n in section 4) due to aging (e.g. see *EC* at EOL in Figure 7 and *EC* at BOL in Figure 11).
Energy storage capacity *EC*, as well as stored energy, cannot be measured directly. It is a calculated value. The advantage of upper definition of energy storage capacity is that the resulting energy value is independent of battery current and internal battery impedances.

Similar to the definition of *SOC* a state of energy (*SOE*) value can be calculated by using stored electric energy and actual energy storage capacity.

State of energy *SOE*

State of energy *SOE* is according to state of charge *SOC* the amount of stored energy related to the actual energy storage capacity:

$$SOE = \frac{E_{stored}(t)}{EC} \quad (11)$$

$$SOE(SOC) = \frac{E_{stored}(SOC)}{EC} = \frac{\int_{q(SOC=0\%)}^{q(SOC)} v_{Bat,OCV}(q) \cdot dq}{\int_{q(SOC=0\%)}^{q(SOC=100\%)} v_{Bat,OCV}(q) \cdot dq} \quad (12)$$

The state of energy is expressed in percentage. Full state (*SOE*=100% and *SOC*=100%) is the reference value for stored energy $E_{stored}(t)$ and means $E_{stored}(t) = EC$. So state of energy is the degree to which a cell or battery has been charged relative to this reference point. Empty state (*SOE*=0% and *SOC*=0%) means $E_{stored}(t) = 0$ kWh.

According to equation (8) the change of stored energy ΔE_{stored} can also be calculated by using the *SOE* start value SOE_{Start} and the *SOE* end value SOE_{End} of a charging or discharging process:

$$\Delta E_{stored} = \int_{q(SOE_{Start})}^{q(SOE_{End})} v_{Bat,OCV}(q) \cdot dq = \int_{E_{stored,Start}}^{E_{stored,End}} dE_{stored} \quad (13)$$

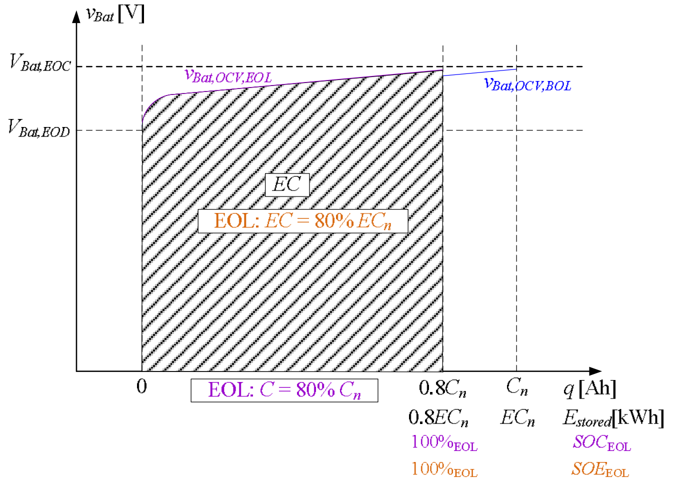

Figure 7: Energy storage capacity *EC* derived from open-circuit voltage at EOL

Similar to stored electric charge and *SOC* in (6) also stored energy is usually expressed by using *SOE* value which relates stored energy E_{stored} to (actual) energy storage capacity *EC*:

$$E_{stored}(SOE) = SOE \cdot EC \quad (14)$$

3 Battery operating values

After characterizing charge and energy content values the important values during battery operation, i.e. during charging or discharging are presented. At first battery current and its related characteristic values expressing the change of stored electric charge of a battery are explained.

3.1 Battery terminal current values

Battery current $i_{Bat}(t)$

The battery current (see Figure 1) is electric current delivered or consumed by a battery at the battery terminals during its discharge or charge (according to [3]). The battery current $i_{Bat}(t)$ can be expressed in amperes (A) or as fractions or multiples of a reference current I_{ref}.

C-rate

C-rate is the rate at which a battery is charged or discharged (see 'discharge rate' in [3]). The C-rate specifies the battery current related to the battery reference current I_{ref} (see section 4, $I_{ref} > 0$).

$$\text{C - Rate} : \frac{|i_{Bat}(t)|}{I_{ref}} \quad (15)$$

Since I_{ref} is directly related to C_n (see section 4) 'C' in the term 'C-rate' indicates that charge or discharge current is given in relation to the rated capacity C_n.

For example in consumer reference system charge with C-rate of '0.5C' means that the battery current is $i_{Bat}(t) = +0.5I_{ref}$ with $I_{ref} > 0$. A discharge with C-rate of '0.2C' means that the battery current $i_{Bat}(t)$ is equal $i_{Bat}(t) = -0.2I_{ref}$. Therefore $i_{Bat}(t) = +I_{ref}$ means charging with a C-rate of '1C'. Otherwise a battery current $i_{Bat}(t) = -I_{ref}$ means discharging with a C-rate of '1C' accordingly. Important battery terminal current values are:

Battery charge current $i_{Bat,C}(t)$ and discharge current $i_{Bat,D}(t)$

The battery charge and discharge current are the electric currents consumed or delivered by a battery at its terminals during its charge (Index '*C*') or discharge (Index '*D*'). In consumer reference system it holds $i_{Bat,C}(t) > 0\text{A}$ and $i_{Bat,D}(t) < 0\text{A}$.

Constant current discharge mode

According to definition of constant power discharge in [5] '*constant current discharge*' mode is the battery operation in which the battery discharge current is held constant and where the power and voltage freely adjust. For constant current discharge mode also the expression '*CC discharging*' is used.

In regard to '*Coulomb Counting*' the following time value for discharging with constant current is interesting.

Constant current discharge times $t_{CC,D}$

The time how long a battery is discharged (Index '*D*') with constant current (Index '*CC*') is called '*constant current discharge time*' $t_{CC,D}$. With $t_{CC,D} = t_{End} - t_{Start}$ and constant discharge current $i_{Bat}(t) = -I_{const}$ the change of stored electric charge ΔQ can be calculated in accordance to equation (4):

$$\Delta Q = \int_{t_{Start}}^{t_{End}} i_{Bat}(t) \cdot dt = -I_{const} \cdot t_{CC,D} \quad (16)$$

The constant discharge current rate can be added in the index. For example $t_{CC,Dx}$ means that battery is discharged (Index 'D') with a constant current with a C-rate of 'xC' (i.e. $i_{Bat}(t) = -xI_{ref}$). To specify from which state of charge the discharging process was started, the *SOC* value can also be given as an index, e.g. $t_{CC,D,SOC=65\%}$. As needed, also the conditions during discharging (e.g. ambient temperature, battery age or *SOC* start or end value) can be expressed in the index of $t_{CC,D}$.

Constant current charge mode

According to definition of constant power charge in [5] '*constant current charge*' mode is the battery operation in which the battery charge current is held constant and where the power and voltage freely adjust. For constant current charge mode also the expression '*CC charging*' is used. In this regard the following time value is interesting.

Constant current charge times $t_{CC,C}$

The time duration how long a battery is charged (Index '*C*') with constant current (Index '*CC*') is called '*constant current charge time*' $t_{CC,C}$. With $t_{CC,C} = t_{End} - t_{Start}$ and with constant charge current $i_{Bat}(t) = I_{const}$ the change of stored electric charge ΔQ can be calculated:

$$\Delta Q = \int_{t_{Start}}^{t_{End}} i_{Bat}(t) \cdot dt = I_{const} \cdot t_{CC,C} \quad (17)$$

The constant charge current can be added in the index. For example $t_{CC,Cy}$ means that battery is charged (Index 'C') with a constant current (Index 'CC') with a C-rate of 'yC' (i.e. $i_{Bat}(t) = yI_{ref}$). To specify from which state of charge the charging process starts, the *SOC* value can also be given as an index, e.g. $t_{CC,C,SOC=40\%}$. As needed also the conditions during charging (e.g. ambient temperature, battery age or *SOC* start and end value) can be expressed in the index of $t_{CC,C}$.

Maximum battery charge current $I_{Bat,C,max}$ and maximum discharge current $I_{Bat,D,max}$

Maximum battery charge or discharge currents of the battery are the maximum charge or discharge currents, which are allowed only for a short period of time (e.g. some seconds) at the battery terminals because of heating reasons. Usually the manufacturer specifies maximum battery charge or discharge currents for certain conditions and time durations.

Maximum continuous battery charge current $I_{Bat,cont,C,max}$ and discharge current $I_{Bat,cont,D,max}$

Maximum continuous battery charge and discharge currents are the maximum allowed charge and discharge currents of the battery, which the battery can consume and deliver continuously at certain conditions specified by manufacturer. If maximum continuous battery charge current is applied continuously to the battery under the specified ambient conditions, the battery is typically kept in thermal balance. Therefore for these values the thermal coordination of the battery is decisive.

Finishing charge rate $I_{Bat,C,finish}$

The finishing charge rate $I_{Bat,C,finish}$ (according to [3]) is the electric current at which a battery is charged towards the end of charge. This means that battery's full state (*SOC*=100%) is reached, if $v_{Bat}(t) = V_{Bat,EOC}$ (see section 3.2) and discharge current is $I_{Bat,C,finish}$ (i.e. $i_{Bat}(t) = I_{Bat,C,finish}$).

Finishing discharge rate $I_{Bat,D,finish}$

The finishing discharge rate $I_{Bat,D,finish}$ (according to finishing charge rate) is the electric current at which a battery is discharged towards the end of discharge. This means that battery's empty state (*SOC*=0%) is reached, if $v_{Bat}(t) = V_{Bat,EOD}$ (see section 3.2) and discharge current is $I_{Bat,D,finish}$ (i.e. $i_{Bat}(t) = -I_{Bat,D,finish}$).

3.2 Battery terminal voltage values

Battery (terminal) voltage $v_{Bat}(t)$

'*Battery voltage*' $v_{Bat}(t)$ or '*battery terminal voltage*' respectively is the voltage which is present between the battery terminals. The battery terminal voltage ($v_{Bat}(t) \geq 0$) depends on operational conditions of the battery (e.g. no-load or discharge). As depicted in Figure 1 and shown in formula (1) the battery terminal voltage $v_{Bat}(t)$ can be calculated by using open-circuit voltage, battery current $i_{Bat}(t)$ and internal impedance $Z_{eq,i}$. Important battery terminal voltage values are:

Constant voltage charge mode

Constant voltage charge is the battery charge operation in which the battery voltage is held constant and where the power and current freely adjust. ('*CV charging*')

Constant voltage discharge mode

Constant voltage discharge is the battery discharge operation in which the battery voltage output is held constant and where the power and current freely adjust. ('*CV discharging*')

Battery charge voltage $v_{Bat,C}(t)$ and battery discharge voltage $v_{Bat,D}(t)$

Battery charge and discharge voltages (according to [3]) are the voltages ($v_{Bat,C}(t) > 0$ and $v_{Bat,D}(t) > 0$) which are present between the battery terminals during battery charging (Index '*C*') and discharging (Index '*D*'). Due to equation (1) and the different current flow directions battery charge voltage is typically higher and battery discharge voltage is typically lower than battery open-circuit voltage.

Battery end-of-discharge voltage $V_{Bat,EOD}$

Battery end-of-discharge voltage (according to [5]) is the specified battery terminal voltage at which the battery discharge is terminated. For battery end-of-discharge voltage (Index '*EOD*') the symbol $V_{Bat,EOD}$ is used ($V_{Bat,EOD} > 0$).

For end-of-discharge voltage also the terms '*final voltage*', '*cut-off voltage*' and '*end-point-voltage*' are applied. Battery end-of-discharge voltage is assumed to be equal over whole battery lifetime. The end-of-discharge voltage $V_{Bat,EOD}$ is typically declared by the manufacturer.

The end-of-discharge voltage may be used to initiate the termination of the discharge process or to start with constant voltage discharge mode ('*CV discharging*'). In this mode the battery terminal voltage $v_{Bat}(t)$ is held constant at $V_{Bat,EOD}$ by reducing battery discharge current $i_{Bat}(t)$. The end of discharging is reached, when battery discharge current becomes lower than finishing discharge rate $I_{Bat,D,finish}$.

Constant current end-of-discharge times $t_{min,EOD,CC}$ and $t_{EOD,CC}$

Starting from a certain *SOC* value the minimum time how long the battery can be discharged with constant current till reaching end-of-discharge voltage $V_{Bat,EOD}$ is called '*minimum constant current end-of-discharge time*' $t_{min,EOD,CC}$. Like for constant current discharge time $t_{CC,D}$ the constant discharge current can be added in the index. For example $t_{min,EOD,CC,Dx}$ means that battery is discharged with a constant current with a C-rate of 'xC'. Also the starting *SOC* value can be given as an index, e.g. $t_{min,EOD,CC,SOC=85\%}$.

In comparison to the minimum constant current end-of-discharge time, which is an important value regarding rated capacity C_n (see section 4), the really measured time how long a battery is discharged with constant current till end-of-discharge voltage is reached, is called '*constant current end-of-discharge time*' $t_{EOD,CC}$. If a battery is discharged to end-of-discharge voltage $t_{min,EOD,CC} \leq t_{EOD,CC}$ is valid.

Battery end-of-charge voltage $V_{Bat,EOC}$

Battery end-of-charge voltage (according to [3]) is the specified voltage attained at the end of a charging process (see also '*finishing charge rate*'). For battery end-of-charge voltage the symbol $V_{Bat,EOC}$ is used ($V_{Bat,EOC} > 0$).

Battery end-of-charge voltage is assumed to be equal over whole battery lifetime. Usually battery terminal voltage is in the range $V_{Bat,EOD} \leq v_{Bat}(t) \leq V_{Bat,EOC}$. The end-of-charge voltage $V_{Bat,EOC}$ is typically declared by the manufacturer.

The end-of-charge voltage is used to initiate the termination of the charge process or to start with constant voltage charge mode ('*CV charging*'). In this mode the battery terminal voltage $v_{Bat}(t)$ is held constant at $V_{Bat,EOC}$ by reducing battery charge current $i_{Bat}(t)$. The end of charging is reached, when battery charge current becomes lower than finishing charge rate $I_{Bat,C,finish}$.

Constant current end-of-charge times $t_{min,EOC,CC}$ and $t_{EOC,CC}$

Starting from a certain *SOC* value the minimum time duration how long the battery can be charged with constant current till reaching end-of-charge voltage $V_{Bat,EOC}$ is called '*minimum constant current end-of-charge time*' $t_{min,EOC,CC}$. Like for constant current charge time $t_{CC,C}$ the constant charge current can be added in the index. For example $t_{min,EOC,CC,Cy}$ means that battery is charged with a constant current with a C-rate of '*y*C'. Also the starting *SOC* value can be given as an index, e.g. $t_{min,EOC,CC,SOC=10\%}$.

The really measured time how long a battery is charged with constant current till end-of-charge voltage is reached, is called '*constant current end-of-charge time*' $t_{EOC,CC}$. If a battery is charged to end-of-charge voltage $t_{min,EOC,CC} \leq t_{EOC,CC}$ is valid.

Full state, initial discharge voltage $V_{Bat,full,initial,D}$

Full state, initial discharge voltage (according to [3]) is the discharge voltage of a fully charged cell or battery at the beginning of the discharge with a certain discharge current or power immediately after any transients have subsided (see Figure 8).

For full state, initial discharge voltage the symbol $V_{Bat,full,initial,D}$ is used ($V_{Bat,full,initial,D} > 0$). Again the discharge current rate can be added in the index. So $V_{Bat,full,initial,Dx}$ means that battery is initially discharged with a current with a C-rate of 'xC' (i.e. $i_{Bat}(t) = -xI_{ref}$).

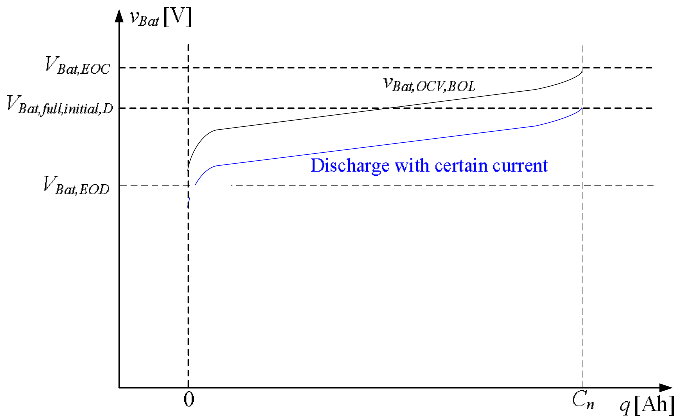

Figure 8: Full state, initial discharge voltage

Empty state, initial charge voltage $V_{Bat,empty,initial,C}$

Empty state, initial charge voltage is the charge voltage of an empty (*SOC*=0%) cell or battery at the beginning of the charge with a certain charge current or power immediately after any transients have subsided (see Figure 9).

For empty state, initial charge voltage the symbol $V_{Bat,empty,initial,C}$ is used ($V_{Bat,empty,initial,C} > 0$). The charge current rate can also be added in the index. Therefore voltage $V_{Bat,empty,initial,Cy}$ means that battery is initially charged with a current with a C-rate of '*y*C' (i.e. $i_{Bat}(t) = yI_{ref}$).

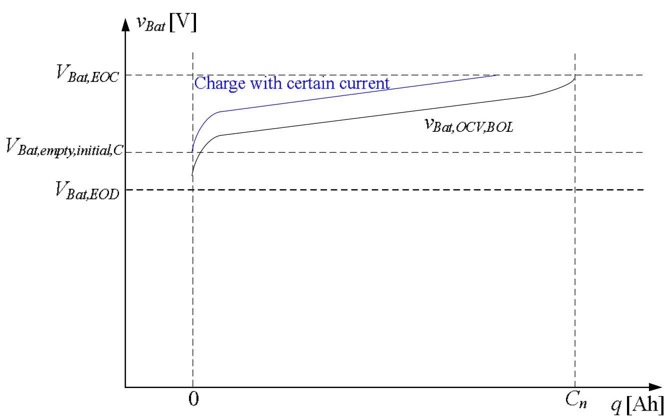

Figure 9: Empty state, initial charge voltage

3.3 Battery terminal power values

Using battery voltage $v_{Bat}(t)$ and battery current $i_{Bat}(t)$ the battery power $p_{Bat}(t)$ at battery terminals can be calculated as given in equation (2). Especially in power system applications electrical power is an important value.

Battery (terminal) power $p_{Bat}(t)$

Similar to battery current the battery power is electric power delivered or consumed by a battery during its discharge or charge at the battery terminals. The sign of the battery power specifies if the battery power is a battery charge power or a battery discharge power. In consumer reference system a negative sign of battery power $p_{Bat}(t)$ specifies battery discharge; a positive sign specifies battery charge.

Battery power is an active power and is expressed in watt or kilowatt (kW). Furthermore battery power $p_{Bat}(t)$ can be expressed as fractions or multiples of a reference power P_{ref} (see also CP-rate).

If internal battery resistance is completely ohmic ($Z_{eq,i} = R_i$) the battery terminal voltage $v_{Bat}(t)$ is

$$v_{Bat}(t) = v_{Bat,OCV}(t) + R_i \cdot i_{Bat}(t)\,. \qquad (18)$$

So battery power $p_{Bat}(t)$ can be calculated by

$$\begin{aligned} p_{Bat}(t) &= v_{Bat}(t) \cdot i_{Bat}(t) \\ &= (v_{Bat,OCV}(t) + R_i \cdot i_{Bat}(t)) \cdot i_{Bat}(t) \end{aligned} \qquad (19)$$

CP-rate

CP-rate is the power rate at which a battery is charged or discharged. The CP-rate is the battery power at the battery terminals related to battery reference power (see section 4, $P_{ref} > 0$):

$$\text{CP - Rate}: \quad \frac{|p_{Bat}(t)|}{P_{ref}} \qquad (20)$$

Since P_{ref} is directly related to C_n (see section 4) 'CP' in the term 'CP-rate' indicates that charge or discharge power is given in relation to the rated capacity C_n.

For example in consumer reference system battery charging with a CP-rate of '0.6CP' means that the battery power $p_{Bat}(t)$ is equal to $p_{Bat}(t) = +0.6\, P_{ref}$. A discharge with CP-rate of '0.3CP' means that the battery power $p_{Bat}(t)$ is equal to $p_{Bat}(t) = -0.3\, P_{ref}$. Furthermore $p_{Bat}(t) = +P_{ref}$ means charging with a CP-rate of '1CP'. Accordingly battery power of $p_{Bat}(t) = -P_{ref}$ means discharging with a CP-rate of '1CP'.

Important battery power values are:

Constant battery power charge

According to [5] constant battery power charge is the battery operation in which the charge power input, i.e. the product of charge current and charge voltage, is held constant and where battery current and battery voltage freely adjust. ('*CP charging*')

Constant battery power discharge

According to [5] constant battery power discharge is the battery operation in which the discharge power output, i.e. the product of discharge current and discharge voltage, is held constant and where battery current and battery voltage freely adjust. ('*CP discharging*')

Battery charge power $p_{Bat,C}(t)$ **and discharge power** $p_{Bat,D}(t)$

Similar to charge and discharge current the battery charge and discharge power are the electric powers consumed or delivered by a battery at its terminals during its charge (Index '*C*') or discharge (Index '*D*'). In consumer reference system it holds $p_{Bat,C}(t) > 0W$ and $p_{Bat,D}(t) < 0W$.

Maximum battery charge power $P_{Bat,C,max}$ and maximum discharge power $P_{Bat,D,max}$

Maximum battery charge or discharge powers of the battery are the maximum charge or discharge power values, which are allowed only for a short period of time (e.g. some seconds) at the battery terminals because of heating reasons. Usually the manufacturer specifies maximum battery charge or discharge powers for certain conditions and time durations.

More interesting are the power values which are related to more or less continuously battery operation. For these power values (depicted for example in Figure 18) both continuous battery currents and battery voltage limits are decisive:

Maximum continuous battery charge power at empty state $P_{Bat,cont,C,max,empty}$

Maximum continuous battery charge power at empty state is the maximum charge power of the battery, which is continuously applicable at the battery terminals starting from empty state. Typically maximum continuous battery charge power at empty state is given by

$$P_{Bat,cont,C,max,empty} = I_{Bat,cont,C,max} \cdot V_{Bat,empty,initial,C} \qquad (21)$$

wherein $I_{Bat,cont,C,max}$ is the maximum continuous battery charge current and $V_{Bat,empty,initial,C}$ is the empty state, initial charge voltage referred to <u>maximum continuous battery charge</u> current for an empty battery. Since battery aging and environmental conditions have got a decisive influence on maximum continuous battery charge power of a cell or a battery, the manufacturer typically provides values for $P_{Bat,cont,C,max,empty}$ at least for beginning of life (BOL) and end of life (EOL) at an ambient temperature of 25°C.

Maximum continuous battery charge power at full state $P_{Bat,cont,C,max,full}$

Maximum charge power, with which the battery can be continuously charged to full state (SOC=100%), is called '*maximum continuous battery charge power at full state*'. With battery end-of-charge voltage $V_{Bat,EOC}$ and finishing charge current rate $I_{Bat,C,finish}$ it can be calculated by

$$P_{Bat,cont,C,max,full} = I_{Bat,C,finish} \cdot V_{Bat,EOC} \qquad (22)$$

$P_{Bat,cont,C,max,full}$ can also be seen as '*finishing charge power rate*' $P_{Bat,C,finish}$.

Maximum continuous battery charge power $P_{Bat,cont,C,max}$

Maximum battery charge power, which can be continuously applied at the battery terminals, is the maximum continuous battery charge power. Typically it is given by

$$P_{Bat,,cont,C,max} = I_{Bat,,cont,C,max} \cdot V_{Bat,EOC} \qquad (23)$$

Thereby $I_{Bat,cont,C,max}$ is the maximum continuous battery charge current and $V_{Bat,EOC}$ is the battery end-of-charge voltage. So $P_{Bat,cont,C,max,empty} \le P_{Bat,cont,C,max}$ and $P_{Bat,cont,C,max,full} \le P_{Bat,cont,C,max}$ are valid. If maximum continuous battery charge power is applied continuously to the battery under specified ambient conditions, the battery temperature always stays within allowed operational range. But due to the voltage limit $V_{Bat,EOC}$ charge power $P_{Bat,cont,C,max}$ can usually not be applied continuously but only for a short time.

Maximum continuous battery discharge power at empty state $P_{Bat,cont,D,max,empty}$

Maximum continuous battery discharge power at empty state is the maximum discharge power of the battery, which is continuously applicable at the battery terminals till reaching empty state. Typically maximum continuous battery charge power at empty state is given by

$$P_{Bat,cont,D,max,empty} = I_{Bat,D,finish} \cdot V_{Bat,EOD} \qquad (24)$$

wherein $I_{Bat,D,finish}$ is the finishing discharge current and $V_{Bat,EOD}$ is the battery end-of-discharge voltage of the cell or battery as declared by the manufacturer ($V_{Bat,EOD} > 0$). $P_{Bat,cont,D,max,empty}$ can also be seen as '*finishing discharge power rate*' $P_{Bat,D,finish}$.

Maximum continuous battery discharge power at full state $P_{Bat,cont,D,max,full}$

Maximum battery discharge power at full state is the maximum allowed discharge power of the battery starting at *SOC*=100%. Typically maximum battery discharge power at full state is given by

$$P_{Bat,cont,D,max,full} = I_{Bat,cont,D,\max} \cdot V_{Bat,full,initial,D} \qquad (25)$$

In this regard $I_{Bat,cont,D,max}$ is the maximum continuous battery discharge current and $V_{Bat,full,initial,D}$ is the initial discharge voltage referred to <u>maximum continuous battery discharge</u> current for a fully charged battery.
Battery aging and environmental conditions have got a decisive influence on maximum battery discharge power of a cell or a battery. Therefore the manufacturer shall provide values for maximum battery discharge power at least for beginning of life (BOL) and end of life (EOL) at an ambient temperature of 25°C.

Maximum continuous battery discharge power $P_{Bat,cont,D,max}$

Maximum continuous battery discharge power is the maximum discharge power of the battery, which can be continuously applied at the battery terminals. Typically maximum continuous battery discharge power $P_{Bat,cont,D,max}$ is equal to maximum battery discharge power at full state

$$P_{Bat,cont,D,max} = P_{Bat,cont,D,max,full} \qquad (26)$$

If maximum continuous battery discharge power is applied continuously to the battery under specified ambient conditions, the battery temperature always stays within allowed operational range. But due to a decreasing open-circuit voltage at battery discharging the discharge power $P_{Bat,cont,D,max}$ can usually not be applied continuously but only for a short time.

Using battery terminal power the battery terminal energy can be derived.

3.4 Battery terminal energy values

Battery (terminal) energy W_{Bat} or $W_{Bat,terminal}$

The battery terminal energy can be calculated using battery power $p_{Bat}(t)$ or battery current $i_{Bat}(t)$ and battery voltage $v_{Bat}(t)$ at the battery terminals:

$$W_{Bat} = \Delta E_{Bat} = \int p_{Bat}(t) \cdot dt = \int i_{Bat}(t) \cdot v_{Bat}(t) \cdot dt \qquad (27)$$

The sign of the battery terminal energy specifies, if the battery delivered or consumed energy at the battery terminals in total over the considered time period. In consumer reference system a negative sign of battery terminal energy W_{Bat} specifies energy delivery in total over the considered time period; a positive sign characterizes energy consumption in total.

In case of constant battery power charge ('*CP charging*') or discharge ('*CP discharging*') also time values can be used to specify battery terminal energy. These time values can also include information about operating and aging conditions.

Constant power discharge time $t_{CP,D}$

The constant power discharge time $t_{CP,D}$ specifies the time, how long the battery at certain conditions is discharged with constant battery power at the battery terminals. In accordance to equation (27) with constant discharge power $p_{Bat}(t) = -P_{const}$ and with $t_{CP,D}$ the battery terminal energy W_{Bat} can be calculated:

$$W_{Bat} = \Delta E_{Bat} = \int_{t_{Start}}^{t_{End}} p_{Bat}(t)\cdot dt = -P_{const}\cdot t_{CP,D} \qquad (28)$$

The constant discharge power can be added in the index. For example $t_{CP,Dx}$ means that battery is discharged (Index 'D') with a constant power (Index 'CP') with a CP-rate of 'xCP' (i.e. $p_{Bat}(t) = -xP_{ref}$). Also the specified conditions for $t_{CP,D}$ like *SOE* start and *SOE* end value, ambient temperature, battery age and actual battery capacity can be provided as indices. For example $t_{CP,D0.7,SOE=90\%,EOL,T=25°C}$ specifies the time how long the battery is discharged at end of life (EOL) with a constant discharge power of 0.7CP starting from an *SOE* value of 90% at an ambient temperature of 25°C.

Constant power charge time $t_{CP,C}$

The constant power charge time $t_{CP,C}$ specifies the time, how long the battery at certain conditions is charged with constant battery power at the battery terminals. In accordance to equation (27) with constant charge power $p_{Bat}(t) = P_{const}$ and with $t_{CP,C}$ the battery terminal energy W_{Bat} can be calculated:

$$W_{Bat} = \Delta E_{Bat} = \int_{t_{Start}}^{t_{End}} p_{Bat}(t)\cdot dt = P_{const}\cdot t_{CP,C} \qquad (29)$$

The constant charge power can be added in the index. For example $t_{CP,Cz}$ means that battery is charged (Index 'C') with constant power (Index 'CP') with a CP-rate of 'zCP' (i.e. $p_{Bat}(t) = zP_{ref}$). Also the specified conditions like *SOE* start and *SOE* end value, ambient temperature, battery age and actual battery capacity can be provided as indices. For example $t_{CP,C1.2,SOE=20\%,BOL,T=30°C}$ specifies the time during which the battery is charged at beginning of life (BOL) with a constant charge power of 1.2CP starting from an *SOE* value of 20% at an ambient temperature of 30°C.

Constant power end-of-discharge times $t_{min,EOD,CP}$ and $t_{EOD,CP}$

The end of discharge depends on $V_{Bat,EOD}$. The time value $t_{min,EOD,CP}$ is called '*minimum constant power end-of-discharge time*' and is the minimum time duration how long the battery can be discharged with constant power till reaching end-of-discharge voltage $V_{Bat,EOD}$ starting from a certain *SOE* value. To specify from which state of energy the charging process is started, the *SOE* value can be given as an index, e.g. $t_{EOD,CP,SOE=70\%}$. Also the CP-rate of constant discharge power can be added to the index.

The really measured time how long a battery is discharged with constant power till end-of-discharge voltage is reached, is called '*constant power end-of-discharge time*' $t_{EOD,CP}$. If a battery is discharged to end-of-discharge voltage $t_{min,EOD,CP} \le t_{EOD,CP}$ is valid.

Constant power end-of-charge times $t_{min,EOC,CP}$ and $t_{EOC,CP}$

The end of charge depends on $V_{Bat,EOC}$. The time value $t_{EOC,CP}$ is called '*constant power end-of-charge time*' and is the minimum time duration how long the battery can be charged with constant power till reaching end-of-charge voltage $V_{Bat,EOC}$ starting from a certain *SOE* value. To specify from which state of energy the charging process is started, the *SOE* value can be given as an index, e.g. $t_{EOC,CP,SOE=30\%}$. Also the CP-rate of constant charge power can be added to the index.

The really measured time how long a battery is charged with constant power till end-of-charge voltage is reached, is called '*constant power end-of-charge time*' $t_{EOC,CP}$. If a battery is charged to end-of-charge voltage $t_{min,EOC,CP} \le t_{EOC,CP}$ is valid.

By measuring battery terminal energy and with usage of stored energy values different efficiency values can be derived.

3.5 Battery terminal efficiency values

Battery discharge efficiency η_D

Battery discharge efficiency (Index '*D*') at the battery terminals can be calculated by

$$\eta_D = \frac{|W_{Bat,D}|}{|\Delta E_{stored}|} = \frac{|\Delta E_{stored}| - |W_{loss,D}|}{|\Delta E_{stored}|} = 1 - \frac{|W_{loss,D}|}{|\Delta E_{stored}|} \qquad (30)$$

$(0 \le \eta_D \le 1)$

During battery discharging in consumer reference system it holds $W_{Bat,D} < 0$, $\Delta E_{stored} < 0$ and $|W_{Bat,D}| \le |\Delta E_{stored}|$. With

$$|W_{Bat,D}| = \left|\int_{t_{Start}}^{t_{End}} p_{Bat,D}(t)dt\right| = \left|\int_{t_{Start}}^{t_{End}} v_{Bat,D}(t)\cdot i_{Bat,D}(t)dt\right| \qquad (31)$$

and

$$|\Delta E_{stored}| = \left|\int_{t_{Start}}^{t_{End}} v_{Bat,OCV}(t)\cdot i_{Bat,D}(t)\cdot dt\right| \qquad (32)$$

discharge efficiency can be derived by

$$\eta_D = \frac{|W_{Bat,D}|}{|\Delta E_{stored}|} = \frac{\left|\int_{t_{Start}}^{t_{End}} v_{Bat,D}(t)\cdot i_{Bat,D}(t)dt\right|}{\left|\int_{t_{Start}}^{t_{End}} v_{Bat,OCV}(t)\cdot i_{Bat,D}(t)\cdot dt\right|} \qquad (33)$$

Battery charge efficiency η_C

Battery charge efficiency (Index '*C*') at the battery terminals can be calculated by

$$\eta_C = \frac{|\Delta E_{stored}|}{|W_{Bat,C}|} = \frac{|\Delta E_{stored}|}{|\Delta E_{stored}| + |W_{loss,C}|} \qquad (34)$$

$(0 \le \eta_C \le 1)$

During battery charging in consumer reference system it holds $W_{Bat,C} > 0$, $\Delta E_{stored} > 0$ and $|W_{Bat,C}| \ge |\Delta E_{stored}|$

With

$$|W_{Bat,C}| = \left|\int_{t_{Start}}^{t_{End}} p_{Bat,C}(t)dt\right| = \left|\int_{t_{Start}}^{t_{End}} v_{Bat;C}(t)\cdot i_{Bat,C}(t)dt\right| \qquad (35)$$

and

$$|\Delta E_{\mathrm{stored}}| = \left|\int_{t_{Start}}^{t_{End}} v_{Bat,OCV}(t)\cdot i_{Bat,C}(t)\cdot dt\right| \qquad (36)$$

battery charge efficiency can be derived by

$$\eta_C = \frac{|\Delta E_{stored}|}{|W_{Bat;C}|} = \frac{\left|\int_{t_{Start}}^{t_{End}} v_{Bat,OCV}(t)\cdot i_{Bat;C}(t)\cdot dt\right|}{\left|\int_{t_{Start}}^{t_{End}} v_{Bat,C}(t)\cdot i_{Bat,C}(t)dt\right|} \quad (37)$$

Battery round trip efficiency η_{RT}

For determination of battery round trip efficiency (Index '*RT*') at the battery terminals it is important that after discharge and charge operation (or charge and discharge operation) the end value of *SOE* (or E_{stored}, *SOC* or $q(t)$ respectively) is the same as the value at beginning of battery charging or discharging operation. Then the battery round trip efficiency can be calculated by

$$\begin{aligned}\eta_{RT} &= \eta_D \cdot \eta_C \\ &= \frac{|W_{Bat,D}|}{|\Delta E_{stored}|}\cdot\frac{|\Delta E_{stored}|}{|W_{Bat,C}|} \\ &= \frac{|W_{Bat,D}|}{|W_{Bat,C}|} \\ &= \frac{|\Delta E_{stored}| - |W_{loss,D}|}{|\Delta E_{stored}| + |W_{loss,C}|} \\ &(0 \le \eta_{RT} \le 1)\end{aligned} \quad (38)$$

Since losses mostly depend on current flow battery round trip efficiency η_{RT} depends on discharging and charging current. Therefore the charge and discharge currents (or charge and discharge powers respectively) should be provided together with battery round trip efficiency η_{RT}.

Furthermore also the change of stored electric charge $q(t)$, stored energy E_{stored}, *SOE* or *SOC* ('*depth of discharge*' (DOD)) is decisive for battery round trip efficiency η_{RT}. Therefore the maximum and minimum value of *SOC*, *SOE*, $q(t)$ or E_{stored} should also be given with battery round trip efficiency η_{RT}.

4 Battery reference values

Rated Capacity C_n

As reference value for capacity the rated capacity C_n is used [6]. For rated capacity also the terms "*nominal capacity*" or "*installed capacity*" can be found. The rated capacity is the quantity of electricity C_n in Ah (ampere-hours) declared by the manufacturer which a single cell or battery can deliver during a *n* hour period when charging, storing and discharging with constant battery current $1/n \cdot I_{ref}$ under specified conditions (see below '*rated capacity verification test*').

For example for lithium-ion batteries typically *n*=5 (hours) is used which indicates a rated capacity C_5. Often rated capacity C_n is related to beginning of life (BOL) of a battery. This means that at BOL and *SOC*=100% (fully charged) the capacity *C* is equal to the rated capacity C_n.

Reference (test) current I_{ref} or I_t

According to [7] the reference (test) current is specified as

$$I_t = I_{ref} = \frac{C_n}{1\,\mathrm{h}} \quad . \quad (39)$$

Therein I_{ref} or I_t respectively is the reference (test) current ($I_{ref} > 0$ and $I_t > 0$) in amperes, C_n is the rated capacity of the cell or battery as declared by the manufacturer ($C_n > 0$) in ampere-hours and *n* is the time base in hours for which the rated capacity is declared.

If for example the rated capacity declared by manufacturer is $C_n = C_5 = 15$Ah, the reference test current is $I_{ref} = I_t = C_n$ /1h = $= C_5$ /1h = 15Ah /1h = 15A.

Rated constant current end-of-discharge time $t_{min,EOD,CC,D1/n}$ or *n*

The rated constant current end-of-discharge time $t_{min,EOD,CC,D1/n}$ is equal to the dimensionless value *n* (see [6]), which is the time base in hours (h) for which the rated capacity C_n is declared. The rated constant current end-of-discharge time $t_{min,EOD,CC,D1/n}$ or respectively $n \cdot$h specifies the minimum time, how long a battery, which is fully charged according to a given charge procedure, can be discharged with constant battery current $1/n \cdot I_{ref}$ at room temperature (25°C ± 5°C) and other conditions specified by manufacturer (see below '*rated capacity verification test*'). For different discharge rate type cells or batteries different rated time bases *n* exist for declaration of rated capacity (see [6]). For really resulting constant current end-of-discharge time $t_{EOD,CC,D1/n}$ it holds

$$t_{CC,D} = t_{EOD,CC} \ge t_{min,EOD,CC,D1/n} = n \cdot \mathrm{h} \quad (40)$$

Rated capacity verification test

The rated capacity verification test is used to proof that under specified conditions the battery or cell has got at least the rated electric charge content. According to [6] the rated capacity verification test shall be performed as follows:

1.	Prior to charging, the cell or battery shall be discharged at 25 °C ± 5 °C at a constant current of $1/n \cdot I_{ref}$, down to a specified battery end-of-discharge voltage $V_{Bat,EOD}$.	*Charging procedure for test purposes*
2.	The empty cells or batteries shall be fully charged in an ambient temperature of 25 °C ± 5 °C, using the following method: a. Charging at constant current of $1/n \cdot I_{ref}$ up to a specified battery end-of-charge voltage $V_{Bat,EOC}$ b. Charging at constant end-of-charge voltage $V_{Bat,EOC}$ down to a "*finishing charge rate*" $I_{Bat,C,finish}$.	
3.	The cell or battery shall be stored in an ambient temperature of 25 °C ± 5 °C, for not less than 1 h and not more than 4 h.	*Idle time*
4.	In the same ambient temperature the cell or battery shall then be discharged at a constant current of $1/n \cdot I_{ref}$ to battery end-of-discharge voltage $V_{Bat,EOD}$ (see Figure 10). The electric charge ΔQ, delivered during discharging, shall not be less than the rated capacity C_n, i.e. for the constant current discharge time $t_{CC,D1/n}$ till end-of-discharge voltage is reached it is valid $t_{CC,D1/n} \ge n \cdot$h and $t_{CC,D1/n} \ge t_{min,EOD,CC,D1/n}$.	*Discharge performance with constant current*

Table 1: Rated capacity verification test

In this regard *n* determines the fraction or multiple of I_{ref}. For example, if $n = 5$, then the discharge current used to verify the rated capacity shall be $-0.2 \cdot I_{ref}$. If $n = 1$, the discharge current used to verify the rated capacity shall be $1.0 \cdot I_{ref}$.

Considering $I_{ref} > 0$ the following formula can be used for calculation of the change of stored electric charge ΔQ during discharge in rated capacity verification test. With constant current discharge time $t_{CC,D}$ till end-of-discharge voltage is reached it results

$$\Delta Q = \left| \int_{t_{full}=0}^{t_{CC,D}} \left(-\frac{I_{ref}}{n} \right) \cdot dt \right| = \left| \frac{1}{n} \cdot \left(-I_{ref} \right) \cdot \int_{t_{full}=0}^{t_{CC,D}} dt \right| \tag{41}$$
$$= \frac{1}{n} \cdot I_{ref} \cdot t_{CC,D} \geq \frac{1}{n} \cdot I_{ref} \cdot n \cdot \mathrm{h} = I_{ref} \cdot \mathrm{h} = C_n$$
$$\left(t_{CC,D} \geq t_{\min,EOD,CC,D1/n} = n \cdot \mathrm{h} \right)$$

If rated capacity is ideally determined, it is $t_{CC,D} = t_{min,EOD,CC,D1/n} =$ $= n\cdot$h. That is

$$\Delta Q = C_n = \left| \int_{q=C_n}^{q=0} dq \right| = \left| \int_{q(SOC=100\%)}^{q(SOC=0\%)} dq \right| \tag{42}$$

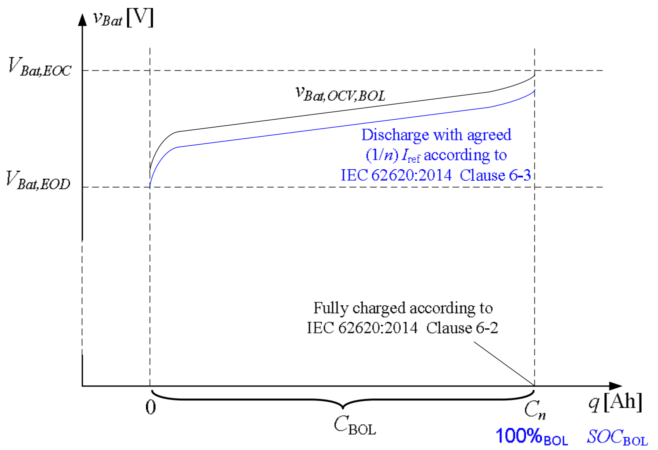

Figure 10: Verification of rated capacity C_n specified for beginning of life (BOL)

Rated energy storage capacity EC_n

The reference value "*rated energy storage capacity*" EC_n is a calculated value. It cannot be measured directly. The rated energy storage capacity of a cell or battery between full and empty state is derived by using rated (charge) capacity C_n and battery open-circuit voltage $v_{Bat,OCV}$ (t) at conditions specified by the manufacturer:

$$EC_n = \int_{q(SOC=0\%)}^{q(SOC=100\%)} v_{Bat,OCV}(q) \cdot dq = \int_{q=0}^{q=C_n} v_{Bat,OCV}(q) \cdot dq \tag{43}$$

Rated energy storage capacity is an energy value and usually expressed in kilo watt hours. For rated energy storage capacity also the terms "*rated energy capacity*", "*rated maximum energy content*", "*rated electrochemical energy capacity*", "*nominal energy capacity*" or "*installed energy capacity*" can be found.

Similar to rated capacity C_n the rated energy storage capacity is usually related to beginning of life (BOL) of a battery. This means that at BOL and SOE=100% (fully charged) the energy storage capacity EC is equal to the rated energy storage capacity (see Figure 11).

For rated capacity verification test the following equation can be used for calculation of the change of stored energy ΔE_{stored} at beginning of life (BOL). With constant current discharge time $t_{CC,D}$ till end-of-discharge voltage is reached it results

$$\left| \Delta E_{stored} \right| = \left| \int_{t_{full}=0}^{t_{CC,D}} v_{Bat,OCV,BOL}(t) \cdot \left(-\frac{I_{ref}}{n} \right) \cdot dt \right|$$
$$= \left| \frac{1}{n} \cdot \left(-I_{ref} \right) \cdot \int_{t_{full}=0}^{t_{CC,D}} v_{Bat,OCV,BOL}(t) dt \right| \tag{44}$$
$$\geq \left| \frac{1}{n} \cdot \left(-I_{ref} \right) \cdot \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat,OCV,BOL}(t) dt \right| = EC_n$$
$$\left(t_{CC,D} \geq t_{\min,EOD,CC,D1/n} = n \cdot \mathrm{h} \right)$$

If rated energy storage capacity is ideally determined, it is $t_{CC,D} = t_{min,EOD,CC,D1/n} = n\cdot$h and $|\Delta E_{stored}| = EC_n$.

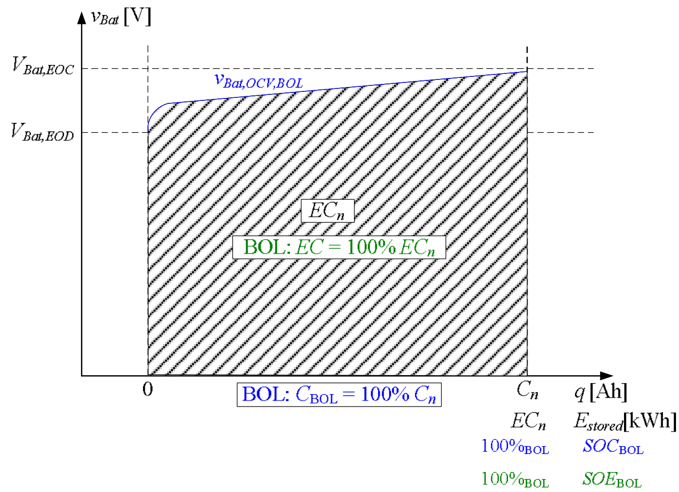

Figure 11: Rated energy storage capacity EC_n derived from open-circuit voltage at BOL

Nominal battery voltage $V_{Bat,nominal}$

Nominal voltage (according to [3]) is a suitable approximate value of the voltage used to designate or identify a cell, a battery or an electrochemical system. The nominal voltage is typically specified by the manufacturer. The following formula can be used to determine a reasonable value for nominal battery voltage

$$V_{Bat,nominal} = \frac{EC_n}{C_n} \tag{45}$$

Reference (test) power values P_{ref} and $P_{ref,n}$

The reference power (P_{ref} > 0) shall be specified as

$$P_{ref} = V_{Bat,EOD} \cdot I_{ref} \tag{46}$$

with I_{ref} as reference (test) current (I_{ref} > 0) and $V_{Bat,EOD}$ as end-of-discharge voltage as declared by the manufacturer ($V_{Bat,EOD}$ > 0). So if for example the manufacturer declares end-of-discharge voltage as $V_{Bat,EOD}$ = 650V and the reference current as I_{ref} = 60A, the reference power is P_{ref} = 39kW.

The reference power P_{ref} is intentionally defined by using the end-of-discharge voltage $V_{Bat,EOD}$ and not by using nominal battery voltage $V_{Bat,nominal}$. By this definition a kind of "*verification test discharge power*" $P_{ref,n}$, with which SOC=0% can be reached, can be defined as

$$P_{ref,n} = V_{Bat,EOD} \cdot \frac{1}{n} I_{ref} = \frac{P_{ref}}{n} \tag{47}$$

Thereby n is the time base for which the rated capacity C_n is declared. Typically it holds $P_{ref,n} = P_{Bat,cont,D,max,empty}$ and $I_{Bat,D,finish} = 1/n\ I_{ref}$ (see Figure 18).

Two other characteristic performance values are the following charging or discharging times known from uninterruptible power supplies (UPS).

Stored energy time $t_{E,stored}$

Stored energy time (according to [8]) is the minimum time during which a battery, under specified service conditions, ensures continuity of load power. So $t_{E,stored}$ is the minimum time how long a battery with a certain stored energy value can be discharged with constant power at the battery terminals. Typically it holds $t_{E,stored} = t_{min,EOD,CP}$.

Thereby the battery is assumed sufficiently charged according to '*restored energy time*' (see below). According to [8] the reference temperature of the battery is usually 25 °C. Additionally the temperature of the battery can be measured in order to derive a necessary adjustment to the expected stored energy time. During '*stored energy time test*' end-of-discharge voltage shall not fall below the specified value before stored energy time $t_{E,stored}$ has elapsed.

Stored energy times can be provided with an index which may include the constant battery terminal power as well as information about discharging and battery aging. For example the time value $t_{E,stored,Dx2,BOL}$ specifies that at beginning of life (BOL) the discharge with a constant discharge power p_{Bat} (t) = $-x2P_{ref}$ between full charge and reaching $V_{Bat,EOD}$ lasts at least $t_{E,stored,Dx2,BOL}$.

Restored energy time $t_{E,restored}$

Restored energy time $t_{E,restored}$ (according to [8]) is the maximum time required to, under normal mode of operation and with the charging capacity installed, recharge the battery so that stored energy time can again be achieved. In this regard also none constant power charging methods may be applied, to reach the necessary stored charge value or stored energy value respectively, e.g. '*CV charging*'. So usually it holds $t_{E,restored} \neq t_{min,EOC,CP}$.

Rated battery discharge efficiency $\eta_{D,n}$

Rated battery discharge efficiency is the discharge efficiency for discharging the battery with i_{Bat} (t) = $-1/n{\cdot}I_{ref}$ for rated constant current end-of-discharge time $t_{min,EOD,CC,D1/n}$ = $n{\cdot}$h starting from SOC = 100%

$$\eta_{D,n} = \frac{|W_{Bat}|}{|\Delta E_{\text{stored}}|} = \frac{\left| \frac{1}{n}\cdot(-I_{ref})\cdot \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat}(t)dt \right|}{\left| \frac{1}{n}\cdot(-I_{ref})\cdot \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat,OCV,BOL}(t)dt \right|} = \frac{\left| \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat}(t)dt \right|}{\left| \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat,OCV,BOL}(t)dt \right|} \qquad (48)$$

Typically rated battery discharge efficiency $\eta_{D,n}$ is determined at beginning of life (BOL) and for certain conditions specified by battery manufacturer. So rated battery discharge efficiency can be determined during rated capacity verification test and may be used as battery acceptance criterion.

If rated capacity C_n is properly defined by the manufacturer, at beginning of life the real constant current end-of-discharge time $t_{EOD,CC}$ is equal or higher than $t_{min,EOD,CC,D1/n}$. The end value for integrals in equation (48) is always $t_{min,EOD,CC,D1/n}$. If rated energy storage capacity is ideally determined, it is $t_{EOD,CC} = t_{min,EOD,CC,D1/n} = n{\cdot}$h. Than it holds $|\Delta E_{stored}| = EC_n$ and

$$\eta_{D,n} = \frac{\left| \int_{t_{full}=0}^{t_{\min,EOD,CC}} p_{Bat}(t)dt \right|}{EC_n} \qquad (49)$$

Assuming that the battery terminal voltage $v_{Bat}(t)$ is only depending on open-circuit voltage $v_{Bat,OCV}(t)$ and on the voltage drop over the internal battery resistance R_i, it is

$$v_{Bat}(t) = v_{Bat,OCV}(t) + R_i \cdot i_{Bat}(t) \qquad (50)$$

Thereby $p_{Bat}(t)$ can be calculated by

$$p_{Bat}(t) = v_{Bat,OCV}(t)\cdot i_{Bat}(t) + R_i \cdot i_{Bat}^2(t)\ . \qquad (51)$$

With $i_{Bat}(t) = -1/n{\cdot}I_{ref}$ it results

$$\begin{aligned} |W_{Bat}| &= \left| \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat,OCV}(t)\cdot i_{Bat}(t) + R_i \cdot i_{Bat}^2(t)dt \right| \\ &= \left| \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} \left[\underbrace{v_{Bat,OCV}(t)\cdot\left(-\frac{I_{ref}}{n}\right)}_{<0} + \underbrace{R_i\cdot\left(-\frac{I_{ref}}{n}\right)^2}_{\geq 0} \right] dt \right| \\ &= \left| \left(-\frac{I_{ref}}{n}\right) \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} v_{Bat,OCV}(t)dt \right| - \left| R_i \cdot \left(\frac{I_{ref}}{n}\right)^2 \cdot \int_{t_{full}=0}^{t_{\min,EOD,CC,D1/n}} dt \right| \\ &= |\Delta E_{stored}| - \frac{1}{n^2}\cdot R_i \cdot I_{ref}^{\ 2} \cdot t_{\min,EOD,CC,D1/n} \end{aligned} \qquad (52)$$

By that it is valid

$$\eta_{D,n} = \frac{|W_{Bat}|}{|\Delta E_{stored}|} = \frac{|\Delta E_{stored}| - \frac{1}{n^2}\cdot R_i \cdot I_{ref}^{\ 2} \cdot t_{\min,EOD,CC,D1/n}}{|\Delta E_{stored}|} = 1 - \frac{\frac{1}{n^2}\cdot R_i \cdot I_{ref}^{\ 2} \cdot t_{\min,EOD,CC,D1/n}}{|\Delta E_{stored}|} \qquad (53)$$

If rated energy storage capacity is ideally determined, it holds at beginning of life and at specified conditions

$$\eta_{D,n} = 1 - \frac{\frac{\text{h}}{n}\cdot R_{i,BOL}\cdot I_{ref}^{\ 2}}{EC_n} \qquad (54)$$

5 Characteristic values for constricted operating ranges

The height of battery current and battery power is decisive for the SOC value to which a battery can be charged or discharged. Therefore operational values limit the SOC range in which a certain constant current or power can be applied on the battery. The electric charge which is available between these SOC limits is the usable capacity C_{use} at certain operational conditions. There are different values which describe the constricted operating ranges of batteries.

Usable capacity regarding constant battery current $C_{use,CC}$

The usable capacity $C_{use,CC}$ is the capacity of a cell or a battery which can be used at certain operational conditions with certain charge or discharge currents. Like capacity C the usable capacity $C_{use,CC}$ is specified at certain operational conditions. The (actual) capacity C of a battery is always equal or higher than the usable capacity.

Due to possibly higher battery discharge currents than $i_{Bat}(t) = -1/n \cdot I_{ref}$ the end-of-discharge voltage can be reached at a higher SOC value than 0%. This is depicted in Figure 12, in which the three blue curves show the terminal voltage $v_{Bat}(t)$, if the battery is discharged with three different battery currents $i_{Bat}(t)$ starting from a fully charged battery. The graphs are valid for beginning of life and it holds $1/n<x3<x2<x1$. If only the discharge rate is given in the index of usable capacity $C_{use,CC}$, e.g. *D* for 'discharge' and "*x1*" for the C-rate, the discharging to determine the usable capacity $C_{use,CC\ Dx1}$ always starts from SOC=100% (see Figure 12). Besides discharge rate also further specific battery discharge conditions like battery aging value can be added in the index of usable capacity $C_{use,CC}$.

Similarly also at a higher charge rate the end-of-charge voltage is reached at lower SOC values than at lower charge currents. In Figure 13 the three green curves show the terminal voltage $v_{Bat}(t)$, if the battery is charged with three different battery currents $i_{Bat}(t)$ starting from an empty battery. The graphs are valid for beginning of life and it holds $1/n<y3<y2<y1$. If only the charge rate is given in the index of usable capacity $C_{use,CC}$, e.g. *C* for 'charge' and "*y1*" for the C-rate, the charging to determine the usable capacity $C_{use,CC,Cy1}$ always starts from SOC=0% (see Figure 13). Besides charge rate also further specific battery charge conditions like ambient temperature can be added in the index of usable capacity $C_{use,CC}$.

Figure 12 and Figure 13 can be combined to a set of curves as depicted in Figure 14, from which the usable capacity $C_{use,CC}$ can be derived for different constant charge and discharge currents. For example in Figure 14 both, a certain discharge rate (e.g. '*Dx1*') as well as a certain charge rate (e.g. '*Cy3*'), are used to specify the usable capacity $C_{use,CC,Cy3,Dx1}$. The resulting usable SOC range is typically smaller than 100%.

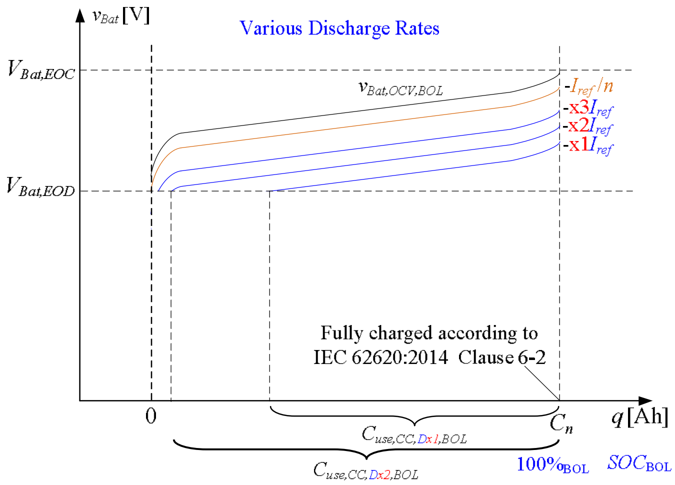

Figure 12: Reduction of usable capacity C_{use} by higher discharge currents at BOL

Sets of curves as depicted in Figure 14 shall be provided by the manufacturer for

- discharging currents in the range $I_{Bat,D,max} \leq i_{Bat}(t) \leq -1/n\ I_{ref,}$ and for
- charging currents in the range $1/n\ I_{ref,} \leq i_{Bat}(t) \leq I_{Bat,C,max}$.

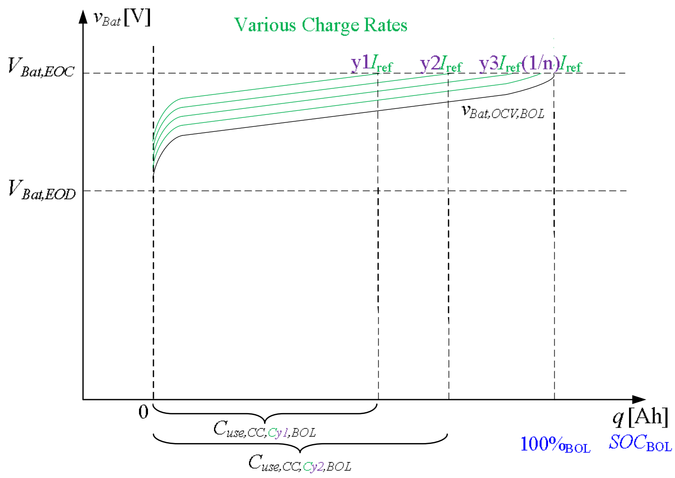

Figure 13: Reduction of usable capacity C_{use} by higher charge currents at BOL

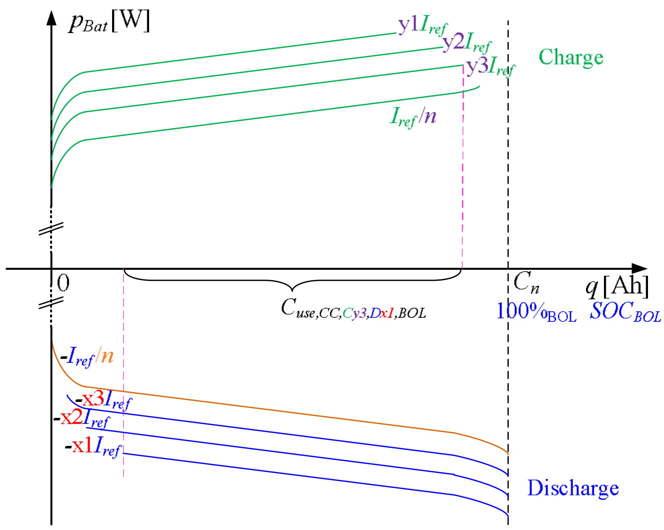

Figure 14: Set of curves for determination of usable capacity C_{use} for different constant charge and discharge currents at beginning of life (BOL)

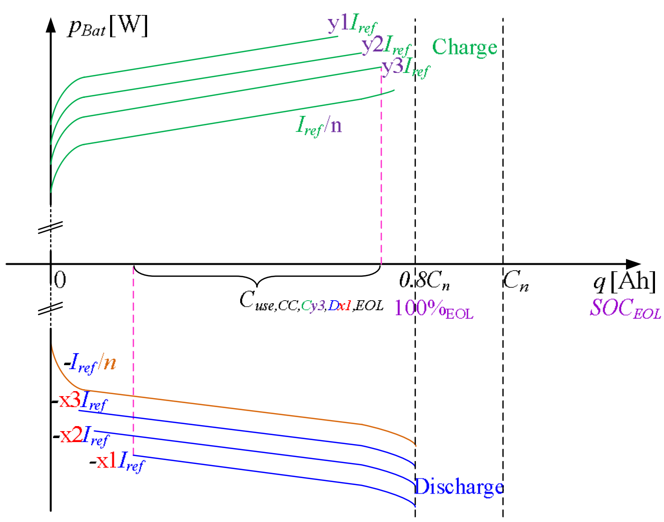

Figure 15: Set of curves for determination of usable capacity C_{use} for different constant charge and discharge currents at end of life (EOL)

Since battery aging has a decisive influence on the usable capacity (see Figure 14 and Figure 15) the set of curves for usable capacity determination are typically provided at least for beginning of life (BOL) and for end of life (EOL).
The advantage of this definition of usable capacity is, that a kind of '*usable capacity verification test*' can be performed similar to the '*capacity verification test*'.

Also time values with constant charge or discharge current can be used to specify the (minimum) usable capacity of a battery.

Usable constant charge and discharge current times

Additional to constant current end-of-discharge times $t_{min,EOD,CC}$, $t_{EOD,CC}$ and constant current end-of-charge times $t_{min,EOC,CC}$, $t_{EOC,CC}$, which only consider the lower or the upper *SOC* limit, further '*usable constant current times*' can be given for a certain usable capacity. For example regarding the usable capacity $C_{use,CC,Cy3,Dx1,BOL}$ shown in Figure 14 the usable constant current times $t_{min,use,CC,Cy3,BOL}$ and $t_{min,use,CC,Dx1,BOL}$ can be specified. The usable constant current time $t_{min,use,CC,Cy3,BOL}$ defines the minimum time for charging from minimum *SOC* to maximum *SOC* of usable capacity $C_{use,CC,Cy3,Dx1,BOL}$ with a constant charge current of $i_{Bat}(t)$ = y3I_{ref} at beginning of battery life. Accordingly the usable constant current time $t_{min,use,CC,Dx1,BOL}$ means the minimum time for discharging from maximum *SOC* to minimum *SOC* of usable capacity $C_{use,CC,Cy3,Dx1,BOL}$ with a constant discharge current of $i_{Bat}(t)$ = -x2I_{ref} at beginning of battery life. Usable constant current times depend on battery age and are defined for certain environmental conditions specified by the manufacturer.

Similar to the definition of usable capacity regarding constant battery current the usable capacity regarding constant battery power can be defined.

Usable capacity regarding constant battery power $C_{use,CP}$

The usable capacity is the capacity of a cell or a battery which can be used under certain operational conditions with constant charge or discharge power. Due to possibly higher battery discharge powers than $p_{Bat}(t) = -1/n \cdot P_{ref}$ the end-of-discharge voltage can be reached at a higher *SOC* value than 0% (or at higher *SOE* value than 0% respectively). Similarly at a higher charge rate the end-of-charge voltage is reached at lower *SOC* values (or *SOE* values respectively) than at lower charge powers. Furthermore for high charge rates the minimum *SOC* value, at which this high charge power is possible, can be higher than *SOC*=0% (see z4P_{ref} in Figure 18).
By using the sets of curves as depicted in Figure 14 or Figure 15 envelopes for charge and discharge operations can be derived as depicted in Figure 16 and Figure 17 for BOL and EOL.
As shown in Figure 18 and Figure 19 these envelopes can be used to determine the usable capacity C_{use} regarding constant battery charge and discharge powers.
For example the usable charge capacity $C_{use,CP,Cz4,Dx1}$ specifies the usable capacity with constant discharge power $x1P_{ref}$ and constant charge power z4P_{ref}. So 'Dx1' specifies discharging with a constant power with a CP-rate of *x1* ($p_{Bat}(t) = -x1 \cdot P_{ref}$) and 'Cz4' specifies charging with constant power with a CP-rate of *z4* ($p_{Bat}(t) = z4 \cdot P_{ref}$).
Again the set of curves for usable capacity are typically provided at least for beginning of life (BOL) and for end of life (EOL) (see Figure 18 and Figure 19).

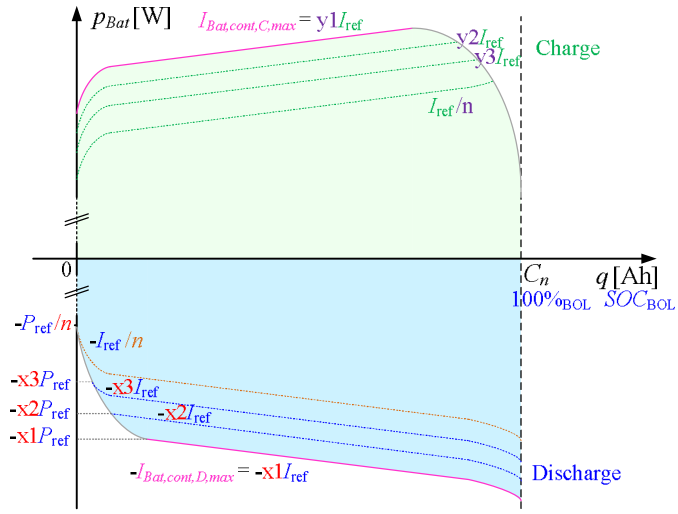

Figure 16: Envelope of allowed battery charge and discharge powers at BOL

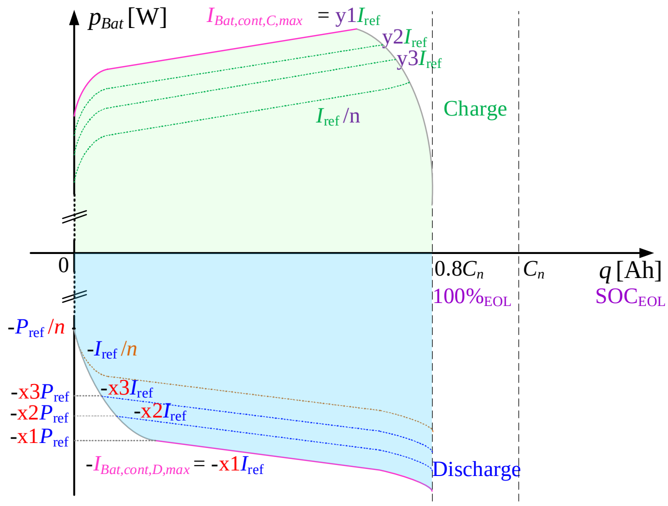

Figure 17: Envelope of allowed battery charge and discharge powers at EOL

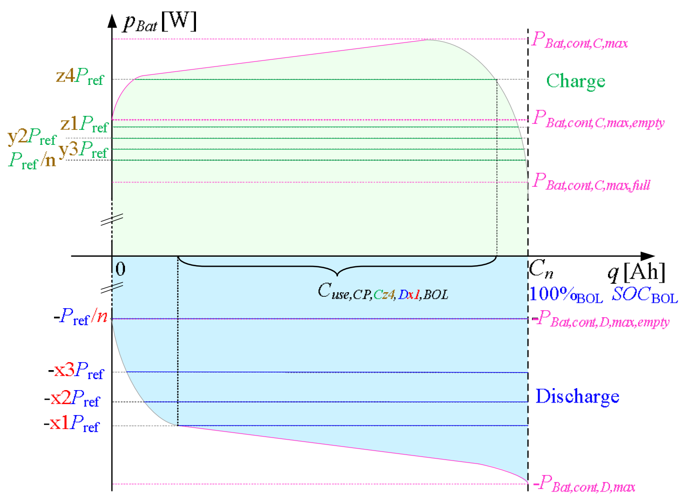

Figure 18: Determination of usable capacity regarding constant powers at BOL

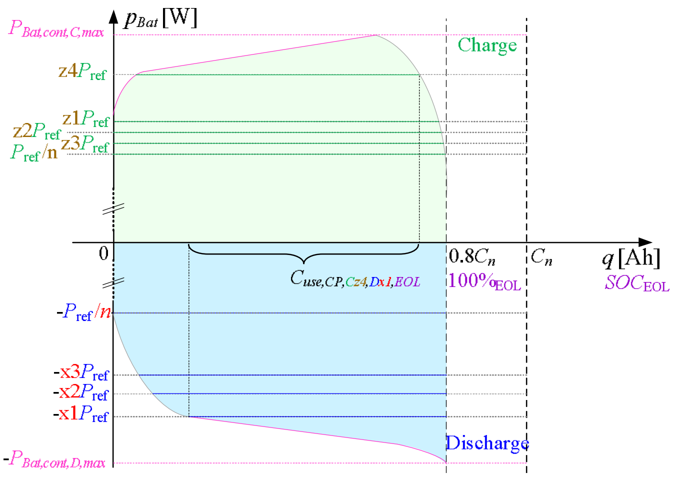

Figure 19: Determination of usable capacity regarding constant powers at EOL

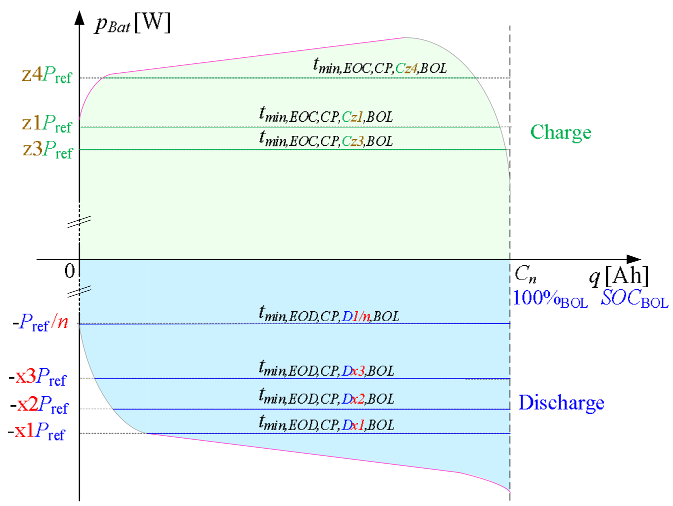

Figure 20: Stored and restored energy times for different constant powers at BOL

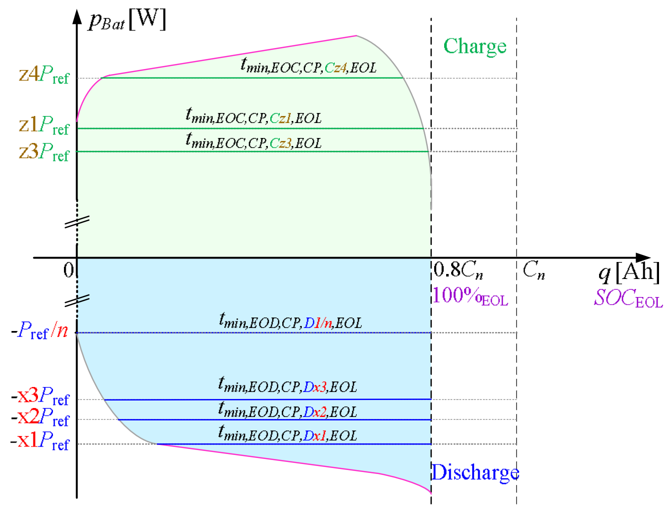

Figure 21: Stored and restored energy times for different constant powers at EOL

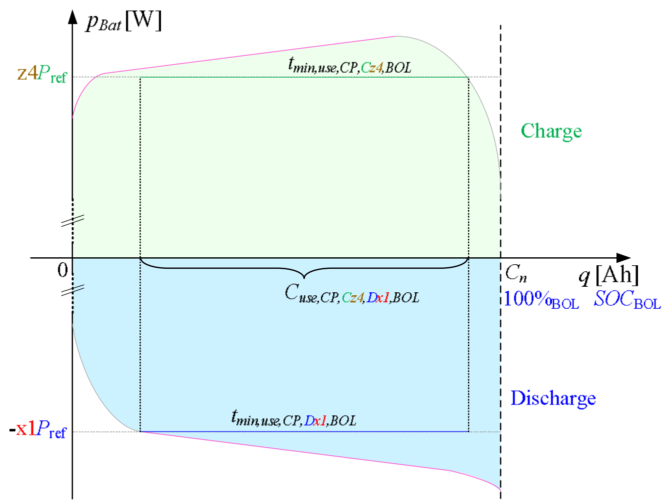

Figure 22: Stored and restored energy times for a certain usable capacity at BOL

Usable constant charge and discharge power times

For a constant power discharge starting from full state the minimum discharge times (= stored energy times) can be added in Figure 16 and Figure 17 as depicted in Figure 20 and Figure 21. Furthermore for *SOC* ranges at which a certain constant power charge is possible, the minimum charge times (= restored energy times) are put in Figure 20 and Figure 21. It should be noted that it is not possible to directly draw conclusions from the depicted *SOC* ranges to the actual constant charge and discharge power times. These time values are typically provided by the battery manufacturer regarding a certain *SOC* range, a specified battery age and given ambient conditions.

'*Usable constant power times*' can be specified for usable capacities additionally. For example for the usable capacity $C_{use,CP,Cz4,Dx1,BOL}$ shown in Figure 18 the usable constant power times $t_{min,use,CP,Cz4,BOL}$ and $t_{min,use,CP,Dx1,BOL}$ can be specified (see Figure 22). The usable constant power time $t_{min,use,CP,Dx1,BOL}$ means the minimum time for discharging from maximum *SOC* to minimum *SOC* of usable capacity $C_{use,CP,Cz4,Dx1,BOL}$ with a constant discharge power of $p_{Bat}(t)$ = -x1P_{ref} at beginning of battery life. The time duration $t_{min,use,CP,Dx1,BOL}$ can also be seen as usable stored energy time $t_{E,stored,use,Dx1,BOL}$. Accordingly the usable constant charge power time $t_{min,use,CP,Cz3,BOL}$ defines the minimum time for charging from minimum *SOC* to maximum *SOC* of usable capacity $C_{use,CP,Cz4,Dx1,BOL}$ with a constant charge power of $p_{Bat}(t)$ = z4P_{ref} at beginning of life. Since the battery is always charged with constant power, to restore the maximum *SOC* value of the usable capacity $C_{use,CP,Cz4,Dx1,BOL}$ the time duration $t_{min,use,CP,Cz4,BOL}$ can also be seen as usable restored energy time $t_{E,restored,use,Cz4,BOL}$. With reduction of the usable capacity due to aging also the usable constant power times are reduced (see $C_{use,CP,Cz4,Dx1,EOL}$ in Figure 23). The time values $t_{min,use,CP,Dx1,BOL}$ and $t_{min,use,CP,Cz4,BOL}$ shall be provided by battery manufacturer.

In regard to UPS applications usable constant power times and usable (re)stored energy times can be specified by the manufacturer for a certain battery age and for certain environmental conditions.

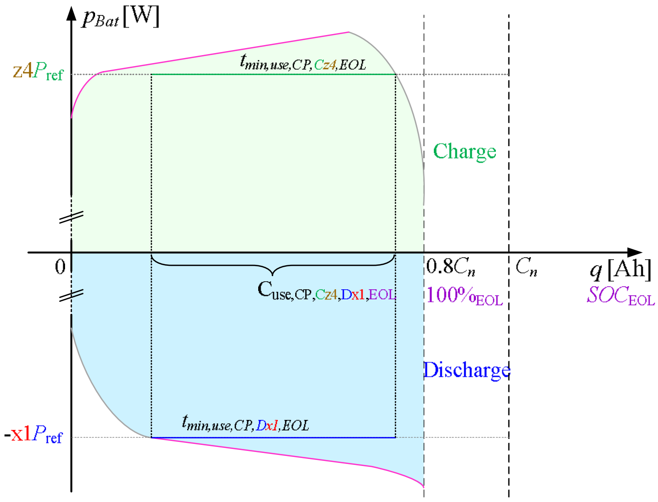

Figure 23: Stored and restored energy times for a certain usable capacity at EOL

Usable energy storage capacity EC_{use}

The usable energy storage capacity (or '*usable energy capacity*') is the energy storage capacity of a cell or a battery which can be used under certain operational conditions. For usable energy storage capacity the sign EC_{use} shall be used. Equation

$$EC_{use} = \int_{q(SOC_{min})}^{q(SOC_{max})} v_{Bat,OCV}(q) \cdot dq \qquad (55)$$

can be used to calculate usable energy storage capacity EC_{use} (see Figure 24).

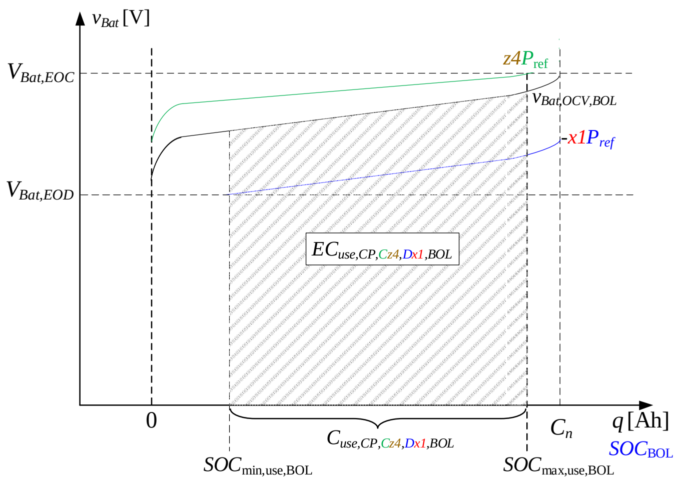

Figure 24: Determination of usable energy storage capacity regarding constant powers at BOL

Additionally with formula

$$SOE(SOC) = \frac{E_{stored}}{EC} = \frac{\int_{Q(SOC=0\%)}^{q(SOC)} v_{Bat,OCV}(q) \cdot dq}{\int_{q(SOC=0\%)}^{Q(SOC=100\%)} v_{Bat,OCV}(q) \cdot dq} \qquad (56)$$

and from usable capacity C_{use} the usable energy storage capacity and its dependency on SOE can be derived (e.g. see Figure 18 and Figure 25).

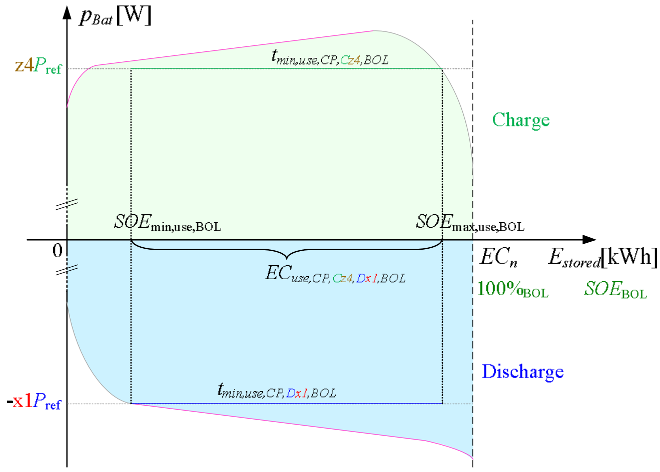

Figure 25: Envelope of allowed battery charge and discharge powers at BOL referred to SOE with usable energy storage capacity

As with usable capacity, also usable energy storage capacity can be specified regarding constant battery current $EC_{use,CC}$ and regarding constant battery power $EC_{use,CP}$.

Similarly the usable energy storage capacity at certain operational conditions can be specified by the related minimum and maximum SOE limits. The (actual) energy storage capacity is always equal or higher than the usable energy storage capacity. Besides operational conditions also battery aging and environmental conditions have got a decisive influence on usable energy storage capacity of a cell or a battery.

6 Conclusions

A consistent set of characteristic battery values is presented in this article. Even if there are some simplifications and some ideal assumptions the definitions can built a good base to achieve a common understanding regarding battery performance values for battery manufacturers and integrators of battery storage solutions in electrical power systems. Especially the presented power and energy values as well as the clarifications regarding usable energy storage capacity and usable constant power times support the comprehension of energy providers regarding performance capability of batteries. In general the values characterized in this article are well suited to be used for the design of battery storage systems and as criteria to examine the performance of batteries and secondary cells.

In addition to the presented set of battery values further distinctive battery values applicable for determination of battery performance can be found in literature and for practical applications. Regarding battery aging the terms '*state of health*' (SOH) and '*equivalent cycle*' are important values not treated in this article (see [9]). Also the measurement of internal a.c. and d.c. resistance as described in [6] can be used as acceptance criterion of batteries.

REFERENCES

[1] Shing-Lih Wu, Hung-Cheng Chen, Shuo-Rong Chou, Fast Estimation of State of Charge for Lithium-Ion Batteries, Energies Journal, 2014, 7, 3438-3452.

[2] Seref Soylu, Electric Vehicles - Modeling and Simulations, ISBN 978-953-307-477-1, 201.

[3] IEC 60050-482: 2004, International Electrotechnical Vocabulary - Primary and secondary cells and batteries.

[4] IEC/TS 62600-1: 2011, Marine energy – Wave, tidal and other water current converters – Part 1: Terminology.

[5] IEC 61427-2: 2015, Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 2: On-grid applications.

[6] IEC 62620: 2014, Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications.

[7] IEC 61434: 1996, Secondary cells and batteries containing alkaline or other non-acid electrolytes – Guide to the designation of current in alkaline secondary cell and battery standards.

[8] IEC 62040-3: 2011, Uninterruptible power systems (UPS) – Part 3: Method of specifying the performance and test requirements.

[9] M. Galeotti, L. Cin, C. Giammanco, S. Cordiner, A. Di Carlo, Performance analysis and SOH (state of health) evaluation of lithium polymer batteries through electrochemical impedance spectroscopy, Journal of Energy Storage, 2015.05.148.