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Benefits of Lithium-Titanate Based Batteries for Heavy-Duty Vehicles

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Summary

The hybridization of heavy-duty vehicles is an opportunity to significantly reduce the fuel consumption. Because of the demanding requirements, the battery of this vehicle has to have a long life-time and a good performance over a wide temperature range. A promising technology is Lithium-titanate. Its applicability is studied within the publicly funded project HevyBat. The paper describes the objectives of the project as well as first results.

Keywords: heavy duty, lithium-ion battery, battery model, thermal management, cycle life

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1 Introduction

Lithium-titanate (LTO) cells are a recent and promising candidate of the lithium-ion technology in industrial applications. The commonly used graphite anode is thereby replaced by a LTO electrode. This leads to some important benefits of the LTO technology like fast battery charging, enhanced safety, good low temperature performance (below 0 °C) and long lifetime.

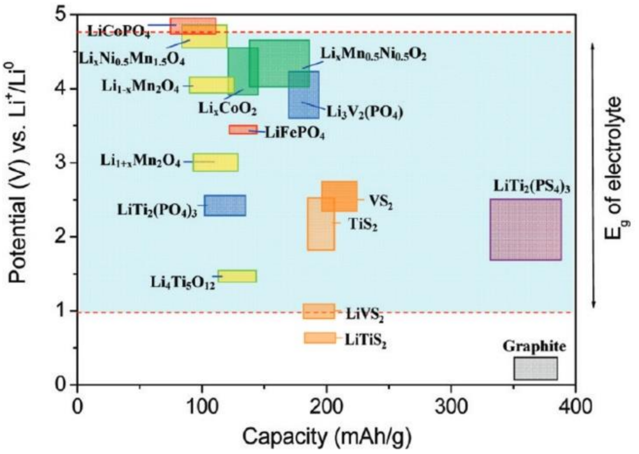

Figure1: Voltage versus capacity of several electrode materials showing the different position of LTO and graphite with respect to the stability range of the electrolyte [5].

For instance, owing to the facts that the formation of a solid electrolyte interface (SEI) as reported for graphite/carbon anodes is not given (see Figure 1) and LTO is a so-called zero-strain material, high cycle numbers and calendar life can be obtained. [1-4]

On the other hand, LTO cells have a significantly lower energy density as well as a low nominal voltage of 1.9 V to 2.4 V, depending on the material of the positive electrode. The resulting higher price per kWh seems to prevent a real breakthrough of the LTO cells.

However, niche and/or new markets in the industrial field (e.g. trains, ferryboats, busses and inland waterway vessels) become more attractive for the use of LTO technology, since special requirements can thereby be fulfilled.

Within the project HevyBat (heavy-duty battery for on/off-track vehicle hybridization), funded by the German Federal Ministry of Transport and Digital Infrastructure, a scalable solution for a LTO-based battery for heavy-duty applications is to be developed and different scenarios of operation are considered. In this paper first results of the HevyBat project are presented.

2 Application requirements

Different heavy-duty applications like trains, busses and inland waterway vessels are suited for the use of LTO batteries. The application lifetime is between 14 years for busses and up to 40 years for inland waterway vessels. [6] The performance demand is depending on the application. To identify the requirements of these applications an analysis of the load profiles was done.

2.1 Rail-based vehicles

In order to assess the requirements of the train, a load profile of a hybrid locomotive (route Chemnitz/DE Vejprty/CZ) was approved to determine the required energy and power of the battery. The electric drive power is provided by a diesel-engine generator unit and a lithium-ion battery. During braking, the lithium-ion battery is partially recharged by energy recuperation. Figure 2 shows a histogram of the performance during various operational conditions. The first peak, viewed from the left, is approx. -500 kW and represents the recuperation during braking. The second peak is approx. 20 kW and shows the power requirement when turning. The third peak is about 44 kW and shows a power requirement while entering the railway station. The fourth peak is 347 kW and represents the drive power.

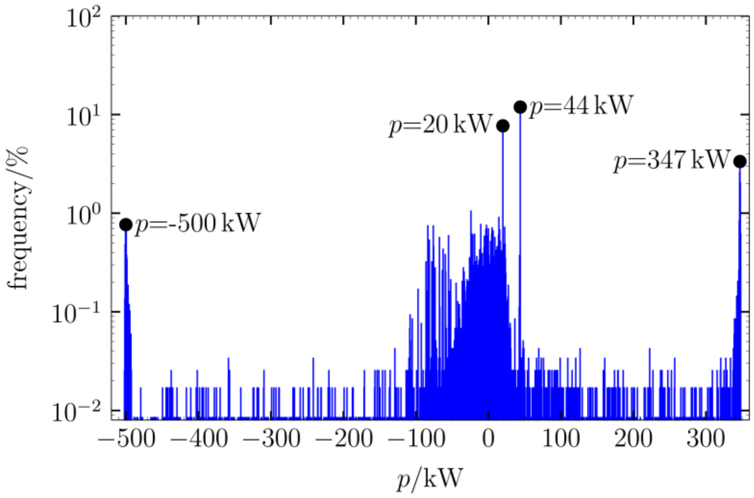

Figure2: Railway application with distribution of C-rate for the given route scenario from Chemnitz/DE to Vejprty/CZ.

For the trip from Chemnitz to Vejprty, the train requires approx. 38 kWh from the battery system. When designing a battery system, charging conditions below 10 % state of charge (SOC) and above 90 % SOC should be avoided. Furthermore, an aging of 20 % must be considered so that the battery system is still fully operational after a certain number of cycles. Thus, a battery system of about 60 kWh would result for this application. The battery system currently installed in the train (based on NMC/C cells) has a capacity of approx. 150 kWh. This has been selected because of an increased aging at high depth of discharge (at small SOC swing dominates the calendar aging) and high C-rates (in this paper based on Ah capacity). Figure 3 shows the frequencies of C-rates for a variation of battery capacity. It can be seen that, with a capacity of 60 kWh, the C-rates rise to approx. 8 C during recuperation. In addition to a high cooling demand, this would also result in a lower life span of the cells.

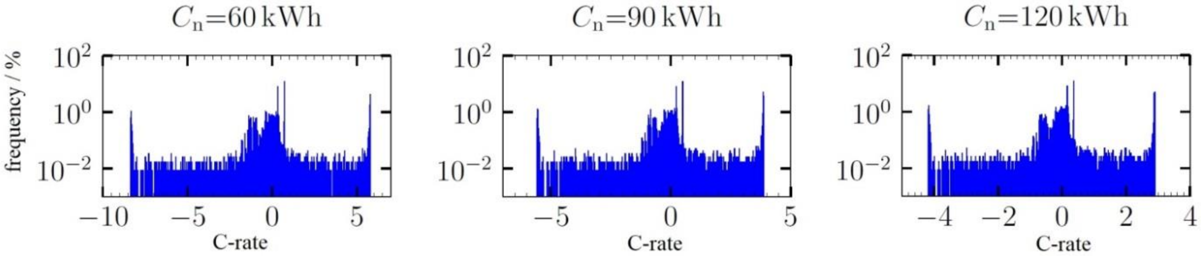

Figure3: Railway application with distribution of C-rate for different energy contents of the battery.

2.2 Road application

Electric buses for public transportation with the opportunity of fast charging were selected as a reference for road applications. The charge process is done with up to 500 kW via a pantograph, which is mounted on the bus roof. The power demand p(t) as well as the energy e(t) is shown in Figure 4. The power output of the battery system is approx. 150 kW during acceleration processes and the power consumption during braking (recuperation) is about -180 kW.

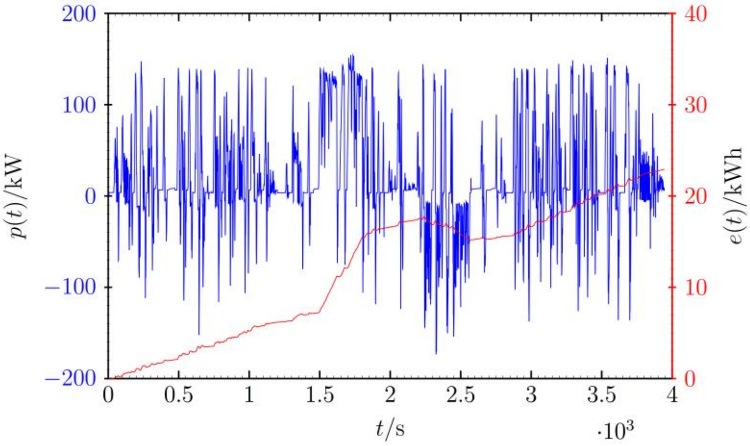

Figure4: Load profile of an electric bus scenario, given with power (left) and energy (right) demand.

In this load profile, energy of approx. 23 kWh from the battery system is required. If it is assumed that recharging of the battery only takes place at the final stop (no opportunity charging), an energy content of approx. 23 kWh must be provided from the battery system. Analogous to the train, charge levels below 10 % SOC and over 90 % SOC should be avoided. An aging of 20 % is considered so that the battery system is still fully operational even after a certain number of cycles. Thus, a battery system of about 36 kWh would result.

The battery system installed in the electric bus has a capacity of approx. 122.5 kWh. This has been selected because of an increased aging behavior at high discharge depths and charging power.

In analogous manner to the train, the capacity of the battery was varied to determine the C-rates. With a capacity of 36 kWh, the C-rate rises to about 5 C, with 60 kWh to 3 C and with 120 kWh to 1.5 C.

2.3 Inland waterway vessels

It is not always possible to provide a shore-side power supply at the port, which means that the diesel unit of the inland waterway vessel runs continuously. In order to avoid this, a battery system whose load profile is shown in Figure 5 is to be used. Similar to Figure 4, the power p(t) and energy of the battery e(t) are plotted. Port-times are marked with grey-shaded areas. Since in this time no diesel generator runs, the load profile is independent of the simulation of the generators. The selected port-times are the basis for the capacity design of the battery system since the supply of entire port-times without diesel generator and only with battery and fuel cell are to be ensured. Thus, a battery system of about 350 kWh (see Figure 5, dark grey shaded area) would result for this application.

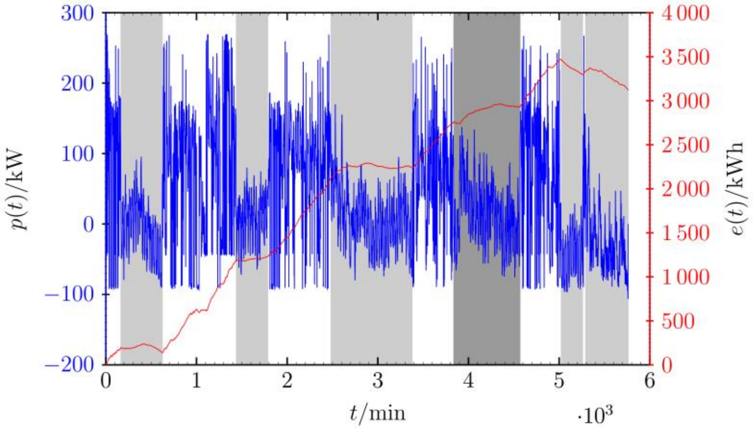

Figure5: Inland waterway application given by a typical load-time profile (left: power demand, right: energy demand).

In determining the C-rates, a distinction was made between manoeuvring by means of the bow beam and docked at the port. The C-rates range from approx. 2 C with a capacity of 350 kWh to 5 C with a capacity of 150 kWh, if top-up charging is possible.

2.4 Comparison of the transport modes

High performance is required for a short duration at all applications. An over-dimensioning of the accumulators occurred due to the often required extended lifetime and the high C-rates. In particular the applications train and bus offer the possibility of opportunity charging. This means that the power density is more important because of fast charging and high performance, which would be ideal for a LTO battery. In the case of inland waterway vessel, the possibility to use LTO as battery is strongly dependent on the time in the port. If there is no shore-side power supply, the battery system has to be designed larger so that the C-rates for such a system are small and, then, it is preferable to use high energy storage with e.g. NMC/C cells.

3 Selection of LTO cells

Dedicated tests of commercially-available LTO cells were performed in order to determine the electrochemical characteristics like charge/discharge behavior vs. temperature, temperature increase during charge/discharge, cycle and calendar life, cell impedance vs. temperature as well as power capability. Cell types of cylindrical, pouch and prismatic shape and of a nominal capacity of >10 Ah were chosen.

3.1 Power density and energy density

In Figure 6 an overview is given for the range of LTO cells with different cathode materials tested with respect to charging power density and energy density at 25 °C.

On the basis of their energy density the cells in this investigation can be divided into two groups. Cells with NMC as positive electrode material have an energy density of more than 70 Wh/kg. Cells with NCO, LFP and NMO material can be found in the range of 40 to 70 Wh/kg.

The investigated cell types with prismatic as well as cylindrical design allow higher charging currents and thus a better recuperation performance, which is an important requirement of the applications above.

It can be seen that prismatic cells with NMC cathode provides a good compromise between power and energy density. Compared to a commonly used NMC pouch cell with graphite anode the energy density of the NMC-blend/LTO cell is about 40 % lower. However, in order to ensure a long service life and high C-rates, batteries are designed to be larger than actually required. Therefore, the energy density as evaluation criterion alone is not sufficient.

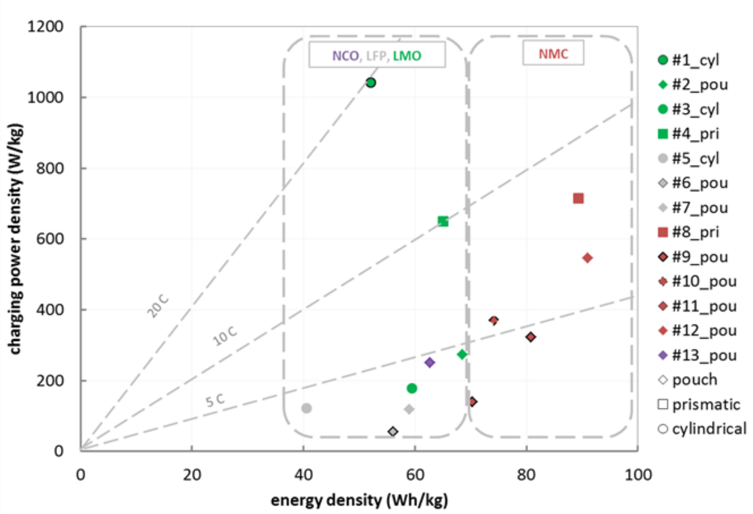

Figure6: LTO cells with different cathode material with respect to charging power and energy density.

3.2 Lifetime evaluation

In order to compare the lifetime of NMC/C with NMC-blend/LTO, cells were cycled with a C-rate of 1 C and a depth of discharge (DOD) of 100% at 25 °C. The NMC/C cell 1 reaches the end of life (EOL, 80 % nominal capacity) after approximately 2.100 full cycles as can be seen in Figure 7. Through partially cycling between 4.1 V to 3.0 V (lower SOC swing) the cycle life can be raised to 2.500 cycles (NMC/C 2). The NMC-blend/LTO cell reaches the EOL after 10.000 cycles. Thus, the cycle lifetime of the NMC-blend/LTO cells is 4 times greater than the NMC/C cell with lower SOC swing. To achieve this lifetime, the SOC swing of the NMC/C cell would have to be significantly decreased, so that the calendar aging of the cell predominates. In case of the applications bus and train above the SOC swing is approximately 30 %. With NMC-blend/LTO a SOC swing of 90 % would be possible so that the approx. 40 % smaller energy density of the cell is no longer relevant.

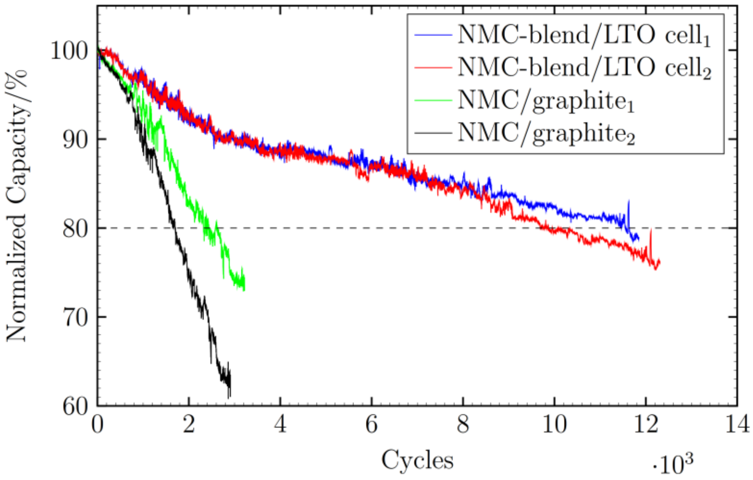

Figure7: Comparison of lifetime between NMC/graphite and NMC-blend/LTO at full cycles at 25 C (NMC/graphite1 with full DOD; NMC/graphite2 with reduced DOD; LTO cells with full DOD).

At approximately 7.500 cycles the remaining capacity of the two NMC-blend/LTO cells with identical load is drifting apart over time. One way to limit the impact of this drift is the use of an active balancing system, which is also part of the HevyBat project.

3.3 OCV-SOC characteristic of different LTO cells

In addition to the energy and power density, the open-circuit voltage curves (OCV) of different LTO cells were compared. The OCV curve is important for the development of algorithms, e.g. the determination of SOC and state of health (SOH). The accuracy of the algorithms depends on the accuracy of the measurement and the slope of the OCV curve. Figure 8 shows the OCV curves of LTO cells with different cathode material.

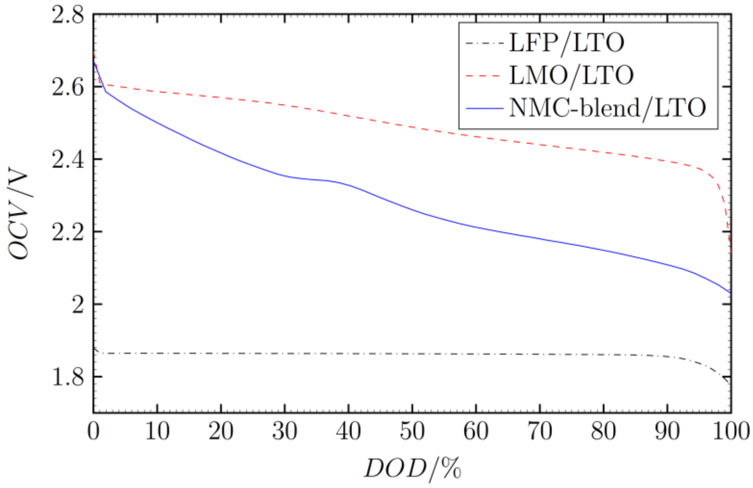

Figure8: OCV curves for three different LTO cells (LFP/LTO, NMC-type/LTO and LMO/LTO).

The gradient of the OCV curve between two fixed points (SOC1 = 10 %, SOC2 = 90 %) was determined in order to estimate the measuring accuracy for the SOC. Table 1 shows the results. A voltage measurement accuracy of 2 % is assumed.

Table1: Error due to the OCV curve

Cathode	NMC-blend	LMO	LFP
Diff. / mV	397	189	9
mV / SOC-%	4.97	2.36	0.11
Error / %	0.40	0.85	17.6

The NMC-blend/LTO cells exhibit the greatest voltage variation between the two fixed points. The resulting error for the SOC determination is approximately 0.4 %. At a DOD of approx. 35 %, the voltage curve of the given NMC-blend/LTO shows a small plateau, which should be taken into account. LFP/LTO cells have a very large error due to the very flat voltage profile, which makes a SOC determination by using OCV more difficult.

3.4 Results of the benchmark

Based on the previous benchmark, 23 Ah NMC-blend/LTO prismatic cells were selected for the project. Besides the excellent lifetime this cell has a very low internal resistance and a high efficiency at high current rates compared to high power (HP) and high energy (HE) NMC/C cells (see Figure 9).

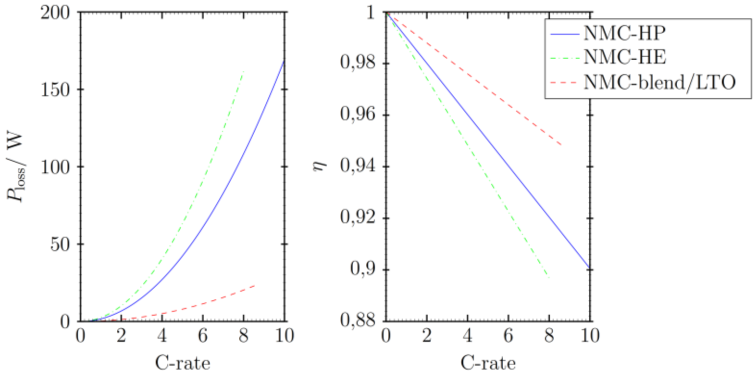

Figure9: Power dissipation and efficiency for different C-rates and cells [8].

4 Modelling

With the help of a battery model, operational strategies for the LTO battery are to be developed. In order to simulate the behaviour of the lithium-ion battery, an electrical model of the NMC-blend/LTO cells was created with which the static and dynamic behaviour of the cell can be reproduced.

4.1 Electrical equivalent circuit

Basically, the electrical equivalent circuit of a lithium-ion cell consists of an idealized voltage source and impedance connected in series. The voltage source represents the open-circuit voltage of the cell, which was determined by the linear interpolation method (LIM) because of the small hysteresis. For modelling the impedance of the lithium-ion cell a series combination of a resistor, two ZARC elements and one Warburg impedance is used (see Figure 10). The resistor R_i describes the internal resistance of the cell and the first ZARC element the charge transfer process. The second ZARC element and the Warburg impedance describe the effects of mass transfer in the battery. An inductive behaviour (above 1 MHz) was not depicted because it was not relevant for the applications within the project. [9] This equivalent circuit has been realized using the modelling language Modelica.

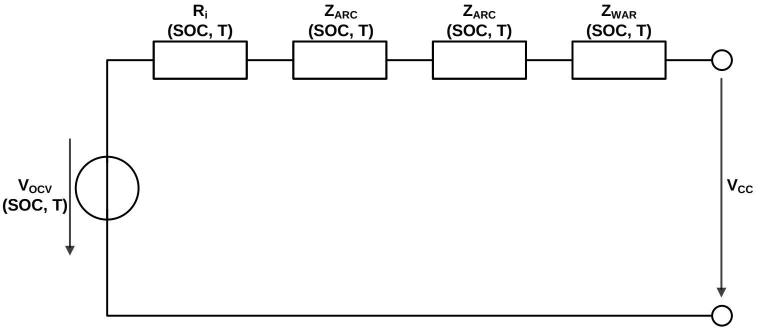

Figure10: Equivalent circuit of a lithium-ion cell.

4.2 Parameterization

The determination of the parameter values of those elements were performed by means of electrochemical impedance spectroscopy (EIS). The model should depict the behaviour of a real lithium-ion cell at any operating point. Thus, the parameters were determined at different temperatures (-25 °C, -10 °C, 0 °C, 25 °C, 35 °C, 50 °C) and SOC (10 %, 25 %, 50 %, 75 %, 90 %). Figure 11 shows a Nyquist plot at SOC = 50 % and different temperatures. The measurement was done within a frequency range of 1 mHz to 2 kHz. A least-square fitting algorithm was used to identify the parameters for the equivalent circuit which are stored in the model via look-up tables.

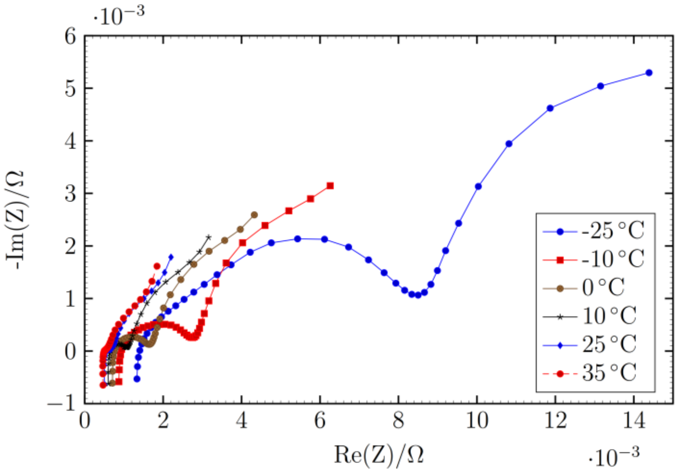

Figure11: Nyquist plot at SOC = 50 % for temperatures ranging from -25 °C to 35 °C (23 Ah NMC-blend/LTO cell).

4.3 Verification

For the verification of the model, a load profile shown in Figure 12 has been used, which consists of different charging and discharging pulses with values of 0.2 C, 1 C, 2 C, 3 C and 4 C. Figure 13 shows the measured and the calculated voltage of the NMC-blend/LTO cell at 25 °C.

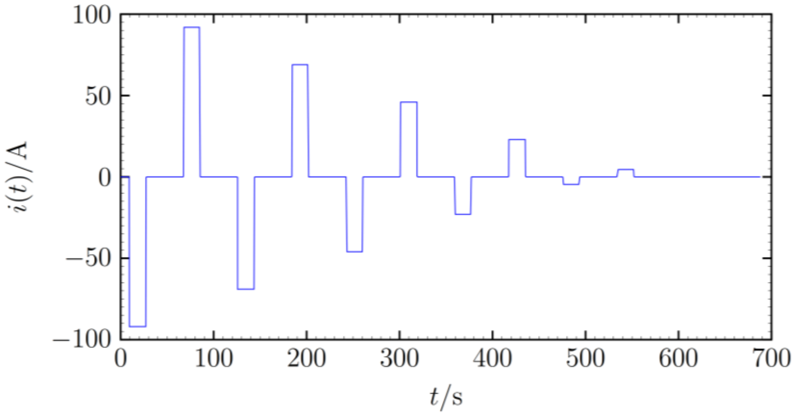

Figure12: Load profile for the verification of the model.

The measured and the calculated data show good agreement, the error is less than 0.4 % as can be seen in Figure 14.

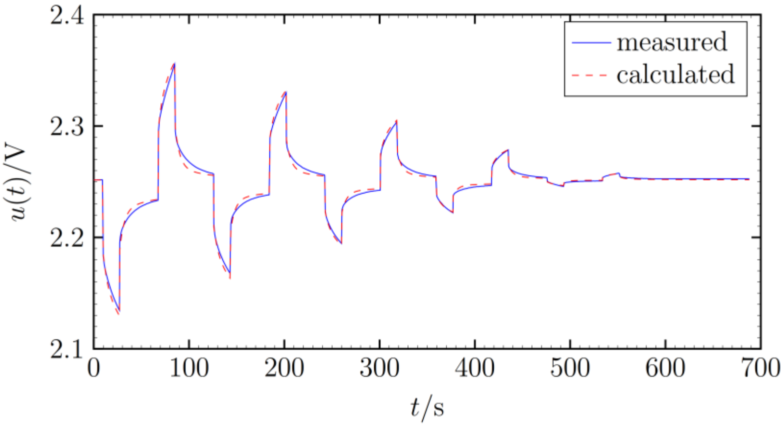

Figure13: Measured and simulated voltage response to the load profile.

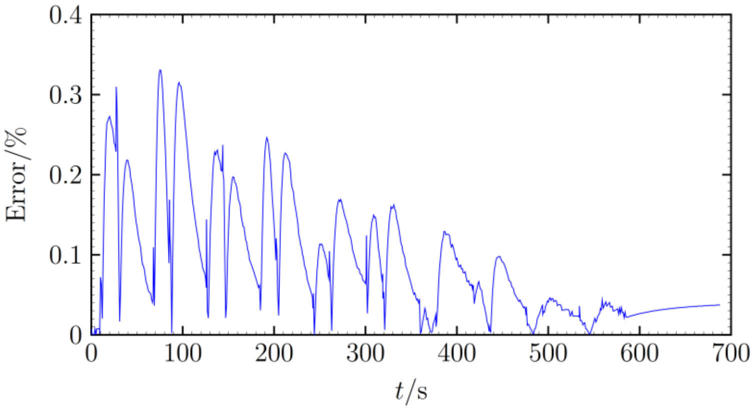

Figure14: Difference between simulated and measured voltage.

5 NMC-blend/LTO Module

Based on the application electric bus from section 2.2, two battery systems have been designed to compare NMC-blend/LTO and NMC/C HP in terms of weight, cost and lifetime. The battery has a voltage of approx. 660 V and is to be charged with a power of 180 kW. The required energy is 23 kWh. Table 2 shows the results of the comparison. Due to the high charging performance the LTO battery can be designed smaller than the battery with NMC/C. Furthermore, the LTO battery has a cycle lifetime which is more than twice as large as the battery with NMC/C cells. On the other hand, the costs are more than 50 % higher and an economical usability is limited to applications with low energy requirements or the possibility of opportunity charging like buses for public transportation.

Table2: Comparison of LTO and NMC HP modules

Module	NMC-blend/LTO	NMC/C HP
internal resistor of the cell	0.6 mΩ	0.8 mΩ
Weight of the cell	550 g	1265 g
Temperature range charge	-40…55 °C	5…45 °C (< 3C)
Battery energy	31 kWh	61 kWh
Charging current (max.)	6 C	3 C
Weight	100 %	144.6 %
Volume	100 %	155.7 %
Cycle life	10.000 (100 % DOD)	4.000 (80 % DOD)
Cost	100 %	45 %

Since LTO modules become more attractive and a lot of R&D effort is underway in this field, a stress test was done with a commercial 12S2P module without a dedicated cooling system to investigate the charging performance.

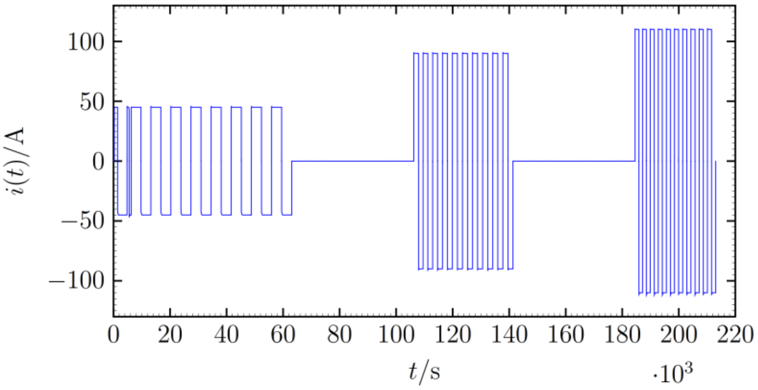

Figure15: Load profile for commercially available 12S2P LTO module.

Figure 15 shows the load cycle for the stress test which consists of 3 times 10 cycles each are run with rates of 1 C, 2 C and approximately 3 C at 25 °C.

Figure 16 shows the results of the stress test. It is apparent that the higher the currents the higher the resulting temperatures. The maximum operating temperature of the module is 55 °C. This limit is already exceeded at current rates of 2 C. At 3 C, almost the safety shutdown is activated. The obtained results suggest that it does not fulfil the requirements given in the project. The test shows that a LTO module without a dedicated cooling system is not possible.

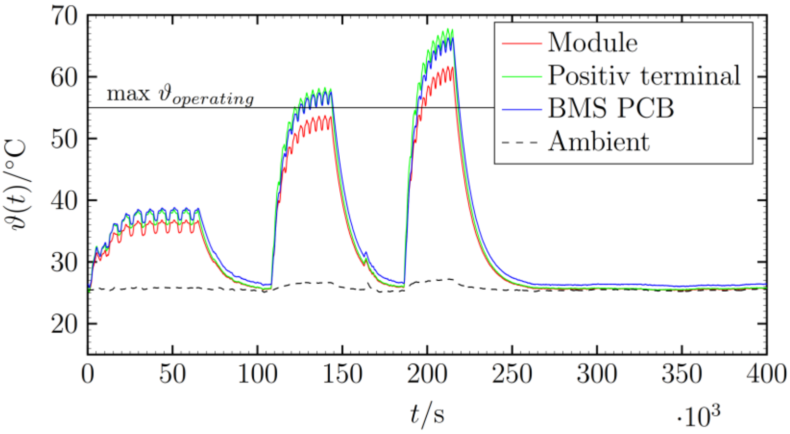

Figure16: Temperature profile of the 12S2P module for current rates of 1C, 2C and 3C.

Therefore, a small scalable module with a special air cooling system is to be developed based on the selected NMC-blend/LTO cells. The air cooling was chosen because of the lower weight and the easy implementation compared to other cooling concepts. Figure 17 shows a 3D drawing of a module which has a 24S2P structure. The module consists of sub-modules with 8 cells each, which makes it possible to extend the module by additional cells. The BMS of this module is able to handle up to 36 cells. The module should carry a continuous current of 280 A.

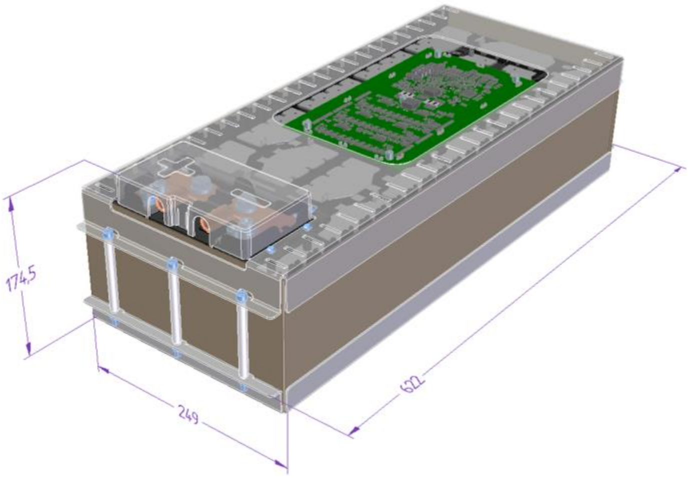

Figure17: 3D Modell of the LTO module (24S2P).

Figure 18 shows a submodule with a 4S2P structure. The plastic parts at the bottom and top of the cells are used as an airflow regulator. This is intended to achieve a uniform flow around the cells. Temperature differences between the cells and the resulting aging are thereby to be minimized.

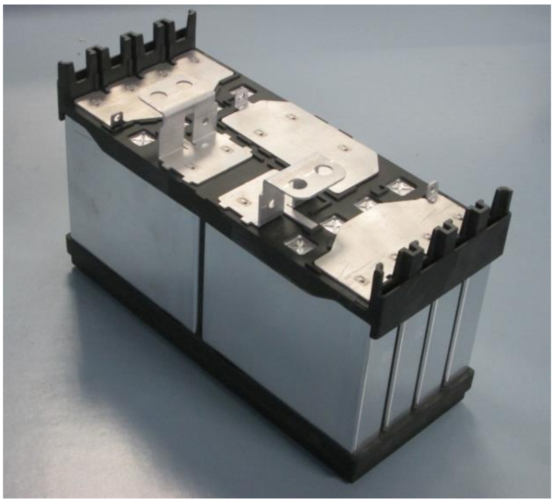

Figure18: Sub-module (4S2P).

For the verification of this cooling concept the stress tests will be performed with the sub-modules in analogous manner to the commercially available module. To do this, a test bench is to be built, which allows a variation of the air flow.

6 Conclusion

This paper shows the work content and initial results within the project HevyBat. In the first step, the focus was on the selection of a suitable LTO cell for building a battery module. For this purpose, a requirement analysis was carried out using three applications (maritime, rail-based and electric bus). The analysis showed that the LTO technology is suitable for the use in the given heavy-duty applications. The requirements of these applications were then used to define the benchmark tests of the LTO cells. A cell model was created to simulate the electrical behaviour of the cell in the respective applications. Furthermore, a concept for an LTO module was derived and implemented in the form of a sub-module based approach.

Future work will focus on the realization of a thermal model and operating strategies. A verification of the thermal management is then to be carried out.

Acknowledgments

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