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Determination of Lithium-Ion Battery Capacity for Practical Applications

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Abstract: Batteries are becoming highly important in automotive and power system applications. The lithium-ion battery, as the fastest growing energy storage technology today, has its specificities, and requires a good understanding of the operating characteristics in order to use it in full capacity. One such specificity is the dependence of the one-way charging/discharging efficiency on the charging/discharging current. This paper proposes a novel method for the determination of battery capacity based on experimental testing. The proposed method defines battery energy capacity as the energy actually stored in the battery, while accounting for both the charging and discharging losses. The experiments include one-way efficiency determination based on multiple cycles conducted under different operational and ambient conditions, the goal of which is to acquire the charging/discharging energies. The measured energies are corrected for one-way efficiencies to obtain values actually stored in a battery during charging or actually extracted from the battery during discharging. The proposed method is tested in a laboratory and compared against two existing baseline methods at different ambient temperatures. The results indicate that the proposed method significantly outperforms the baseline methods in terms of the accuracy of the determined battery energy capacity and state-of-energy. The prime reason for the good performance of the proposed method is that it accounts for both the operational (efficiency) and the ambient (temperature) conditions.

Keywords: battery capacity; energy capacity; state-of-charge; state-of-energy; round-trip efficiency; one-way efficiency

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1. Introduction

Battery systems are often considered as a source/sink with defined operational capabilities and fixed limitations in available capacity. In reality, battery systems consist of different connection combinations of battery cells with characteristics that depend on both the operational and the ambient conditions.

In the following subsections, we first explain the common terms used to describe the battery characteristics, then we present our literature review, define the present paper's contribution and, finally, present the organization of the rest of the paper.

1.1. Battery Parameters

Battery capacity is a measure of a battery's ability to store a certain amount of charge or energy. It represents the amount of electricity or energy generated due to electrochemical reactions in the battery. It can be defined as battery charge capacity, measured in Ah, or as battery energy capacity, measured in Wh. It is important to distinguish between the nominal average battery capacity defined by the manufacturer and the actual battery capacity. The nominal capacity is defined for a new battery used under controlled conditions. The actual available battery capacity depends on the operational and environmental conditions, as well as the age and state-of-health of the battery.

Battery state-of-charge is a measure of the amount of charge currently stored in a battery with respect to the fully charged battery. On the other hand, battery state-of-energy is a measure of the amount of energy currently stored in a battery with respect to the fully charged battery. Finally, battery state-of-health is a measure of the overall battery condition:

$$SOH = \frac{Q^{\mathrm{m}}}{Q^{\mathrm{n}}} \cdot 100\%, \tag{1}$$

where Q^{m} is the capacity of cycle number m in Ah, while Q^{n} is the nominal capacity of the battery in Ah [1].

C-rate is a ratio of the charging or discharging electrical current in Amperes and the nominal charge capacity of a battery in Ampere-hours. At 1C, the battery (dis)charges with the current corresponding to its Ah rating (e.g., 1C for a 10 Ah battery is 10 A, 0.5C is 5 A, etc.). On the other hand, P-rate is a ratio of the charging or discharging power in Watts and the nominal energy capacity of a battery in Watt-hours. At 1P, the battery (dis)charges with the power corresponding to its Wh rating (e.g., 1P for a 10 Ah battery with 10 V nominal voltage is 100 W, 0.5P is 50 W, etc.).

Battery efficiency can be defined as a measure that accounts for the losses occurring during battery charging and discharging. Since the only quantities that can be measured are the charging/discharging current, the battery voltage, and the heat losses, the efficiency can be determined and evaluated in the following ways:

- Battery Coulombic efficiency—based on the current measurements [2];
- Battery voltaic efficiency—based on the voltage measurements [2];
- Battery energy efficiency—based on both the current and the voltage measurements [3,4] or based on the heat loss measurements [5].

As mentioned above, in industry applications, the measures of power and energy (P-rate) are more convenient than measures of current and charge capacity (C-rate), as the appliances (consumers) are defined by the consumption of power and energy. Thus, this work considers the energy capacity and energy efficiency parameters.

Furthermore, battery efficiency can be calculated as round-trip efficiency or as one-way (charging/discharging) efficiency.

Round-trip energy efficiency can be calculated as the ratio of the energy discharged from the battery and the energy charged into the battery over the same SOC range:

$$\eta^{\mathrm{cycle,E}} = \eta^{\mathrm{ch,E}} \cdot \eta^{\mathrm{dis,E}} = \frac{E^{\mathrm{dis}}}{E^{\mathrm{ch}}}, \tag{2}$$

where $E^{\mathrm{ch}} = U^{\mathrm{ch}} \cdot I^{\mathrm{ch}}$ and $E^{\mathrm{dis}} = U^{\mathrm{dis}} \cdot I^{\mathrm{dis}}$ are determined by experimental measurements taken across battery terminals. This means that neither the exact amount of energy stored in the battery, nor the exact amount of energy available to extract from the battery, can be determined. As the round-trip efficiency can be defined as the charging times the discharging efficiency ($\eta^{\mathrm{cycle,E}} = \eta^{\mathrm{ch,E}} \cdot \eta^{\mathrm{dis,E}}$), one-way efficiencies are, in the literature, sometimes defined as the square root of round-trip efficiency, which would imply that one-way charging and discharging efficiencies are equal [6,7]. Additionally, in many studies, it can be seen that the charging efficiency is neglected, i.e., it is set to 1, while the one-way discharge efficiency takes over the entire value of the round-trip efficiency [8]. In both cases, an error in determining the battery capacity is inevitable because the one-way efficiency of both charging and discharging depends on factors such as operating and ambient conditions. Also, a battery cannot have 100% charging efficiency regardless of the power rate.

One-way efficiency can be determined in three ways:

- Using heat loss measurements;
- Using open-circuit voltage vs. state-of-charge characteristics;

- using voltage/current measurements and the solution of the nonlinear optimization problem that consists of several measured round-trip efficiencies.

As stated in [5], it is possible to measure the heat released from the battery and calculate the one-way efficiency of the battery under different operational and environmental conditions. However, as the total heat release from the battery is the sum of the irreversible and reversible heat generation, the efficiency determined in this way neglects the effects of reversible heat generation.

One-way battery energy efficiency can be determined based on the open-circuit voltage vs. state-of-charge characteristics [3]. The advantages of this method are its simplicity and the possibility to determine the one-way efficiency dependence on the state-of-charge level. The downside of this method is that it neglects Coulombic losses.

Another method for the determination of one-way energy efficiencies, presented in [4], is based on the solution of the nonlinear optimization problem that consists of several round-trip to one-way efficiency relationships, where round-trip efficiencies are experimentally determined parameters. One-way energy efficiencies determined in this way account for both the voltaic and the Coulombic losses. The downside of this method is that it ignores the nonlinearity of the charging/discharging characteristics.

Operational conditions are primarily related to the rate of charging and discharging current/power of the battery. Power and energy are the primary values of interest in the power system industry and the automotive industry, as opposed to the current and charge values. Thus, this work focuses on battery power characteristics that can easily be translated into energy characteristics. Ambient temperature has the greatest effect on the battery performance characteristics as compared to other ambient parameters such as humidity and vibrations [9], which is the reason for including the temperature effect in our work.

1.2. Literature Review

Different methods for the estimation of the battery cell energy capacity are evaluated in a large number of industry and scientific works [10]. The most common method is the calculation of the remaining battery energy capacity (in Wh) as a multiplication of the nominal energy capacity ($E^{\mathrm{n}} = U^{\mathrm{n}} \cdot Q^{\mathrm{n}}$, where U^{n} is the nominal voltage of the battery in V and Q^{n} is the nominal charge capacity of the battery in Ah, both determined by the manufacturer) and the state-of-charge (SOC) determined by Coulomb counting [11,12], as expressed in (3). However, this method neglects voltage charging and discharging characteristics, dynamic processes and battery capacity dependence on the power, the state-of-charge, the state-of-health, the ambient parameters, etc.

$$E_{\mathrm{SOC}}^{\mathrm{remaining}}(t) = E^{\mathrm{n}} \cdot SOC(t). \tag{3}$$

Another common method is defining the remaining battery energy capacity (in Wh) as a multiplication of the state-of-energy (SOE) and the nominal energy, where the state-of-energy is determined as a ratio of the integrated charged or discharged power ($P^{\mathrm{ch}} = U^{\mathrm{ch}} \cdot I^{\mathrm{ch}}$, $P^{dis} = -U^{dis} \cdot I^{dis}$, in W) and the nominal or maximum energy of the battery (in Wh) [7,13–15]:

$$E_{\mathrm{SOE}}^{\mathrm{remaining}}(t) = E^{\mathrm{n}} \cdot SOE(t), \tag{4}$$

$$SOE(t) = SOE(t-1) + \frac{1}{E^{\mathrm{n}}} \cdot \int_{\mathrm{t}-1}^{\mathrm{t}} P^{\mathrm{ch/dis}}(\tau) d\tau. \tag{5}$$

Both common methods neglect the energy capacity dependence on operational and environmental parameters. To reduce the error of operational losses, fixed operational round-trip efficiency is commonly accounted for in the method presented in [16]. Many other more complex methods have been developed for the determination of the remaining energy; for example, equivalent circuit models with implemented information about

electrolyte characteristics [17], impedance and resistance experimental measurements [18], and other methods based on experimental and historical data [19]. Equivalent circuit models are highly dependent on input data (usually collected from controlled laboratory environments), so their application in real dynamic operations may result in inaccurate estimations of the remaining energy.

On the other hand, methods that use Kalman filters are able to provide more accurate results in dynamic situations. In [20], an online capacity estimation method based on enhanced Coulomb counting with the adaptive Kalman filter was applied to eliminate the capacity estimation error. The Kalman filter updates the covariance and noise from the error, and the capacity estimation is performed by the fusion of the Gaussian probability density functions of the predicted value (based on state-of-health estimation) and the measured capacity value. The reduced error in estimation is experimentally verified. A method for SOE estimation based on SOC estimation with an extended Kalman filter upgraded with current, voltage, and temperature response prediction is presented in [21]. The presented method accounts for the full life cycle of the battery. Additionally, the authors presented a method for the estimation of the entire battery pack state-of-energy. A dual forgetting factor-based adaptive extended Kalman filter for SOC estimation is presented in [22]. The authors combined the existing extended Kalman filter for online SOC estimation [13,23–25] with the SOE estimation method [12] to obtain reliable SOC and SOE estimations.

Methods with prediction algorithms are often limited to capacity estimation under given conditions. The authors of [26] developed a prediction technique for the estimation of the remaining driving range of an electric vehicle. The proposed method considers operational dynamics, but neglects temperature variability. On the other hand, the authors of [27] presented a predictive algorithm that predicts both future operation and temperature conditions. The model for operation conditions is based on an equivalent circuit model, and temperature prediction is based on historical data.

Methods with neural networks that use historical data may consider environmental and operational impact on capacity, but they highly depend on the quantity and choice of historical data and the methods used for the training of the models [28,29]. Similarly, fuzzy logic models are able to provide highly precise estimations based on historical and experimental data under given operational and environmental conditions [30]. Machine learning model [31] has proved that the diversity of feasible data is critical for estimation with high accuracy. The presented model uses a multichannel technique based on voltage, current, and temperature profiles, and our results show that it outperforms the conventional method, which only uses voltage profile.

As stated in [32], the disadvantages of complex models are the accuracy dependence on training/historical data, computational costs, and development complexity.

1.3. Contribution

The conducted literature review indicates that the existing baseline methods for battery capacity determination neglect the influence of the charging and discharging current/power rate on one-way efficiencies, and thus on the determination of the battery capacity value. Moreover, in most cases, the influence of ambient temperature on the battery characteristics is also neglected, which limits the possibility of applying these methods in varying ambient conditions. To overcome this research gap, this paper offers the following contributions:

- It proposes a method for determining battery capacity that considers charging/discharging (one-way) efficiencies, as well as different ambient temperatures;
- To verify the proposed method, an experimental comparison is performed to compare it with the baseline methods.

1.4. Organization of the Paper

The rest of the paper is organized as follows. The novel method for battery capacity estimation is presented and elaborated in Section 2. Section 3 presents the experimental

setup, a description of the baseline methods, a case study, and the experimental results. Finally, an overview of the presented work is given in Section 4.

2. Proposed Method for Determination of Average Battery Energy Capacity and State-of-Energy

This section describes the proposed method for battery energy capacity determination step-by-step, as shown in Figure 1.

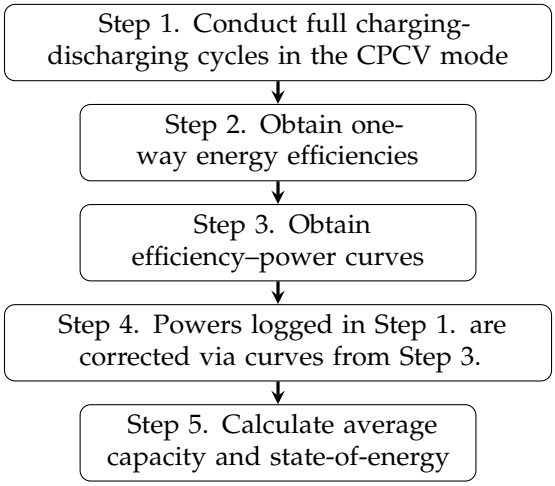

Figure 1. Algorithm for the determination of average battery energy capacity and state-of-energy in the method *Proposed* .

In the first step, the battery is cycled with the aim of obtaining the charging and discharging energies for a number of full cycles. Cycles are always started at a fully depleted battery (a fully depleted battery means that a non-depleted battery is discharged until the battery's low-voltage limit has been reached and the current has dropped below the specified cut-off value) (0% SOE), while each charging and discharging process is terminated when the current drops below the low cut-off threshold (an end-of-charge current specified by the manufacturer). Full cycles in the constant power–constant voltage (CPCV) mode are conducted, always using the same charging/discharging P-rate within a cycle. In CPCV mode, the battery is charged and discharged at constant power until the effect of voltage saturation, where the battery voltage reaches the high (for charging) or the low (for discharging) voltage limit. In that moment, the constant voltage mode begins and the power consequently decreases. The set of K full cycles is repeated at each considered ambient temperature, in order to obtain the efficiency–power characteristics for different ambient temperature conditions.

The second step is the one-way efficiency determination. As Coulombic losses for the observed lithium-ion battery cell are less than 1% [33], their effect is neglected in this research. Thus, one-way efficiencies are determined from the open-circuit voltage vs. state-of-charge (OCV-SOC) characteristic (in this work, the OCV-SOC characteristic is also determined for each considered ambient temperature), according to [3]:

$$\eta_{\mathrm{k}}^{\mathrm{Prop,ch,E}} = \frac{\int_0^{T^{\mathrm{ch}}} U^{\mathrm{OC}}(soc) \cdot I_{\mathrm{k}}^{\mathrm{ch}}(\tau) d\tau}{\int_0^{T^{\mathrm{ch}}} U_{\mathrm{k}}^{\mathrm{ch}}(\tau) \cdot I_{\mathrm{k}}^{\mathrm{ch}}(\tau) d\tau}, \tag{6}$$

where $k \in [1 \ldots K]$, $U^{\mathrm{OC}}(soc)$ is an OCV-SOC characteristic and $I_{\mathrm{k}}^{\mathrm{ch}}(\tau)$ is the charging current, and

$$\eta_{\mathrm{k}}^{\mathrm{Prop,dis,E}} = \frac{\int_0^{T^{\mathrm{dis}}} U_{\mathrm{k}}^{\mathrm{dis}}(\tau) \cdot I_{\mathrm{k}}^{\mathrm{dis}}(\tau) d\tau}{\int_0^{T^{\mathrm{dis}}} U^{\mathrm{OC}}(soc) \cdot I_{\mathrm{k}}^{\mathrm{dis}}(\tau) d\tau}, \tag{7}$$

where $I_k^{dis}(\tau)$ is the discharging current. In this way, it is possible to determine one-way charging and discharging efficiencies $\eta_k^{Prop,ch,E}$ and $\eta_k^{Prop,dis,E}$ for all K P-rates. Here, only the CP mode of each cycle (for both charge and discharge) is used to determine the efficiencies, so that the one-way efficiencies correlate with the P-rates.

Battery efficiency is a nonlinear function depending on operating conditions (power rate). To approximate this nonlinearity, an efficiency–power curve is introduced in the third step based on linear interpolation between K determined one-way efficiencies in the whole range of the operating powers, as shown in Figures 2 and 3.

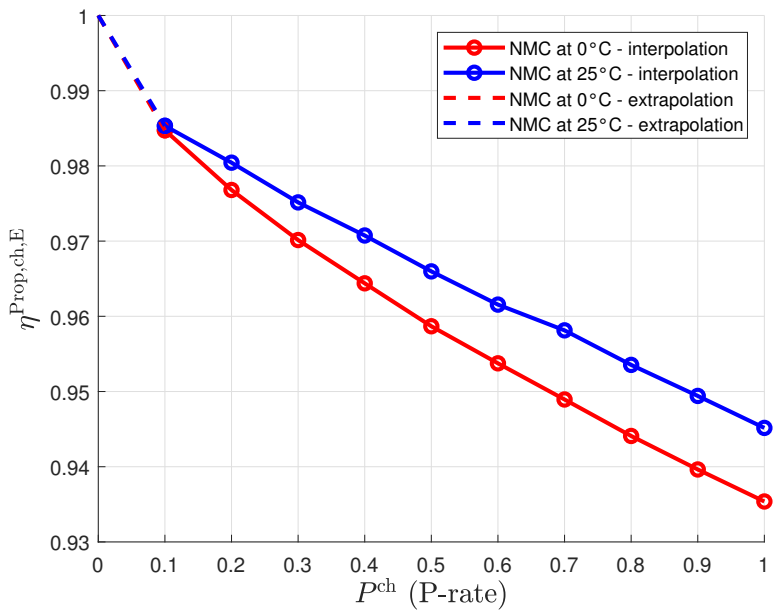

Figure 2. Charging efficiencies depending on the P-rate in the CP mode.

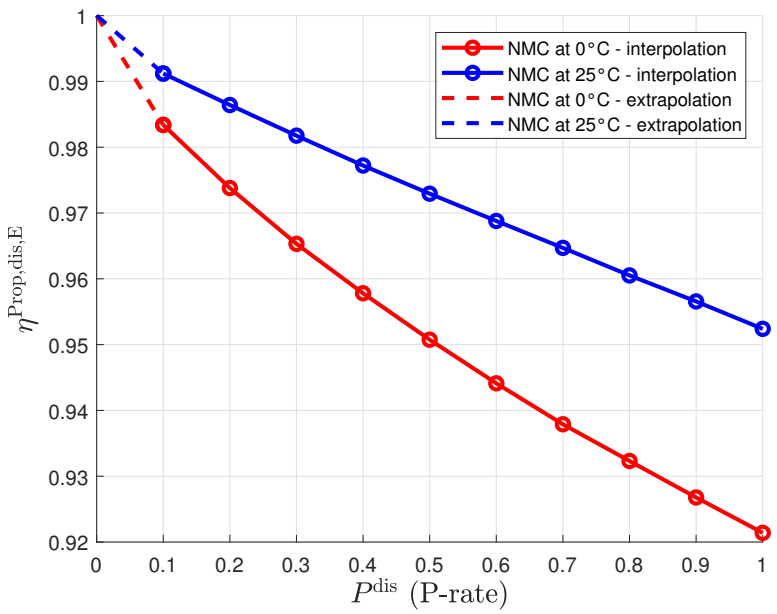

Figure 3. Discharging efficiencies depending on the P-rate in the CP mode.

In the fourth step, for every full cycle (out of K full cycles in the CPCV mode), the logged powers ($P_{\mathrm{k}}^{\mathrm{ch}}(t)$ and $P_{\mathrm{k}}^{\mathrm{dis}}(t)$) are corrected for one-way energy efficiencies by using the determined efficiency–power curves:

$$P_{\mathrm{k}}^{\mathrm{Prop,ch}}(t) = \eta^{\mathrm{Prop,ch,E}}(P^{\mathrm{ch}}) \cdot P_{\mathrm{k}}^{\mathrm{ch}}(t), \tag{8}$$

$$P_{\mathrm{k}}^{\mathrm{Prop,dis}}(t) = \frac{P_{\mathrm{k}}^{\mathrm{dis}}(t)}{\eta^{\mathrm{Prop,dis,E}}(P^{\mathrm{dis}})}, \tag{9}$$

where $\eta^{\mathrm{Prop,ch,E}}(P^{\mathrm{ch}})$ and $\eta^{\mathrm{Prop,dis,E}}(P^{\mathrm{dis}})$ are charging and discharging efficiency–power curves from Figures 2 and 3, respectively.

Finally, in the fifth step, by integrating the corrected powers, K values of $E_{\mathrm{k}}^{\mathrm{Prop,ch}} = \int_0^{T^{\mathrm{ch}}} P_{\mathrm{k}}^{\mathrm{Prop,ch}}(\tau)d\tau$ and K values of $E_{\mathrm{k}}^{\mathrm{Prop,dis}} = \int_0^{T^{\mathrm{dis}}} P_{\mathrm{k}}^{\mathrm{Prop,dis}}(\tau)d\tau$ are obtained, representing the energy stored in a battery during charging and energy extracted from a battery during discharging, respectively. In an ideal case, values of the corrected energies $E_k^{\mathrm{Prop,ch}}$ and $E_k^{\mathrm{Prop,dis}}$ are all the same, representing the energy that can be stored in a battery. In reality, due to various effects and uncertainties (various electrochemical phenomena, e.g., loss of lithium ions due to lithium plating, as well as measurement uncertainties), these values slightly vary, and the battery energy capacity is declared to be the mean of all the corrected energies:

$$E_{\mathrm{av}}^{\mathrm{Prop}} = \frac{\sum_{k=1}^{K} E_{\mathrm{k}}^{\mathrm{Prop,ch}} + \sum_{k=1}^{K} E_{\mathrm{k}}^{\mathrm{Prop,dis}}}{2 \cdot K}. \tag{10}$$

Expression (10) represents the fifth and last step of the *Proposed* method, where state-of-energy is defined as

$$SOE(t) = SOE(t-1) + \frac{1}{E_{\mathrm{av}}^{\mathrm{Prop}}} \cdot \left(\int_{\mathrm{t}-1}^{\mathrm{t}} P^{\mathrm{Prop,ch}}(\tau)d\tau - \int_{\mathrm{t}-1}^{\mathrm{t}} P^{\mathrm{Prop,dis}}(\tau)d\tau \right), \tag{11}$$

where $P^{\mathrm{Prop,ch}}(t)$ and $P^{\mathrm{Prop,dis}}(t)$ are corrected powers, given by (8) and (9), for the time frame $\langle t-1, t]$.

3. Experimental Verification of the Proposed Method for Determination of Battery Energy Capacity and State-of-Energy

3.1. Experimental Setup

A lithium nickel manganese cobalt oxide (NMC) battery cell type is tested. The manufacturer's specifications of this cell are listed in Table 1. Battery cells used in the experiments are displayed in Figure 4. To reduce the error due to inconsistent cell parameters, the experimental procedure described in Section 3.3 was applied to six identical battery cells, the specifications of which are given in Table 1. Since similar results were obtained for all cells, the verification was successful, and only one set of results is presented in the present paper.

The experiments were conducted using a professional Itech IT-M3413 bidirectional DC power supply (inverter) with the following voltage and current characteristics: 0∼150 V, −12∼12 A [34]. The control was set up using in-house developed NI LabVIEW software (https://www.ni.com/en/support/documentation/release-notes/product.labview.html, accessed on 6 September 2023). A compressor-cooled Memmert ICP110 incubator with a working temperature range of −12∼+60 °C was used to create specific testing environments. The experimental setup is displayed in Figure 5, where the bidirectional DC power supply used for charging and discharging of the battery cells is located in the middle of the figure, the battery cells under test are located in a compressor-cooled incubator on the right-hand side, while a graphical interface of the in-house developed control program is presented on the left-hand side of the figure.

Figure 4. Battery cells under test.

Table 1. Specifications of the tested battery cell.

Parameter \ Battery Cells	NMC
Type	18,650
Nominal capacity	3.0 Ah
Nominal energy capacity	10.8 Wh
Nominal voltage	3.6 V
Charging voltage	4.2 V
Discharge cut-off voltage	2.5 V
Cut-off current	0.05 A
Max. charge current	1.33 C
Max. discharge current	6.67 C

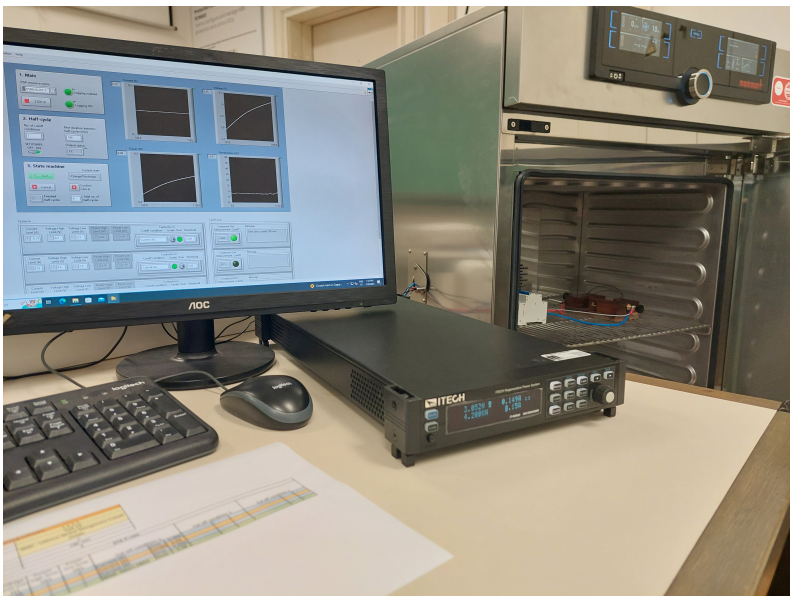

Figure 5. Experimental setup.

3.2. Compared Methods for Determination of Battery Energy Capacity and State-of-Energy

Building on the existing state-of-the-art techniques, this paper presents a novel method for determining the capacity and state-of-energy of the battery, with the aim of outperforming the existing baseline methods in terms of accuracy. As described in Section 2, the *Proposed* method is based on one-way efficiencies, and considers the effect of different operating and environmental conditions.

Two established (baseline) methods for battery energy capacity and state-of-energy calculation are compared with the *Proposed* method: method *Nominal*, where the determination of the state-of-energy is based on the manufacturer's data only, and method *Conventional*, where the determination of the state-of-energy is based on the measured round-trip efficiency.

3.2.1. Method *Nominal*

Nominal average voltage is defined as U^{n} in V and nominal Coulombic capacity as Q^{n} in Ah. Both values are specified by the battery manufacturer, who may also specify the nominal average energy capacity under different ambient temperatures. On the other hand, energy efficiency is usually not defined by the manufacturer. Thus, the average energy capacity of the battery estimated with the method *Nominal* is $E_{\mathrm{av}}^{\mathrm{Nom}} = U^{\mathrm{n}} \cdot Q^{\mathrm{n}}$ at ambient temperature 25 °C, and for other ambient temperatures, the average energy capacity is as defined by the manufacturer.

The manufacturer's data for the battery under test are the following: $E_{\mathrm{av}}^{\mathrm{Nom}} = 10.8$ Wh at 25 °C, $E_{\mathrm{av}}^{\mathrm{Nom}} = 8.64$ Wh at 0 °C. Energy efficiencies are not defined, so round-trip and one-way efficiencies are defined as follows: $\eta^{\mathrm{Nom,ch,E}} = \eta^{\mathrm{Nom,dis,E}} = \eta^{\mathrm{Nom,cycle,E}} = 1$.

3.2.2. Method *Conventional*

To account for the energy losses while estimating energy capacity, in method *Conventional*, the round-trip efficiency is determined experimentally, whereby a fully depleted battery (0% SOE) is fully charged (to 100% SOE) and then fully discharged under given operating and environmental conditions. The charging and discharging energies are defined as $E^{\mathrm{Conv,ch}} = \int_0^{T^{\mathrm{ch}}} U^{\mathrm{ch}}(\tau) \cdot I^{\mathrm{ch}}(\tau) d\tau$ and $E^{\mathrm{Conv,dis}} = \int_0^{T^{\mathrm{dis}}} U^{\mathrm{dis}}(\tau) \cdot I^{\mathrm{dis}}(\tau) d\tau$. The round-trip efficiency is then calculated as

$$\eta^{\mathrm{Conv,cycle,E}} = \frac{E^{\mathrm{Conv,dis}}}{E^{\mathrm{Conv,ch}}}. \tag{12}$$

One-way charging and discharging efficiencies are calculated as square roots of the round-trip efficiency to account for charging and discharging losses separately:

$$\eta^{\mathrm{Conv,ch,E}} = \eta^{\mathrm{Conv,dis,E}} = \sqrt{\eta^{\mathrm{Conv,cycle,E}}}. \tag{13}$$

The average battery capacity is calculated as an average of the charging and discharging energies from an experimental full round-trip cycle (0–100% SOE) with one-way efficiencies accounted for:

$$E_{\mathrm{av}}^{\mathrm{Conv}} = \frac{E^{\mathrm{Conv,ch}} \cdot \eta^{\mathrm{Conv,ch,E}}}{2} + \frac{E^{\mathrm{Conv,dis}}}{2 \cdot \eta^{\mathrm{Conv,dis,E}}}. \tag{14}$$

In the experimental verification below, the fixed round-trip efficiency measured for a 1.0P charging/discharging cycle at an environmental temperature of 0 °C is $\eta_{0^\circ\mathrm{C}}^{\mathrm{Conv,cycle,E}} = 0.8648$, while at an environmental temperature of 25 °C, it amounts to $\eta_{25^\circ\mathrm{C}}^{\mathrm{Conv,cycle,E}} = 0.8991$. According to (13), one-way efficiency in this method is determined as the square root of round-trip efficiency. Thus, for 0 °C, $\eta_{0^\circ\mathrm{C}}^{\mathrm{Conv,ch,E}} = \eta_{0^\circ\mathrm{C}}^{\mathrm{Conv,dis,E}} = \sqrt{\eta_{0^\circ\mathrm{C}}^{\mathrm{Conv,cycle,E}}} = 0.9300$, while for 25 °C, $\eta_{25^\circ\mathrm{C}}^{\mathrm{Conv,ch,E}} = \eta_{25^\circ\mathrm{C}}^{\mathrm{Conv,dis,E}} = \sqrt{\eta_{25^\circ\mathrm{C}}^{\mathrm{Conv,cycle,E}}} = 0.9482$.

In this method, the battery capacity is defined as in (14); see Table 2 for specific numbers.

Table 2. Estimated average battery energy capacities.

Method \ Temperature	0 °C	25 °C
Nominal	8.64 Wh	10.80 Wh
Conventional	9.86 Wh	10.53 Wh
Proposed	10.05 Wh	10.68 Wh

3.2.3. Method *Proposed*

In method *Proposed*, the battery energy capacity is obtained with one-way efficiencies and ambient temperature accounted for. The efficiency–power curves are determined as described in Section 2. Ten P-rates ($K = 10$) are chosen to cover the expected battery's operational range. Thus, the battery is fully cycled from a 0.1 P-rate to a 1.0 P-rate with 0.1P steps at ambient temperatures 0 °C and 25 °C. The obtained charging and discharging efficiencies are shown in Table 3 and in Figures 2 and 3. The cells under test are significantly more efficient at higher environmental temperatures; this is especially the case for the discharging efficiency. At 1P, the discharging efficiency at 25 °C is over 0.95, while at 0 °C, it is just above 0.92. The charging efficiencies are much closer, at 0.945 and 0.935.

Table 3. One-way energy efficiencies for NMC battery cell.

Conditions \ P-Rate	0.0P	0.1P	0.2P	0.3P	0.4P	0.5P	0.6P	0.7P	0.8P	0.9P	1.0P
Charging at 0 °C	1	0.985	0.977	0.970	0.964	0.959	0.954	0.949	0.944	0.940	0.935
Discharging at 0 °C	1	0.983	0.974	0.965	0.958	0.951	0.944	0.938	0.932	0.927	0.921
Charging at 25 °C	1	0.985	0.980	0.975	0.971	0.966	0.962	0.958	0.954	0.949	0.945
Discharging at 25 °C	1	0.991	0.986	0.982	0.977	0.973	0.969	0.965	0.961	0.957	0.952

The proposed average battery energy capacity is then determined according to (10) and related equations; see Table 2 for specific numbers.

A graphical comparison of battery energy capacities determined in charging and discharging cycles, with and without one-way efficiencies accounted for, is presented in Figure 6 for the ambient temperature of 25 °C. Here, it is evident that the measured discharging energy (E^{dis}) is always lower than the measured charging energy (E^{ch}) within the cycle, the difference being greater for higher P-rates. This is normal and expected, since current/voltage measurements are taken across battery terminals. When correction for one-way efficiencies is applied (see Section 2), the values of $E^{\mathrm{Prop,dis}}$ and $E^{\mathrm{Prop,ch}}$ are obtained, representing the estimated values of energies actually stored in the battery. As presented in Figure 6, their values are approximately the same, indicating that charging/discharging energy losses are accurately described by one-way efficiencies.

3.3. Case Study

In the manufacturer's product specification of the battery under test, nominal quantities are defined with standard charge at 0.5 C-rate and with standard discharge at 0.2 C-rate. To be in line with these data, the experimental test is arranged accordingly. The considered methods for battery energy capacity and state-of-energy determination (the proposed method and the baseline methods) are compared by applying them to the full charge/discharge cycle depicted in Figure 7. The battery under test is first fully depleted. Then, the battery is fully charged at 0.5 P-rate in time frame $[t_1, t_2]$, and, finally, fully discharged at 0.2 P-rate in time frame $[t_2, t_3]$ (see Figure 7). Both charging and discharging are performed in the CPCV mode, which means they are terminated after a specified

voltage limit has been reached and the current has dropped below a specified cut-off value. Therefore, at the end of discharge (at t_3) the battery is at $SOE = 0\%$, and this value is used as a benchmark for the comparison of the accuracies of the three methods. Since charging and discharging rates are different, the battery cells are tested under different operating conditions. To test the methods under different environmental conditions, all the tests are performed in a compressor-cooled incubator at two different temperatures: 0 °C and 25 °C.

At the end of the case study cycle, states-of-energies are calculated as follows:

- In methods *Nominal* and *Conventional*, state-of-energy is defined as (15)

$$SOE(t) = SOE(t-1) + \frac{1}{E_{\mathrm{av}}} \cdot \left(\int_{t-1}^{t} \eta^{\mathrm{ch,E}} \cdot P^{\mathrm{ch}}(\tau) d\tau - \int_{t-1}^{t} \frac{P^{\mathrm{dis}}(t)}{\eta^{\mathrm{dis,E}}} d\tau \right), \quad (15)$$

  where $P^{\mathrm{ch}}(t)$ and $P^{\mathrm{dis}}(t)$ are powers measured from the side of the inverter in time frame $\langle t-1, t]$, while triplets $(E_{\mathrm{av}}, \eta^{\mathrm{ch,E}}, \eta^{\mathrm{dis,E}})$ are either $(E_{\mathrm{av}}^{\mathrm{Nom}}, \eta^{\mathrm{Nom,ch,E}}, \eta^{\mathrm{Nom,dis,E}})$ or $(E_{\mathrm{av}}^{\mathrm{Conv}}, \eta^{\mathrm{Conv,ch,E}}, \eta^{\mathrm{Conv,dis,E}})$.
- In method *Proposed*, state-of-energy is calculated according to (11).

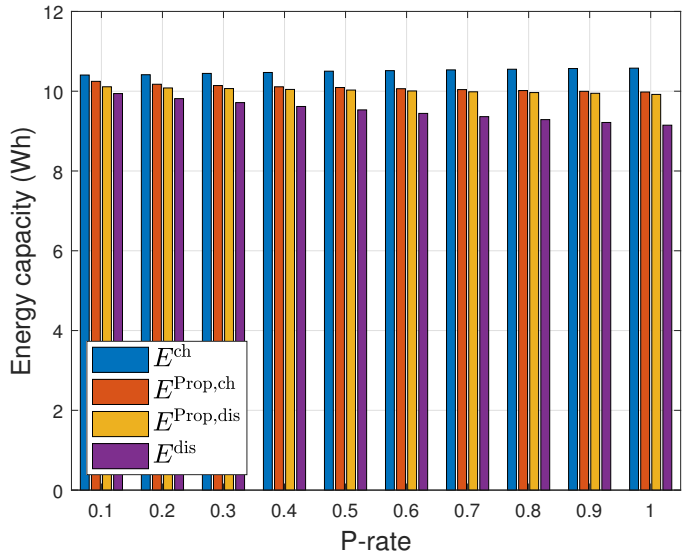

Figure 6. Charging and discharging battery energy capacities at 25 °C.

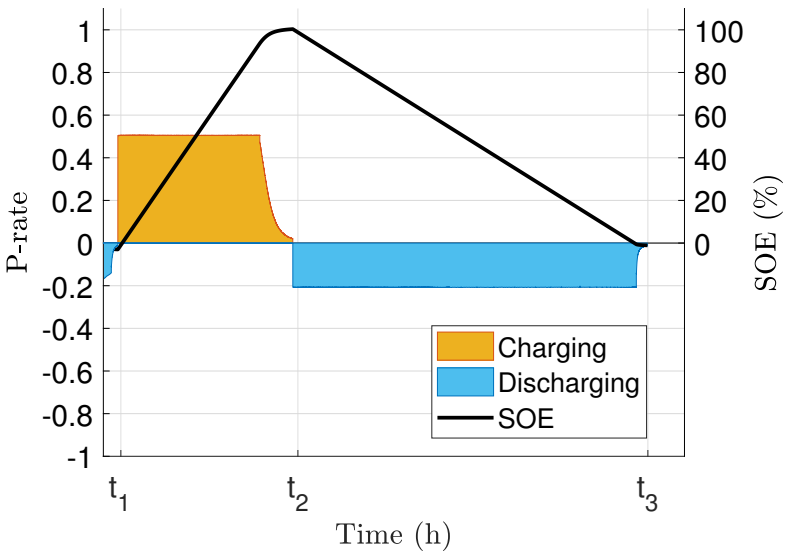

Figure 7. Case study cycle.

3.4. Results

An overview of the estimated average energy capacities is presented in Table 2.

As mentioned in Section 3.3, the experiments were conducted at two different temperatures: 0 °C and 25 °C. The nominal value of the average battery energy capacity at an ambient temperature of 25 °C is 10.8 Wh. As the battery completed a certain number of cycles through experimental testing, the capacity degraded, as expected. Methods *Conventional* and *Proposed* use data from experimental measurements, so the estimated capacity is lower than the nominal capacity. The nominal value of the average battery energy capacity at an ambient temperature of 0 °C is declared as 80% of the average nominal capacity at 25 °C. This estimate seems exaggerated because higher values were determined by experimental measurements with the *Conventional* and the *Proposed* methods. Namely, the estimated capacity at 0 °C is 96.6% for method *Conventional* and 94.1% for method *Proposed* compared to the estimated values at 25 °C.

An overview of the determined states-of-energies at the end of the case study cycle is presented in Table 4.

The real value of the state-of-energy at the end of the case study cycle is 0%, i.e., the battery is fully depleted, as described in Section 3.3 (thus explaining the 0% values in the row *Measured*). Values in rows *Nominal*, *Conventional*, and *Proposed* were calculated from the expressions (15) and (11), respectively (thus, they are directly dependent on the accuracy of the capacity and one-way efficiency values used). The results demonstrate that, in this case study, the method *Proposed* provides much more accurate estimations for both ambient temperatures as compared to estimations with methods *Nominal* and *Conventional*. This is because the method *Proposed* uses battery parameters determined under different ambient temperature and operating conditions. The most important distinction compared to the two baseline methods is that the *Proposed* method uses variable one-way efficiencies (adapted to the power rate), as well as the battery capacity averaged over a wide range of cycles conducted at different rates. Although the method *Conventional* uses battery parameters determined under different ambient temperatures as well, its disadvantage is that only one fixed battery energy efficiency is used, which is based on a single fixed charging/discharging power rate at a given temperature. Therefore, this model cannot be adapted to different operating conditions, and thus, the estimation is less accurate. Method *Nominal* uses values determined by the manufacturer, and thereby neglects operational effects, as well as the state-of-health of the battery. Therefore, the estimations with the method *Nominal* are the least accurate.

Table 4. Estimated states-of-energies at the end of the case study cycle.

Method \ Temperature	0 °C	25 °C
Measured	0%	0%
Nominal	11.11%	6.56%
Conventional	9.05%	6.38%
Proposed	2.73%	1.84%

4. Conclusions

In this work, we analyze battery capacity and state-of-energy estimation, along with their dependence on the operational and ambient conditions. The operational conditions are related to the charging and discharging current/power rates, while the ambient conditions are related to the ambient temperatures at which the batteries are used. Both operational and ambient conditions affect the efficiency and the health of the batteries to different extents, depending on the range of observed conditions. The established (baseline) methods for the estimation of battery capacity and state-of-energy either consider only nominal values given by the manufacturer, or neglect the variable operational and/or ambient conditions. Our work presents a novel method that considers both the variable

operational and ambient conditions. It is based on the experimental determination of one-way (charging and discharging) efficiencies for different current/power rates under different ambient conditions. Prerequisites for implementing the presented method (at each given temperature) are as follows: (i) conduct a set of full charging/discharging cycles, (ii) determine one-way efficiencies, (iii) determine efficiency–power characteristics, and finally, (iv) calculate energies actually stored in the battery during each full charging (and energies actually extracted from the battery during each full discharging). The method estimates the current state of the battery (for the given ambient temperature); thus, it is recommended that the procedure is repeated periodically in order to take into account the battery's aging effects.

The accuracy of the proposed method is proven by testing NMC cells. Laboratory tests demonstrated that the proposed method is significantly more accurate than the baseline ones. At the end of the case study battery cycle, the real state-of-energy was 0%, i.e., the battery was fully depleted. With the proposed method, the estimated value of the state-of-energy is 2.7% at the ambient temperature of 0 °C and 1.8% at the ambient temperature of 25 °C, which is considerably more accurate than the baseline methods, where the results range from 6.4% to 11.1%.

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Nomenclature

The following nomenclature is used in this manuscript:

E^{ch}	Charging energy obtained by integration of P^{ch}
E^{dis}	Discharging energy obtained by integration of P^{dis}
$E_{\mathrm{av}}^{\mathrm{Nom}}$	Average battery capacity estimated with method *Nominal*
$E_{\mathrm{av}}^{\mathrm{Conv}}$	Average battery capacity estimated with method *Conventional*
$E_{\mathrm{av}}^{\mathrm{Prop}}$	Average battery capacity estimated with method *Proposed*
$E^{\mathrm{Prop,ch}}$	Charging energy obtained by integration of $P^{\mathrm{Prop,ch}}$ in method *Proposed*
$E^{\mathrm{Prop,dis}}$	Discharging energy obtained by integration of $P^{\mathrm{Prop,dis}}$ in method *Proposed*
$\eta^{\mathrm{cycle,E}}$	Round-trip energy efficiency
$\eta^{\mathrm{ch,E}}$	One-way charging energy efficiency
$\eta^{\mathrm{dis,E}}$	One-way discharging energy efficiency
$\eta^{n,cycle,E}$	Nominal round-trip energy efficiency defined by the manufacturer
$\eta^{Nom,ch,E}$	One-way charging energy efficiency in method *Nominal*
$\eta^{Nom,dis,E}$	One-way discharging energy efficiency in method *Nominal*
$\eta^{Conv,cycle,E}$	Round-trip energy efficiency in method *Conventional*
$\eta^{Conv,ch,E}$	One-way charging energy efficiency in method *Conventional*

$\eta^{Conv,dis,E}$	One-way discharging energy efficiency in method *Conventional*
$\eta^{Prop,ch,E}$	One-way charging energy efficiency in method *Proposed*
$\eta^{Prop,dis,E}$	One-way discharging energy efficiency in method *Proposed*
$P^{\mathrm{ch}}(t)$	Charging power measured across battery terminals
$P^{\mathrm{dis}}(t)$	Discharging power measured across battery terminals
$P^{\mathrm{Prop,ch}}(t)$	Charging power corrected via efficiency–power characteristic in method *Proposed*
$P^{\mathrm{Prop,dis}}(t)$	Discharging power corrected via efficiency–power characteristics in method *Proposed*
$SOE(t)^{\mathrm{Nom}}$	State-of-energy in method *Nominal*
$SOE(t)^{\mathrm{Conv}}$	State-of-energy in method *Conventional*
$SOE(t)^{\mathrm{Prop}}$	State-of-energy in method *Proposed*

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