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# Application-independent protocol for predicting the efficiency of lithium-ion battery cells in operations

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ABSTRACT

Despite a continuous reduction in battery prices, investment in storage systems carries a high risk. Indeed, many applications lack an adequate test protocol and method to predict the performance of batteries in operations. In this paper, we focus on lithium-ion battery energy storage systems (BESS), for which we introduce a novel method. With this method, predicting the efficiency of lithium-ion BESS becomes possible for any application from a single set of measurements. We show that evaluating the battery resistance as a function of the C-rate provides general “capability charts” based on which the efficiency can be evaluated under arbitrary operation profiles. Application-specific test procedures therefore become unnecessary. We have applied the novel procedure on three different lithium-ion cell technologies and illustrate its accuracy in the example of grid-connected BESS used for primary control reserve.

## 1. Introduction

Battery energy storage systems (BESS) are already used in many industrial applications such as mobility [1,2], integration of renewable energy sources (RES) [3], and ancillary services in distribution and transmission grids [4,5]. In Italy, for example, regulations mandate RES to contribute to the security and stability of the network [6–8]. However, RES plants are subject to the variable nature of the primary resources (wind, sunlight). BESS can help RES integration by providing additional power capability and energy capacity. They are indeed well suited to a variety of grid applications, such as primary control reserve (PCR), secondary control reserve, voltage regulation, peak shaving, load shifting and energy trading [9,10]. Installed BESS capacity for grid application is now in excess of 2.5 TWh worldwide [11].

Much attention is being paid to the capital costs of BESS, in particular to the initial investment. Progress on that front is accelerating with increasing deployment, since the price of battery cells, like that of photovoltaic (PV) modules and other high-technology, mass-produced devices, is exponentially decreasing with the cumulated volume of production. As a result, the price of lithium-ion batteries is expected to reach 150 US$/kWh by 2030 [12]. However, the total cost of ownership of BESS includes other factors such as, in some cases, air conditioning to maintain the system in its operating temperature range, and in all cases by the cost of electricity lost over a charge/discharge cycles. Both are determined by the efficiency of the battery; losses can also lead to accelerated degradation of the battery [13], [14]. The energy efficiency is hereinafter defined as the ratio between the energy made available by the battery and the one required to charge it. The efficiency depends on many factors such as the ambient temperature, state of charge (SoC) excursion and current rate (C-rate) in charge and discharge [13], [15], [16].

Product datasheets published by cell manufacturers provide information on e.g., energy density, power density, number of cycles to failure. However, information on efficiency is scarce and is insufficient to compare the performance of different batteries. In addition, we found a lack of standardized testing procedures to compare different cells for a specific usage in spite of an abundant literature on the characterization of lithium-ion battery cells. In Ref. [17] the authors asses the performance of three different lithium-ion cells for plug-in hybrid electric vehicles (PHEV) under the IEC 62660-1 standard [18]. This standard defines ad-hoc conditions of test for lithium-ion cells used in electric vehicles. There is therefore no guarantee that the test results are applicable in other applications. In Ref. [19] the authors tested various cells and modules and claim to have used “consistent set of test

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**Table 1**
Main characteristics of the tested cells, from the manufacturer's datasheets.

| Chemistry | Geometry | Model | Capacity [mAh] | Energy density [Wh/kg] | Power density [W/kg] | Voltage range [V] | Rated voltage [V] |
|---|---|---|---|---|---|---|---|
| LFP | Cylindrical | A123 ANR26650 | 2500 | 110 | 2600 | 2–3.6 | 3.3 |
| LNCO | Cylindrical | BOSTON POWER Swing5300 | 5300 | 205 | 1000 | 2.75–4.2 | 3.65 |
| LTO | Prismatic | GWL POWER LY-LTO-30Ah | 30000 | 42 | – | 1.85–2.75 | 2.4 |

procedures intended to determine their performances characteristics for automotive applications". They indeed develop their own testing procedures starting from the USAB/DOE programs [20]. In Ref. [21] the authors developed specific testing procedures for both automotive and stationary applications. In Refs. [22], [23] different performance testing protocols are proposed for lithium-ion cells. In particular, [24] defines the battery efficiency measurement under different test conditions, such as: fast charge test, aging test, actual operation test and battery vibration test. In Ref. [25] the ISO/CD 12405-1/2 and IEC 62660-1 (Section 7.8.1.2 "Energy efficiency test – test by temperature") standards are compared and the measurement of efficiency is defined for the pulse tests under different current rates (ranging from 1/3C–10C), current profiles, temperatures (from −20 °C to 45 °C) and SoC levels (from 20% to 100%).

In this paper, we address the issue of estimating lithium-ion BESS efficiency for any possible usage profile (i.e. each possible application). In Section 3, we present the novel methodology, the associated testing procedure, and the testing results which show the "capability charts" to be used for the efficiency estimation. Finally, in Section 4, the accuracy of the proposed methodology is illustrated on the grid application of primary control reserve.

## 2. Methods and materials

Literature separates BESS efficiency into two major definitions: coulombic and energy efficiencies [26].

The coulombic efficiency $\eta_C$ is defined as ratio between the extracted and injected charge over a cycle defined by SoC limits:

$$\eta_C = \frac{\int I_{discharge} dt}{\int I_{charge} dt} \tag{1}$$

This ratio is an indicator of the reversibility of the redox reactions taking place in a cell. A coulombic efficiency of 1 means that the same electric charge has been moved during the charge and discharge phases (respecting the same SoC limits). Coulombic efficiency for lithium ion cells is typically very close to unity. Deviations from unity imply parasitic reactions, which lead to capacity losses due to the alteration of the active materials at the electrodes [27]. Reducing these deviations to achieve stable cells require developments on the electrolytes, electrode materials and electrode coatings.

Energy efficiency $\eta_E$ relates to the amount of extracted and injected energy between two SoC limits. Efficiency impacts directly on the operational costs and it is an effective indicator to compare different technologies. In fact, higher efficiency means lower joule losses which turn in lower energetical costs to charge the battery (given the same load to be met) and to supply air conditioning systems to control ambient temperature. Typically the round trip efficiency is defined as in [24]:

$$\eta_E = \frac{\int I_{discharge} V dt}{\int I_{charge} V dt} \tag{2}$$

Efficiencies are related to the operating conditions such as ambient temperature, SoC range, C-rates and the charging/discharging modes[1]: constant current (CC), constant voltage (CV), pulsed charge, etc.

The available testing procedures present two main limitations: (i) the time required to map the battery efficiency over the different operating conditions; (ii) discrepancy between test and operational current profiles, leading to uncertainty on the actual field efficiency of BESS.

In the present paper, three lithium-ion cell technologies have been adopted as a benchmark for the analyses: lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (LNCO) and lithium titanate (LTO). In Table 1 we summarize the manufacturers' specifications.

The tests have been run at the BFH–CSEM Energy Storage Research Center (ESReC), located in Nidau, Switzerland, using the following equipment (Fig. 1):

- Constant current (CC): current is injected or extracted until specific voltage limits are reached.
- Voltage controlled (CV): current is injected or extracted based on the difference between the current cell voltage and the fixed charger voltage. The process continues until the current goes below a specific threshold.
- PEC– ACT 0550 battery tester equipped with 20 parallel, 5V-50A channels. This specific battery tester is a fully programmable machine and each channel can be programmed and used independently by the user. The machine has 100 μsec based internal sampling, control and capacity calculations and the FPGA hardware controls both current and voltage with a ± 0.005% FSD accuracy on the voltage readings and ± 0.03% FSD accuracy on current readings. For the purpose of this work, the battery tester was used to charge and/or discharge the different Li-ion cells by following a dedicated testing procedure (detailed in Section 3.1). Each cell was physically connected to one of the channels of the battery tester.
- ESPEC-ARU 1100 climatic chamber with a volume of 1100 L and a temperature range of −45 °C/180 °C. This machine has been used to control the ambient temperature during the testing procedure executed with the battery tester. The cells have been physically located inside the climatic chamber.

## 3. Novel methodology for efficiency estimation

We propose a test methodology to estimate the energy efficiency of lithium ions cells independently from the current profile of the application. The idea is to map the losses of BESS as a function of different current rates in both charge and discharge. This allows to draw so-called "capability charts" which can be used to derive efficiency for every possible usage profile, without having to run tests tailored on the specific application.

We assumed that the power losses during a charge-discharge cycle are mainly due to joule effect and equals to $RI^2$ where $I$ is the

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[1] Charge and discharge can be current or voltage controlled. Specifically.