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Methodology to assess a hybrid-battery system for utilization in railway vehicles

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Abstract

The objective of this paper is to present the methodology to investigate the applicability and potential benefits of a hybrid-battery system for utilization in railway vehicles. This system is comprised of two different battery technologies, combining the advantages of both technologies in one system. To achieve this goal, suitable battery systems have been evaluated in a market analysis, the resulting data was then processed in DLR developed vehicle- and battery-simulation tools. It is shown that, depending on the operational scenario and battery performance indicators, the combination of different battery technologies in one hybrid-system can lead to benefits regarding system volume, weight and investment cost, compared to single battery technology solutions. Further research will include the impact on battery lifetime and life cycle cost and aims to identify optimized operational scenarios.

Keywords: railway, hybrid, battery, sustainability

1 Introduction

With regards to global efforts to reduce CO2 emissions, the railway sector has the obligation and potential to directly and indirectly contribute to this goal. Through technical innovations, emissions from the vehicles themselves can be avoided. On the other hand, traffic from other transport sectors might be re-directed onto the rails. One possibility to reduce greenhouse gas emissions is the additional electrification of non-electrified railway networks. However, this solution is not economically or technically feasible in all circumstances and requires long implementation cycles.

Currently, partly and non-electrified track sections are commonly operated by diesel powered vehicles. [1] The substitution of those vehicles with battery electric multiple units (BEMU) and locomotives is discussed and, in some cases, already implemented as one possible solution. However, vehicle-centric issues like limited space or axle load restrictions can limit the installable energy on the vehicle and therefore the range provided by the battery storage system. In addition, battery technology specific limitations in terms of energy density, battery lifetime or other key performance indicators (KPI) may also cause issues in this application. To mitigate these potential obstacles, this paper presents the methodology to investigate the applicability of a hybrid-battery system (HBS). This HBS is composed of one high energy- (HE) and one high power- (HP) battery subsystem, aiming to compensate the disadvantages of one technology by the advantages of the other and vice versa. For example, while high C-rates and deep discharge states have negative implications on the battery lifetime of one technology, the impact on another technology may be less pronounced. On the other hand, certain technologies provide limited energy densities, but longer cycle life and better safety properties on the other hand.

Our goal is to assess the principle feasibility of this approach and to quantify the possible advantages related to different optimization criteria. These criteria include system weight, space demand and cost in this first investigation. In addition, the implications of the hybrid approach on the battery system lifetime will also be addressed.

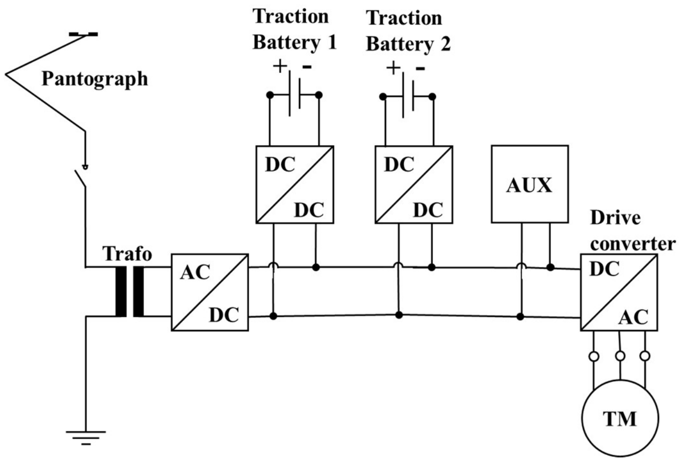

Figure 1: Simplified topology of a hybrid battery drivetrain

2 Methods

To analyze the general applicability of a hybrid-battery solution, an exemplary, non-electrified (catenary free) railway line from Frankfurt to Saarbrucken was chosen. Under assumption of a generic, regional service reference vehicle, the trajectory, the power demand at the wheel and the energy demand at the intermediate circuit as well as at the battery system was calculated. This calculation is based on DLR developed hybrid-battery tool utilizing a MATLAB framework.

To represent the current state of the art of railway applicable battery systems, a comprehensive market analysis and technology assessment was conducted. Relevant technology specific characteristics, such as gravimetric and volumetric energy- and power-density, of available lithium ion battery (LIB) systems have been identified and quantified. Data was acquired on cell-, module- and branch-level. Utilizing this data, cell to module and module to branch factors have been derived for the different battery technologies. To ensure comparability, the relevant performance indicators have been assessed on module-level. All data was also aligned with the DLR RailTechMonitor, a comprehensive database of rail qualified components and devices.

The focus of this assessment was put on the three mainly utilized automotive LIB chemistries, lithium iron phosphate (LFP), lithium titanate oxide (LTO) and lithium nickel manganese cobalt oxide (NMC). In this stage of the analysis, LTO battery solutions have been categorizes as high-power batteries, while LFP and NMC batteries are classified as high-energy systems. Depending on specific battery KPIs, this categorization might be subject to change.

To dimension the energy storage, a simplified operational strategy was presumed. For this reason, the initial assumption is that the power between the high-energy and the high-power battery is split at a defined threshold. This means that the required power for traction and auxiliary systems is provided by the HE battery until this threshold is reached. After reaching that point, the additional power will be delivered by the HP battery. In this simplified approach, the same threshold applies for charging and discharging the batteries. This power split was varied in 100 kW steps, calculating the required energy for both battery chemistries in each step. The results have been processed to identify a preliminarily optimized battery combination regarding the parameters weight, volume and cost. Figure 2 shows an example of the total power demand (blue) and the resulting power curves at the LTO battery (red) and the LFP battery (yellow) at an exemplary power split of 500 kW.

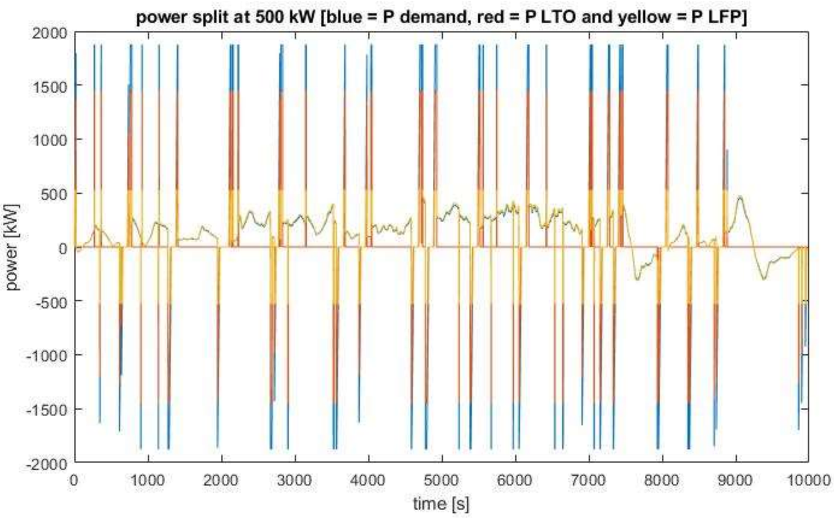

Figure 2: Exemplary power profile (blue) and resulting power gradient of the LFP battery (yellow) and LTO battery (red) with a power split at 500 kW

3 Results

For the chosen scenario, possible combinations of one HE and one HP battery have been investigated, namely LTO-NMC and LFP-LTO. The assumed KPIs of the respective modules are compiled in table 1. For reasons of simplification an identical constant efficiency of 95 % was assumed for all batteries.

Chemistry	NMC	LFP	LTO
Max. Cont. C-Rate	3	1	7
Max. Peak C-Rate	5	3	7
Grav. Energy Density [Wh/kg]	117	83	40
Vol. Energy Density [Wh/l]	98	64	44
Lower DoD Limit [%]	75	80	85

Table 1: KPIs of chosen battery systems, values based on DLR technology assessment

To illustrate results of the explained methodology, the battery system volume is chosen as the optimization criteria here. Based on the values quantified above, a combination of LTO and NMC batteries does not result in a decrease of the system volume for the chosen scenario, as illustrated in Figure 3. The system volume minimum is reached if the battery system is purely based on NMC chemistry.

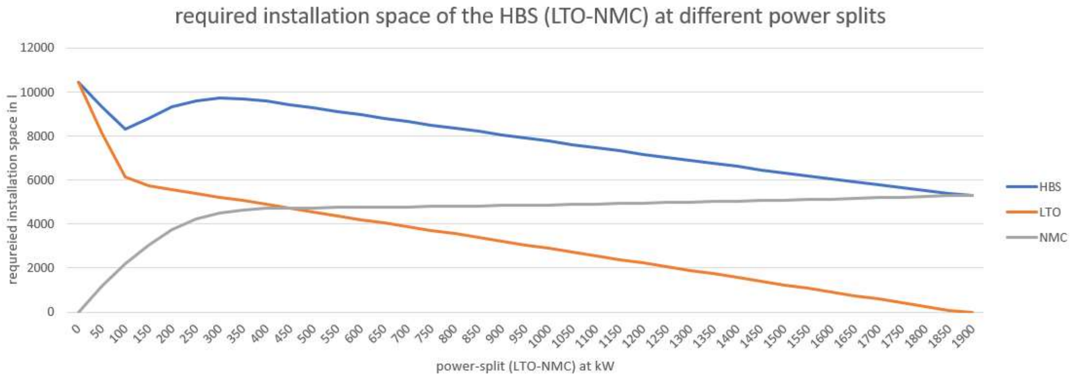

Figure 3: System volume of LTO-NMC system as function of the power split

The space requirement for a combination of LFP and LTO batteries is shown in Figure 4. In this case, the system volume minimum is reached at a power split of about 100 kW. This means that power demand is provided by the HE battery until 100 kW are reached, with the HP battery facilitating the power above this value. The battery system volume is decreased by 11 % compared to a purely LTO based solution and by 33 % compared to an LFP-only system.

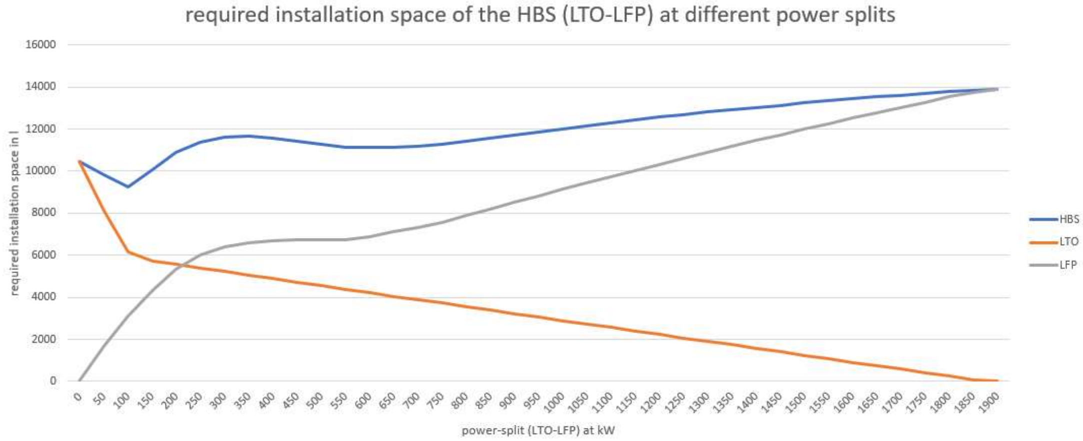

Figure 4: System volume of LFP-LTO system as function of the power split

In conclusion, in the chosen scenario, with regard to installation space, an NMC based battery is the best option. If the NMC technology is not a possibility for certain reasons, an LFP-LTO HBS is an attractive alternative.

Utilizing the DLR hybrid-battery tool, other optimization criteria can also be analyzed for the chosen scenario. The weight reduction potential at the discussed power split is also considerable. The HBS implicates a weight reduction of 20 % compared to a conventional LTO system and 15 % over an LFP based solution. The initial investment costs of the battery system can be reduced by 6 % compared to an LTO-only system and by 40 % compared to an LFP-only battery.

Optimization Criteria	HBS at 100 kW Power Split	LTO-only Battery System	LFP-only Battery System
Weight	9179 kg	+ 20 %	+ 15 %
Volume	9249 l	+ 11 %	+ 33 %
Investment Costs	646,565 €	+ 6 %	+ 40 %

Table 2: Results of an LTO-LFP hybrid battery system at different KPIs

Additionally, the charge throughput at each battery can be calculated for every power split. In combination with DLR developed battery ageing models and considering the maximum allowed number of cycles, the dimensioning of the HBS can be optimized regarding battery lifetime and therefore life cycle cost.

4 Conclusions and Contributions

While hybrid energy systems already exist on the market, those hybrid systems combine two of the following technologies: battery, catenary/overhead electrification, fuel cell (FC), internal combustion engine (ICE) and ultracapacitor (UC). [2] The combination of two different battery chemistries on a system level presents a novel approach in the transportation sector.

This preliminary investigation aims to establish a methodology to evaluate possible benefits of the hybrid-battery system approach for specific scenarios and different optimization criteria. It was shown that the hybridization of the battery system can lead to a decrease in system volume, weight and investment cost. While not every battery combination or scenario might yield these benefits, the identification of beneficial factors and advantageous battery performance values is one of the next steps of this investigation.

Depending on the use case, the utilization of an HBS may lead to an increase in application possibilities for BEMUs, allowing to service conventionally operated lines with a more environmentally friendly solution without large infrastructural measures, such as electrification. Additionally, the combination of two different battery chemistries can help to avoid operational states that are disadvantageous for certain battery technologies, such as high C-rates or low charging states. This can lead to longer battery lifetimes and subsequently lower life cycle cost and a more sustainable system. Other benefits through utilization of more complex operational strategies are also a realistic consideration. The integration of charging infrastructure (overhead line extension or overhead line islands) into non-electrified railway tracks may also lead to benefits for the HBS and is subject to following studies. Further developments in battery technology are also expected. Those advancements will be monitored closely and periodically integrated into this analysis.

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