Performance Testing of a Megawatt-Scale Battery Storage for Energy Trading

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ABSTRACT

Large-scale battery energy storages (BESS) are being used more and more for various applications such as system services in the power grid. The importance of their use in short-term energy trading, such as day-ahead and intraday trading, has been growing steadily due to increasing and more dynamic energy prices. In current technical and economic simulations and trading models, batteries are often represented as energy reservoirs that can charge and discharge a constant power within a specified time frame, which can lead to significant discrepancies between planned and physical delivery. Since batteries and consequently BESS cannot deliver the same power over the whole state of charge (SOC) range, their real operating ranges and limits have to be investigated in order to successfully use BESS in energy trading. With an intraday performance test of the lithium-manganese-oxide (LMO) batteries of our hybrid BESS M5BAT, we show capabilities and limitations of the battery units. The results show that the LMO batteries meet the performance and requirements of the intraday market over a wide SOC range. However, especially in the upper and lower SOC ranges, the power available from the batteries is reduced. When parameterizing trading models for batteries, special attention has to be given to the efficiencies of the batteries, power electronic components and transformers under the respective load points so that the deviations between the trading plan and reality do not become too large. Based on our results for a relatively aggressive profile, we find that LMO batteries are well suited for short-term energy trading applications, adhering to safe temperature levels in the case of our system. Further, we find that with the appropriate knowledge of efficiencies, short-term BESS operations can be optimized with sufficient accuracy. Using the example of M5BAT, this work provides insights in performance characteristics of the operation of BESS.

Keywords: *battery storage system, power capability, hybrid large-scale battery storage system, performance testing, intraday trading.*

1. INTRODUCTION

As a result of the advancing energy transition and the falling prices of Li-ion batteries, the market for battery energy storage systems (BESS) has grown rapidly and further growth is expected in the future [1–3]. On the contrary to home storage systems that are mostly used for better utilization of energy generated from renewable sources, large-scale storage systems have so far often been used for grid services. Due to the fast response time of BESS and the recent market adjustments, the frequency containment reserve (FCR) market is particularly relevant for BESS, which are providing a large portion of the FCR in Germany [4, 5]. In addition to grid services, large-scale BESS can also be used for other applications such as intraday trading, grid boosters or integration of renewable energies. As the market volume for FCR is limited, interest in spot markets for energy trading is increasing. There, the revenue potential has also increased significantly in recent years due to

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more fluctuating prices [6, 7]. The use of BESS for system services is already proven and the utilization rates and lifetimes can be well estimated [8–10]. For energy trading, however, accurate load profiles and resulting battery aging are not publicly available on a larger scale. In addition, to simplify the planning of trading operations, battery storages are often modeled as energy reservoirs with a fixed efficiency [11]. Various trading models were also able to show monetary advantages through value stacking, i.e. the simultaneous operation of different markets [12–14].

In order to better understand the limits of battery storages under load, a performance test has already been carried out on the M5BAT battery storage system [15]. The resulting limitations were used to develop an intraday trading test using the M5BAT multi-use optimization framework [16]. In the context of this work, the intraday trading test was performed. The test provides insight into real battery behavior and identifies gaps where the M5BAT multi-use optimization framework can be improved. In addition, since only the Li-ion (LMO battery units) were used for testing and modeling, the test is representative for other lithium-based BESS.

2. METHODOLOGY

As the goal of the test is to assess the technical capabilities of the LMO system, as well as evaluating the feasibility of optimized operation profiles, a virtual partial M5BAT topology has been defined, consisting of four LMO battery units, four inverters and two transformers, each attached to two inverters and their respective battery units. In order to perform the stress test of the LMO battery units of M5BAT, an aggressive intraday trading profile has been optimized for this specific topology utilizing the M5BAT multi-use optimization framework introduced in [16]. In this case, the single-use operation of the system has been optimized for the application of energy arbitrage in the intraday market. Since the stress test is primarily a technical performance test of the real system and does not consider the monetary output or aging, an aggressive arbitrage trading profile including different levels of power for extended periods of time meets with the testing requirements. In Figure 1 the procedure followed within this test is illustrated. The M5BAT multi-use optimization framework receives user input, timeseries price data and characteristic values for the components. The output is the optimized schedule which then is used for the field testing. The logged data from the field test is evaluated extensively and the results serve as updates for the M5BAT multi-use optimization framework. Also, the results are published within this work.

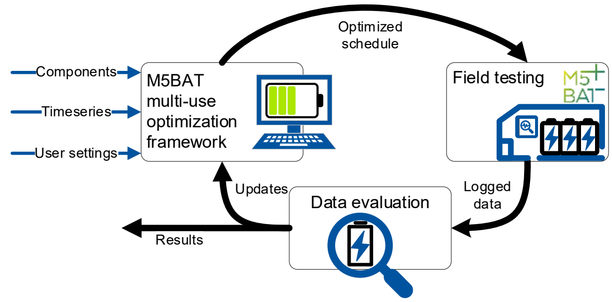

Figure 1: Schematic illustration of the procedure within the scope of this test

Under real trading conditions of a BESS or other assets on the intraday market, power delivery is optimized continuously and can consider real-time technical constraints of the asset when determining the physical delivery in the upcoming time slot. For the purposes of this test, a power delivery schedule had to be approved in advance by our marketing partner, ruling out the possibility of optimizing power delivery in real time or considering unforeseen unavailabilities when trading. Nevertheless, this constraint gives us the opportunity to test the accuracy of our BESS scheduling tool for the planning of a 72-hour delivery plan and to evaluate the extent of the cumulative error across the fulfillment horizon. With this first physical test of our scheduling tool, it is possible to further parametrize the tool and to improve on current parameter assumptions based on experimental results and real operating conditions of M5BAT.

2.1. Model Parametrization

The M5BAT multi-use optimization framework considers energy throughput costs or life cycle costs (LCC) that serve as a proxy for battery aging, penalizing every megawatt hour of energy throughput of the battery unit both while charging and discharging. The LCC are defined in formula (1).

According to Figgener *et al.* [1], system costs for large-scale BESS varied between 310 €/kWh and 465 €/kWh in average for 2022. Since the purpose of the stress test is to test the limits of the current configuration of the LMO battery units of M5BAT, the lower boundary of the price range is assumed as a reinvestment price in order to calculate the energy throughput costs that influence the aggressiveness of the trading algorithm.

With the specific investment cost for a new system estimated at 310 €/kWh to favor cycle intensive trading as per the requirements of the test at hand and the nominal number of cycles at 4000, corresponding with the supplier information given for the installed LMO system

$$LCC\ [€/MWh] = \frac{specific\ investment\ costs\ of\ new\ acquisition}{2 \cdot nominal\ number\ of\ cycles\ of\ existing\ system} \quad (1)$$

[17, 18]. The LCC amount to 38.75 €/MWh for LMO systems.

Further, the available State of Energy (SOE) range has been adjusted as an input for the optimization model, in order to consider the actual power availability of the BESS while maintaining the linearity of the model. The SOE range for which the LMO systems have full power availability has been determined using the test performed in [15] under the assumption that State of Charge (SOC) translates to SOE for the purposes of the power and energy based optimization model employed. With this information, the assumption for a constant power delivery of 630 kW by each LMO battery unit for the SOE range of 10 % to 80 % is derived.

In addition, an initial and final SOE for all battery units is predefined as 50 % in the optimization model. The reason for defining a final SOE for the optimization is to prevent the profit driven objective function from discharging the system completely towards the end of the operation period. Prior to the start of the test, M5BAT was brought to this state of energy by manual override in order to conform to the starting point set in the test profile generated by the model.

In order to avoid discrepancies caused by simplified efficiency models of inverters and transformers, we employ load-dependent efficiency models parametrized with technical data of M5BAT components. In addition to basic efficiency models, assumptions of constant retrievable output powers from the BESS can contribute to discrepancies in fulfillment. In reality, retrievable power outputs of BESS will depend largely on the SOC of the respective battery units. To consider this in the optimized trading profile presented, SOE ranges have been defined for which the LMO battery units of M5BAT can deliver their full power. This parametrization is based on the stress tests conducted on M5BAT by Koltermann *et al.* [15]. Furthermore, energy efficiencies and states of health of the LMO battery units have been modeled according to measurements performed during the operation of M5BAT [10, 15].

2.2. *Input Data and Test Profile*

The input data is a time series of intraday continuous price data from October 5th to 8th 2022 and shown in Figure 2. This 3-day price data is used due to the variety of characteristics such as low-price regions at or below 0 €/MWh and high price spikes to more than 500 €/MWh. The M5BAT multi-use optimization framework calculates the 72 hour schedule plan for intraday trading shown in Figure 2 [16]. This price differences within the test causes the framework to implement phases with low and high energy throughput and additional quick changes between charging and discharging procedures. For the battery high stress and low stress phases are present within the 3-day testing.

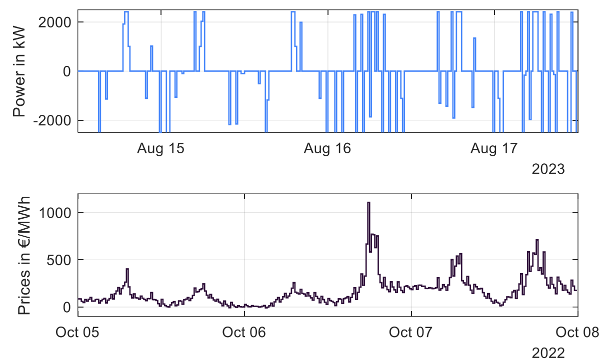

Figure 2: Input Intraday continuous price data from October 5th to 8th 2022 and resulting power profile from August 14th to 17th 2023 [6]

The schedule was directly implemented in the Energy Management System (EMS) of the BESS to perform the test. Due to higher expected temperatures and thus higher loads on the components of M5BAT the test was scheduled for summertime.

3. RESULTS AND DISCUSSION

The intraday continuous test results are focused on the overall SOC, the power output, the temperature development, and the efficiency of the BESS. All results are compared to the model results.

3.1. *SOC*

The previously set SOC or SOE limits of the model were set to 10 % to 80 % according to [15]. Within the testing schedule no SOE adjustments were intended nor performed. In Figure 3 a) the planned and reached SOC trajectory is shown. Within the first rest phase in a high SOC, a difference of 2.5 % between the measured and modeled SOC is recognizable. The rising difference in the rest phase gives an indication that the losses in standby mode were assumed to be too low in the framework. After the discharging cycle (Figure 3 b)) a SOC difference of 6.5 % is visible. The differences that have already arisen here are propagated during the test. Due to the phases of full discharge and falling below the 10 % limit, corrections are made automatically, as less energy is discharged than planned due to throttling. The SOC-differences between the plan and the measurement are presented in Figure 3 c) as a histogram. Mostly the difference is between 4 %-points and 10 %-points, while the largest difference observed is at nearly 16 %-points.

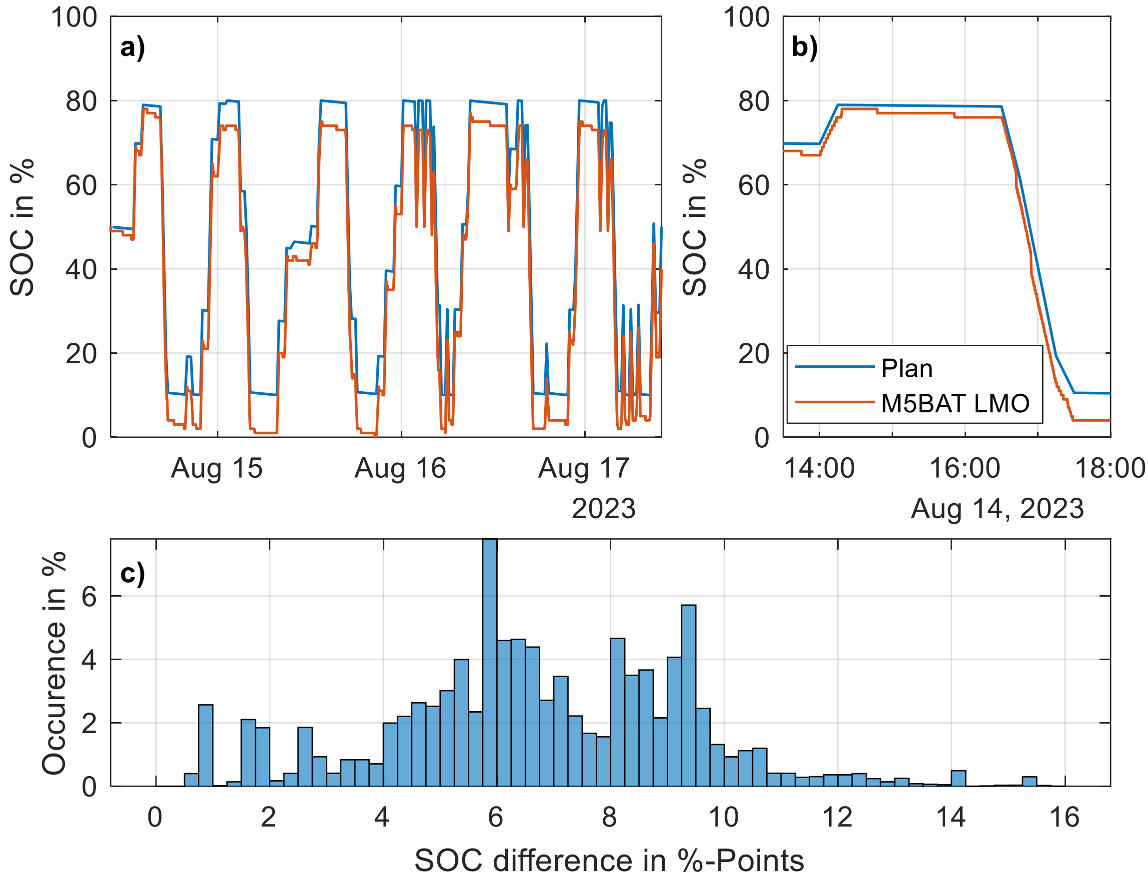

Figure 3: a) and b): Planned and observed SOC trajectory for the 3-day intraday test. c): Occurrence of SOC differences during the testing procedure.

3.2. Power

The planned power profile and the observed power profile are shown in Figure 4. Mostly the planned power profile is met by the BESS, except for phases of low SOC. Changes from charging to discharging at quarter hour marks are performed by the battery units without any problems. When the SOC of 10 % is undercut, a power throttling to protect the batteries is activated by the BMS. When the power throttling gets activated the planned power outputs cannot be met and a deviation in comparison with the original planned operation is observable. On the right side in Figure 4 an example for power throttling is presented. In this case after the 9 % SOC limit is undercut the power output decreases exponentially. At larger marketed capacities this throttling could lead to a balance sheet deviation and cause extra costs for the balancing group manager and in the end for the battery operator.

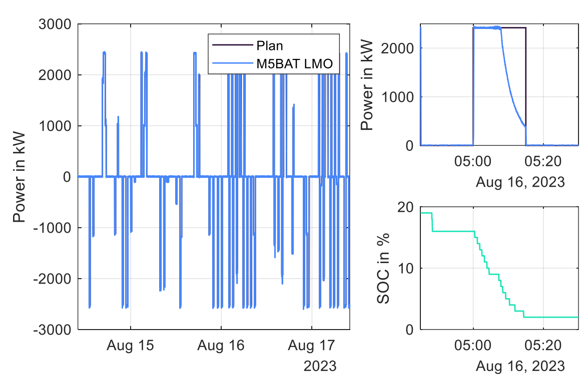

Figure 4: Left: Planned and observed power trajectory for the 3-day intraday test. Right: Power and SOC trajectory for a section with missed targets

If a trading schedule cannot be kept the schedule should be adjusted to keep the 10 % SOC boundary.

3.3. Temperature

Since the battery temperature is not an issue when providing grid services with batteries, the high-power outputs within intraday trading operation represent a different stress profile for the batteries. The provision of FCR service is proven with the BESS M5BAT for a couple of years and temperature issues are not known to date, while the intraday trading operation is not tested intensively with M5BAT yet. In Figure 5 a) the highest and lowest cell temperatures as well as the room temperature are shown. Even though the room temperature shows a minimal increase between 22°C and 23°C, but the room climatization is activated and reduces the room temperature effectively. For the battery cell temperature, two different trends are visible. The coldest cell temperature varies around 25°C for the entire test. No major temperature increase due to the higher load is observed. For the hottest cell, a rising temperature trend is observed. In the process, the cell temperature rises up to 42°C. The difference between the coldest and hottest cell thus increases to 17°C which suggests temperature inhomogeneities within the battery pack. The histograms of the temperature distribution from the hottest and coldest cell from the LMO1 battery unit are presented in Figure 5 b).

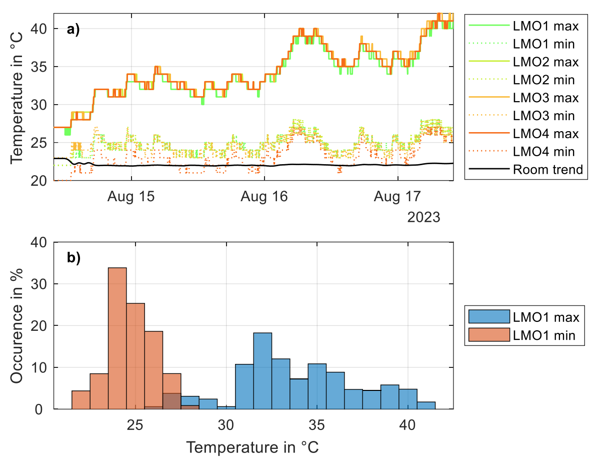

Figure 5: a): Observed temperature trajectory for the 3-day intraday test for the coldest and hottest cells and the room. b): Temperature distribution for the hottest and coldest cells in battery unit LMO1

The two histograms have only a small overlap which means that a temperature difference is present nearly always. Continuous trading operation at different temperatures over a longer period of time leads to different aging behavior within the battery pack.

When analyzing the temperature inhomogeneities further, it becomes evident that the temperature distribution is dependent on the cell position within the rack. As an example, the cell temperatures for battery unit LMO1 rack 1 are shown in the appendix in **Figure 7**. Cells with low cell numbers are located at the top of the rack, while cells with high cell numbers are located at the bottom of the rack. Each group of 16 cells and thus eight temperature measurements is located on one level of the rack. The colored lines in **Figure 7** reveal that cells in the top region always show higher temperatures than cells in the bottom region with a constant temperature gradient. From this distribution, the battery aging induced by increased temperature is assumed to be also inhomogeneous throughout the battery lifetime. Cells in the top region are expected to age faster. An alternative cooling and temperature distribution approach of the manufacturer could fix the shown issue.

3.4. Efficiency

For the efficiency evaluation the considered components are the transformers, inverters, and battery units as well as the whole BESS. From the SOC trend it can be concluded that the model has overestimated the efficiency of the BESS. Figure 6 shows a comparison of the efficiency values between the model output and the measurement. Starting with the battery units, the assumed constant efficiency of the model which is taken from [15] and represents the round-trip efficiency for 2022, is higher than the observed efficiency. The reason for the difference could be that within the performed test the power phases caused higher C-rates than observed in 2022. When excluding the phases with transformer loss compensation the C-rates are tripled compared to 2022 (see **Table 1**). In this regard, the modeled battery efficiency could be improved by the introduction of a C-rate dependent value.

On inverter and transformer side, the framework also overestimated the component efficiency. Here, a difference of 1.3 % to 1.71 % is observed. The data sheets were used for the parametrization of the characteristic load dependent efficiency curves in the model. The difference between the data sheets and reality

Table 1: Measured C-rates of the tested battery units. The shown C-rate takes only data points with an absolute current >0.01C into account [15]

Battery Unit	Measured average absolute C-rate in 2022 [15]	Measured average absolute C-rate in this test	Measured average absolute C-rate with exclusion of loss compensation phases
LMO1	0.2374	0.431	0.667
LMO2	0.2368	0.601	0.6893
LMO3	0.2368	0.3775	0.6702
LMO4	0.2401	0.3306	0.6762

are minor but in the future a data driven approach for efficiency modeling could be used to achieve even more accurate results.

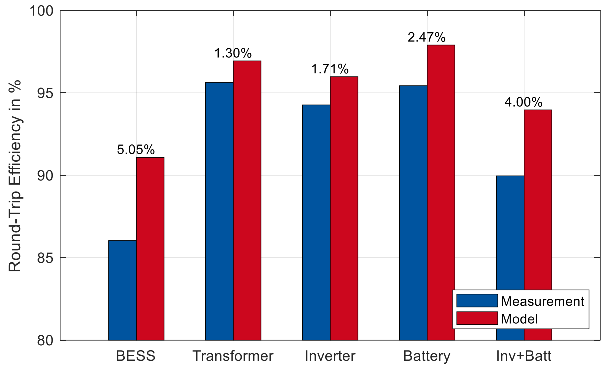

Figure 6: Round-trip efficiency for all components and the BESS observed in the test compared to the model results.

The BESS efficiency differences are the largest due to the compounded errors of every component adding up to the total BESS efficiency error. At 5 % difference the necessity of a continuously optimized schedule for trading becomes apparent. A continuously optimized schedule would be able to deal with any remaining error between reality and model and thus could also manage our current model deviations.

4. CONCLUSION

In conclusion, Li-ion batteries like the LMO batteries shown in our analysis are well suited for intraday trading. The SOC limits of 10 % and 80 % selected for the M5BAT multi-use optimization framework have proven to be effective, since performance limitations are to be expected outside the limits. To reduce deviations between models and the reals system, a trading algorithm should also continuously optimize the positions and consider the current SOC of the battery storage. In the case of very aggressive trading, feedback should also be given on the temperature development to exclude a power limitation due to increased temperature. The M5BAT multi-use optimization framework is already suitable for this task, however the efficiencies of the components need to be updated. With respect to the battery units, a load-dependent efficiency should be implemented. It is also shown that the round-trip-efficiency of approximately 86 % significantly exceeds the efficiencies from FCR operation of approximately 75 %.

AUTHOR CONTRIBUTIONS

Lucas Koltermann: Conceptualization, Methodology, Validation, Investigation, Data Curation, Visualization, Writing - Original Draft

Mauricio Celi Cortés: Conceptualization, Methodology, Validation, Investigation, Data Curation, Visualization, Writing - Original Draft

Najet Nsir: Software, Investigation

Jonas van Ouwerkerk: Validation, Writing - Review & Editing, Project administration, Funding acquisition

Dirk Uwe Sauer: Validation, Resources, Writing - Review & Editing, Supervision, Funding acquisition

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APPENDIX

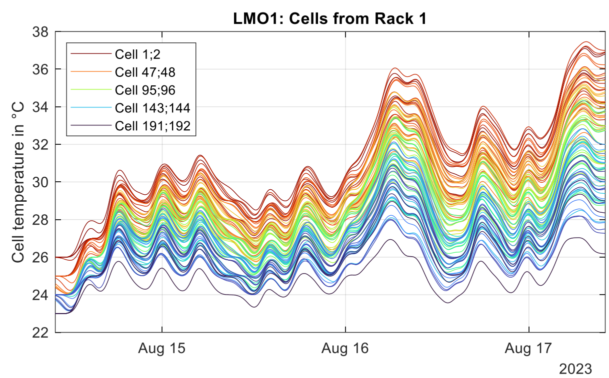

Figure 7: Filtered observed cell temperature for the test. Note: The Cell temperature is always measured for two cells together. Cells with lower cell numbers are in the top region of the rack while cells with higher cell numbers are in the bottom region of the rack.