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Investigation and analysis of accumulators for the use of electrochemical storage in hybrid shunting locomotives

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Abstract

This paper evaluates storage batteries with respect to usage in hybrid shunting locomotives. Topics are the status quo of existing technologies as well as future electrochemical storage technologies. A target system is used to evaluate the technologies. Furthermore, relevant battery characteristics for the usage in hybrid shunting locomotives have been identified. The necessary data have been retrieved from current literature (document analysis) and by a survey made with scientific and industrial experts. The results of the study show, that batteries of the lithium-ion-technology with a lithium-titanate anode and a lithium-iron-phosphate cathode are currently the most suitable batteries for the use in hybrid shunting locomotives. Promising future technologies are under investigation, but these technologies are several years away from their market entry.

Keywords: Current status of batteries; future technologies; relevant charactristics of batteries for hybrid locomotives, battery technologies

1. Introduction

The need to reduce carbon-dioxide and other polluting gases is steadily increasing. To fulfill the rising requirements, the electrification of vehicles on streets and rails is getting more important. On rails without catenary still only diesel locomotives can provide the needed transports of goods, people and vehicles. For commuter trains with many stops and shunting locomotives, a hybrid drivetrain is a promising alternative to a conventional internal combustion engine (ICE). A study by Toshiba reveals the potential to reduce the fuel consumption of shunting locomotives by over one third by equipping them with a traction battery in addition to the ICE [1]. Moreover the NOx emission as well as the noise level can be lowered significantly. The locomotives are propelled by electrical energy from the traction battery alone while the battery state of charge (SOC) is high. Hence hybrid-engines for locomotives need a powerful traction battery, which provides enough power and withstands the environmental influences. There are miscellaneous technologies to store electrical energy yet just a few of them can be used to energize powerful engines like those of shunters. Therefore, a study of relevant storage technologies has become important. To evaluate current and future technologies a literature review and an expert survey have been conducted. The literature review identifies relevant descriptive parameters of electrochemical storages. Moreover, the relevant storage technologies including their specific strengths and weaknesses are described. The subsequent expert survey is used to rate the identified storage parameters regarding their importance for electrochemical storages of hybrid shunting locomotives. Furthermore the results of the literature review are verified in the expert survey and additional information especially regarding the future prospects of the treated technologies are obtained. Finally the rating of the storage parameters is used to form a target system for the systematical assessment of electrochemical storages for hybrid

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shunting locomotives. The results of these studies will be used in specific projects for industrial and scientific partners. They build the foundation for a newly engineered hybrid shunting locomotive. The purpose of this paper is to provide an overview of these technologies to reveal some new ways to use them.

2. Results of the literature review/state of the art

To get a general overview of possible battery technologies a literature review was carried out. The review showed 5 relevant technologies which are currently used in hybrid vehicles. These are namely: lead-acid, nickel-cadmium (NiCd)/nickel-metal hydride (NiMH), sodium nickel chloride, lithium-ion and supercapacitor technology [2–4]. To evaluate, if they are suitable for the usage in a hybrid shunting locomotive, there are some criteria to compare them. Those criteria are: specific energy, specific power, calendrical lifespan, cyclical lifespan, costs, recyclability, security and working temperature [2]. The specific energy describes the amount of energy that can be stored per unit of mass. It is related to the energy density which describes the amount of energy per unit of volume. The specific power shows how much power can be provided per unit of mass. Other criteria are cyclical and calendrical lifespan. The calendrical lifespan is the period, in which the state of health (SOH) naturally descends under a level (usually between 50% and 90%) where the battery is not usable for its purpose any more. The cyclical lifespan tells how many cycles of charge and discharge are typical until the SOH is under the critical value. The criteria cost and recyclability are self-explanatory. At last there is the criteria working temperature. Batteries are sensitive to temperatures outside their working temperature. They discharge quicker or the structures inside the battery may get damaged. Every typical battery technology will be described shortly and rated by their characteristic properties at hand of those criteria.

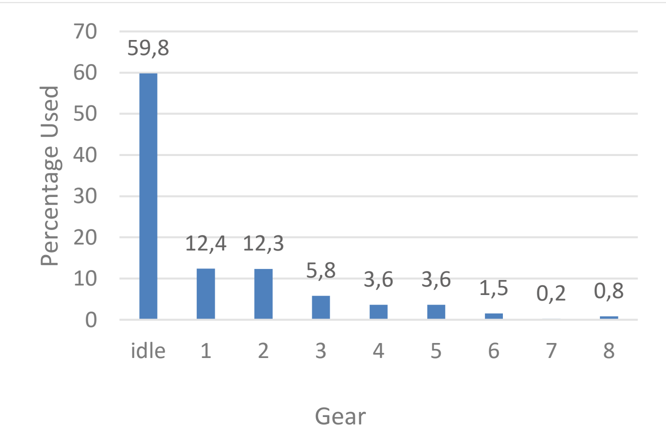

Fig. 1. Typical usage profile of shunting locomotives [5].

To determine what criteria are important for batteries for hybrid shunters, there are some limiting factors. Shunting locomotives have special usage profiles. As it can be seen from Fig. 1, the ICE is idling about 60 % of its operating time. Moreover in 25 % of the time the engine runs in the lowest two gears. However, consumption maps of diesel engines show that they are most efficient at a medium rotational frequency and a high load [6]. The use of a traction battery allows to operate the ICE in a more efficient way. On the one hand the engine can be switched off completely sometimes while the locomotive is powered from the battery. On the other hand the load level of the engine can be increased to an efficient point while it is running. The excess energy is then used to recharge the battery. The described utilization of the battery leads to relatively high requirements regarding the specific power of the used battery technology and medium requirements regarding the specific energy. Another criterion is durability. As shunters usually get to maintenance every eight years, the calendrical lifespan as well as the cyclical lifespan must last at least for this time. Also, as shunters are operated outside, the battery must work proper under typical European ambient temperatures which are between the -25°C and 40 °C. Moreover the adherence of safety requirements is important. There have already been accidents with electrochemical storages on hybrid shunting locomotives in the past which shows the relevance of this factor [7].

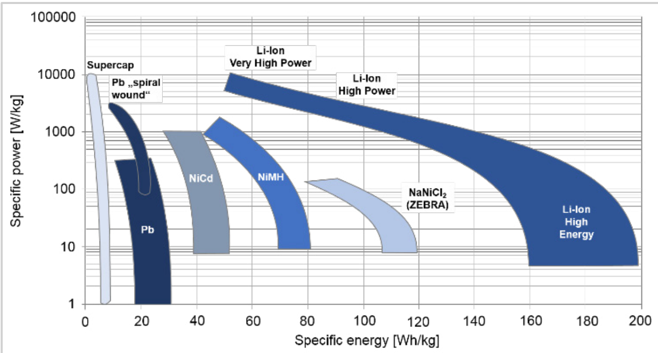

Fig. 2. Ragone plot of various battery technologies [2].

The lead-acid technology is one of the oldest means of storing electrical energy [8]. It has a relatively low specific energy and specific power. The cyclical lifespan lasts between 300 and 2000 loading cycles [2]. Advantages of this technology are the low costs and the good recyclability. The characteristics of this technology reject the usage in full hybrid vehicles like shunters [2]. NiMH-batteries have a significantly higher power density and lifetime than lead-acid batteries. Because of these properties they are widely used in hybrid vehicles. The disadvantages of this technology are the high costs and low performance under the influence of cold temperatures [2]. Because of these reasons, they are only partly suitable for the use in shunters. NiCd-batteries, which are very similar to NiMH-batteries, have better characteristics under cold temperatures. However, they are inferior to NiMH-batteries in other properties and the restrictions on the use of cadmium in the EU are getting stricter. The sodium nickel chloride battery works under different circumstances. It needs a working temperature of about 300 °C. Cooling it down to ambient temperature will damage the battery. The high temperature leads to a self-discharge rate of 10-15% per day, if the battery is not used. These batteries have a high specific energy but a low specific power [2]. They also have a good calendrical and cyclic lifespan [9]. Due to the high working temperature and the consequently high discharge rate, this technology seems not suitable for the usage in shunters. A newer technology, researched since the 1980`s, shows a big potential. The lithium-ion technology has the highest specific power and specific energy of all typical battery-technologies. The combination of used materials for anode and cathode heavily influences the characteristics of these batteries [10]. For applications which need a high standard on security and durability, a combination of a lithium-titanate anode and a lithium-iron-phosphate cathode is recommended. The disadvantage of this type of lithium-ion batteries is a lack of specific energy. As stated above the requirements of hybrid shunting locomotives regarding the specific energy are only moderate. Thus this combination of anode and cathode material seems well suitable for hybrid shunters. Because of the high activity in research on the lithium-ion technology there will probably be better combinations of cathode and anode materials, which will lead to better properties for the batteries [11]. The last technology used to store energy in a portable form is the supercapacitor technology. The functionality of supercapacitors differs from typical batteries. They store energy in the boundary layer of the electrodes. Supercapacitors have high specific power and a long lifespan. Contrary to this they have an extremely low specific energy [12]. Supercapacitors are used for high power applications like regenerative braking or in connection with conventional batteries as hybrid batteries, to combine the strengths of both technologies [3]. All typical specific power and specific energies of these technologies are depicted in Fig. 2. As pointed out, supercapacitors have the lowest specific energy but a high specific power. The lithium-ion technology covers a wide range of specific power and specific energy. Some combinations of anode and cathode materials reach specific power levels of 10000 W/kg while having a specific energy of 50 Wh/kg. Other extreme combinations reach up to 200 Wh/kg while having a specific power of 7 W/kg.

For future purposes in mobility the lithium-sulphur and the lithium-air technology have been detected. Both technologies have the potential to reach high specific energies. Especially the lithium-air technology is in an early research state. Products based on this technology will probably not be available in the next 10 – 20 years [13]. The research activities concerning these technologies are increasing steadily. The current and future technologies are summed up in Table 1.

Table 1. Current and future electrochemical storage technologies.

Current technologies	Future technologies
Lead-acid technology	Lithium-sulfur technology
NiCd technology	Lithium-air technology
NiMH technology	Hybrid capacitor technology
Sodium nickel chloride technology	
Lithium-ion technology	
Supercapacitor technology	

3. Suitability of battery technologies for hybrid shunting locomotives

3.1. Research method

Based on the data of a literature review with the aim of detecting suitable technologies for hybrid shunters as well as to identify relevant battery parameters a questionnaire has been developed. Subsequently the questionnaire has been used in an expert survey to validate the data from the literature review and to gain further insights. It consists of an opening text followed by questions concerning battery parameters, current technologies, future technologies and personal information. In the first part of the questionnaire the participants' assessment of the importance of different battery parameters for the application in hybrid drives was asked. The second part queried the participants' assessments of the technologies that are currently commercially available. Furthermore, the suitability of the technologies for hybrid drives and the future prospects of existing technologies were queried. Afterwards special attention was paid to lithium-ion technology due to the promising development potential [9]. The part was followed by an evaluation of future technologies according to their suitability and their probable availability as products. Thereafter, a ranking of the technologies according to their relevance as future storage technology for hybrid drives was asked. At last the personal data of the participants was recorded. Besides the design of the questionnaire, the selection of experts is also of high importance [14]. To gather a broad opinion, experts from universities and research institutes as well as industrial experts were surveyed.

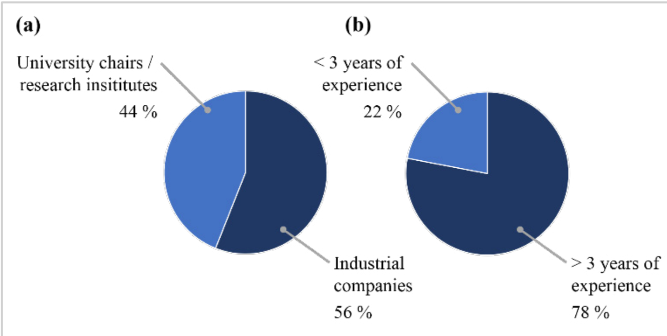

Fig. 3. (a) Background of the participants (b) Experience of the participants.

The identification of the experts was done using different sources. A small part of the experts could be identified through personal contacts as well as contacts of the Chair of production and Operations Management of the BTU Cottbus-Senftenberg. Furthermore, a systematic search on the Internet for departments and research institutions dealing with the topic of electrochemical storage technologies and electromobility was carried out. A total of 94 copies of the questionnaire have been spread to potential participants via e-mail and professional network services. The data collection took place in the period from early January to mid-February 2018. During this period a total of 18 complete datasets have been collected. This equals to a response rate of 19 %. Eight (44 %) of the collected data sets are from participants of university chairs or research institutions. The remaining ten data sets (56 %) were obtained from industrial participants. The industrial participants are either employees of cell manufacturers (60 %) or deal with the topic of electromobility e.g. in the automotive sector (40 %). Most participants (78 %) have over three years of experience in their profession. The information about the participants are summed up in Fig. 3.

3.2. Results of the expert survey

In the first part of the questionnaire the participants were asked to assess battery parameters regarding their importance for the use in hybrid drives of shunting locomotives. The participants had the possibility to rate 11 parameters that were identified in the literature review. Moreover, they had the option to add further parameters. The result is displayed in Fig. 4 and is later used to form a target system for the evaluation of the storage technologies. The highest average rating was obtained for the parameter safety with a value of 3.3 out of 4. Compliance with the safety requirements laid down in standards such as DIN EN 45545 can be regarded as a kind of basic feature due to their obligatory nature. Other important parameters are especially cyclic and calendrical lifespan as well as specific power and power density. These results confirm the assessment gained from the literature review.

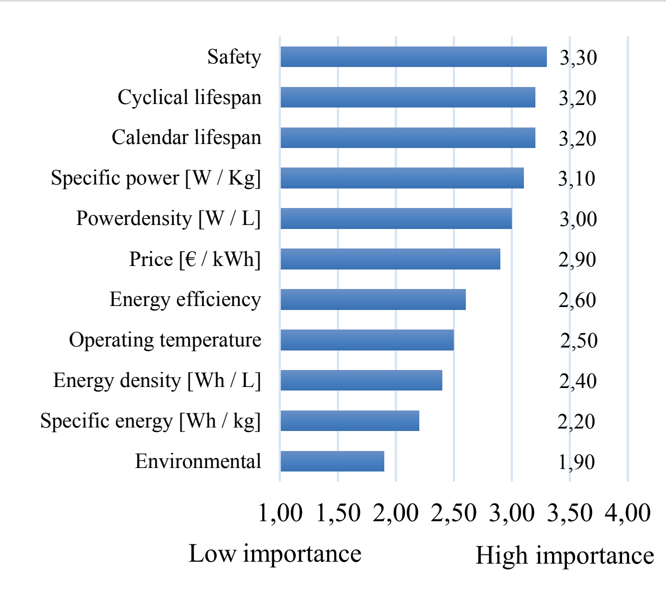

Fig. 4. Average rating of battery parameters.

The second part of the questionnaire began with an assessment of the suitability of current storage technologies for the usage in hybrid drives. The six presented technologies in Fig. 5 were evaluated. The evaluation was carried out on a unipolar, fully verbalized scale with four categories. The possible categories were "Not suitable", "Conditionally appropriate", "Suitable" and "Well suitable". For evaluation, scores of zero to three were awarded for the categories.

The lithium-ion technology reached the highest rating with a score of 2.8 out of 3. Hybrid storages, containing supercapacitors and batteries, followed with a rating of "Appropriate" (2.0). Within the rating of this technology, a slightly better rating was observed among participants with a research background compared to industrial participants. Supercapacitors (1.2), sodium-nickel chloride technology (1.1), NiCd / NiMH technology (1.1) and lead-acid technology (0.8) follow in descending order each with a rating as "conditionally suitable". In the case of sodium-nickel chloride technology, a significant discrepancy was found between the evaluations by scientific participants (1.6) compared to industrial participants (0.8). The explanation for this discrepancy might be that the technology is (to a lesser extent) handled in research, whereas in practice it is irrelevant in the field of electromobility.

Another conspicuous result is the comparatively poor rating of the NiCd / NiMH technology. The NiCd / NiMH technology is currently being used in hybrid vehicles in the automotive sector as well as in locomotives. The practical experience from the use of NiCd batteries in locomotives is positive. In particular, the lifetime and robustness of the batteries are highlighted. Different causes are conceivable for the evaluation as "conditionally suitable". On the one hand, the participants may have devalued the technology compared to the more appropriate lithium-ion technology. On the other hand, both NiCd and NiMH technology have specific weaknesses that could have been the deciding factors in the evaluation. The NiMH technology shows a poor behavior at low temperatures [15] and the NiCd technology has a specific energy of only 50 – 75 Wh / kg [16].

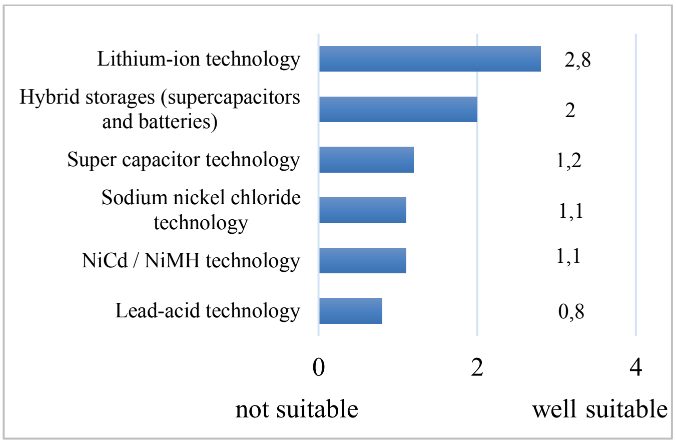

Fig. 5. Suitability of current storage technologies for the use in hybrid drives.

Besides the suitability assessment, the participants have also been asked to estimate the future meaning of the technologies for hybrid drives. The experts chose the meaning of each technology between strongly decreasing (-2) and strongly increasing (+2). For each technology the mean of all valuations was formed. Moreover, the participants were asked for the time horizon when their estimation applies. The three options were < 5 years, 5 – 10 years and > 10 years. The result shows that the lithium-ion technology is expected to become much more important (⌀ +1.44) in the near future. For the supercapacitor technology as well as for hybrid storages of supercapacitors and batteries a slight increase of the importance is predicted for the medium-term future (⌀ +0.44 / ⌀ +0.65). The lead-acid and the NiCd/NiMH-technology are expected to become less important in the near and medium-term future (⌀ -1.22 / ⌀ -1.18). The technologies are used and researched for a long time. Thus there are no substantial advances to be expected while new technologies are getting better and cheaper. The meaning of the sodium nickel chloride technology is expected to remain constant.

Furthermore the experts were questioned about potential future storage technologies, namely the lithium-sulfur, the lithium-air and hybrid-capacitor technology. Especially the hybrid-capacitor technology has been identified as potential storage technology for hybrid vehicles. However, the experts also stated that the three potential technologies are several years away from their practical application in hybrid drives.

A target system has been formed to validate the results of the expert survey regarding the suitability of the different technologies for the use in hybrid shunting locomotives. Furthermore, the target system can be used to evaluate further storage technologies which have not been considered in this article. The target system is based on the battery parameters shown in Fig. 4. Factors that are interlinked with each other have been conflated to avoid biases. This concerns the factors cyclical and calendar lifespan, specific power and power density as well as specific energy and energy density. The factors “Development potential” and “Proven reliability” of the technologies have been added to the target system, as they are relevant for the practical application. This leads to ten parameters for the evaluation in the target system. The weighting of the parameters results from the importance assessment from the expert survey. The two additional factors have both been weighted with 5 %. For better clarity, the parameters were divided into the following four categories:

- Basic features,
- Performance features
- Other features
- State of the art

Table 2. Target system for the evaluation of technologies.

	Weighting
Basic features (24.0%)	
Security	13.7 %
Operating temperature range [°C]	10.3%
Performance features (58.2 %)	
Lifetime (cyclical and calendar-based)	13.3 %
Power ([W / kg] and [W / l])	12.6 %
Price [€ / kWh]	11.9 %
Energy efficiency	10.5 %
Energy content ([Wh / kg] and [Wh / l])	9.8 %
Other features (7.8%)	
Environmental compatibility	7.8 %
State of the art (10.0%)	
Development potential of the technology	5.0 %
Proven reliability of the technology	5.0 %

The entire target system with the valuation of each parameter is displayed in Table 2. No exclusion criteria were defined. A fixed requirement exists only about the applicability of the locomotives between -25 °C and +40 °C. If a technology cannot be used in the entire temperature range, however a climate system can be used to ensure the usability. Thus, failure to comply with the limits does not result in exclusion of the technology. An exclusion might only be caused by a failed approval due to security issues. However, most of the technologies are already in use today, so there are no problems to be expected in this regard.

To allow for enough differentiation, a seven-step bipolar rating scale was chosen. A score of four corresponds to a neutral rating of suitability. Values greater than four are positive, smaller values are negative. Fig. 6 classifies the technologies according to their overall rating on the rating scale. According to the evaluation model, the lithium-ion technology is the most suitable technology for the use in hybrid drives of shunting locomotives. It reaches a total score of 5.91 of 7. Besides the lithium-ion technology the hybrid-capacitor technology as well as the supercapacitor technology seem promising for the application in hybrid shunting locomotives.

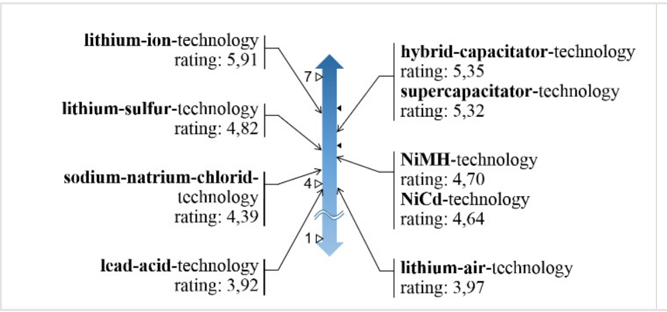

Fig. 6. Rating of relevant battery technologies.

4. Conclusion

The expert survey and the literature review show, that the most suitable battery technology for the use in hybrid shunting locomotives is the lithium-ion technology. The combination of a lithium-titanate anode and lithium-iron-phosphate cathode is currently the best choice. It has the best properties regarding safety and lifespan, while providing enough specific power and specific energy to power a hybrid shunting locomotive during most times of its typical usage. For the peaks in demand and to recharge the battery the diesel engine can be connected. A study of Toshiba shows, that the fuel consumption of a hybrid shunter could be lowered to 64% compared to a usual diesel-electric shunting locomotive. Moreover, the emission of nitrogen oxides is 61% lower and the noise level is reduced by 22dB in average [1]. Assuming the representativeness of the study, the environmental pollution could be lowered worldwide by reconstructing old diesel-electric shunting locomotives to hybrid ones. Also, the combination of supercapacitors with a battery constitutes an option. The French project Plathee uses this kind of energy storage [17]. Several future storage technologies are under investigation. The lithium-sulfur and lithium air technology as well as hybrid supercapacitors might get relevant for hybrid shunting locomotives in the future. Especially the hybrid-capacitor technology reaches a high rating in the evaluation in the target system. Though these future technologies are in a research state and several years away from their practical application in vehicles.

Based on these results, the reconstruction of conventional shunting locomotives to hybrid ones must be researched. There are only few regimentations on how to transport, store or handle those huge batteries. The further research of the chair of Production and Operations Management is on how to accomplish this. A lithium-ion-titanate battery, which energizes a hybrid shunting locomotive, weighs about 1.5 – 3 tons and is categorized as a dangerous good class 9a. Therefore it must be handled with caution. Also, the requirements regarding fire prevention and environmental protection are part of future researches. Finally, there will be a concept for transport, handling and storage for batteries of this category.

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