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Selection of the battery pack parameters for an electric vehicle based on performance requirements

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Abstract. Each type of vehicle has specific power requirements. Some require a rapid charging, other make long distances between charges, but a common feature is the longest battery life time. Additionally, the battery is influenced by factors such as temperature, depth of discharge and the operation current. The article contain the parameters of chemical cells that should be taken into account during the design of the battery for a specific application. This is particularly important because the batteries are not properly matched and can wear prematurely and cause an additional costs. The method of selecting the correct cell type should take previously discussed features and operating characteristics of the vehicle into account. The authors present methods of obtaining such characteristics along with their assessment and examples. Also there has been described an example of the battery parameters selection based on design assumptions of the vehicle and the expected performance characteristics. Selecting proper battery operating parameters is important due to its impact on the economic result of investments in electric vehicles. For example, for some Li- Ion technologies, the earlier worn out of batteries in a fleet of cruise boats or buses having estimated lifetime of 10 years is not acceptable, because this will cause substantial financial losses for the owner of the rolling stock. The presented method of choosing the right cell technology in the selected application, can be the basis for making the decision on future battery technical parameters.

1. Introduction

Currently use of electrically powered vehicles is the leading direction in development of public transport. Reasons include a few important factors. The main advantages are quiet operation and shifting creation of pollutants from densely inhabited areas beyond such areas. It is worth noticing that the energy may originate from renewable resources or coal fired power plants equipped with very efficient systems for exhaust flue gases treatment, which results in small negative impact on the environment. Also the exploitation cost is three times lower for electrically powered vehicle compared with combustion drive. Systems for braking energy recovery support operation wherever it is possible. Unfortunately, transport with electrically powered vehicles has certain disadvantages. Actually all of them are related to the use of chemical batteries to store energy. With high cost of batteries and substantial weight and volume, they impose significant range restrictions compared to equivalents of combustion technology. Additionally, they require infrastructure to charge at designated stations. That infrastructure may have negative impact on urban distribution grids, which also requires analyses on the investment stage. Traction batteries, being components that constitute a substantial vehicle worth, are a subject of many analyses on their efficient operation. This paper focuses on the battery selection based on predicted operation conditions.

Batteries with lithium-ion cells are of the most often used type for electrical vehicle power storage. Principle of operation of such cells is based on reversible process of lithium ion (Li+) transfer between cathode and anode, called intercalation for charging, and deintercalation for discharging [1].

Batteries of lithium-ion group share a common feature, which is the design based on positive electrode of metal oxides with lithium content, negative electrode made of porous carbon, and electrolyte with lithium salts dissolved in a mix of organic solvents. There are research projects running that aim to improve properties of cells, that focus on changing composition of specific components. This allows to build different versions and it is the differences in composition of changed components that decide about performance and operating properties of a given technology.

Currently the batteries most frequently used for transport applications are based on the following compounds [2]:

- $LiFePO_4$ (LFP);
- $Li_4Ti_5O_{12}$ (LTO);
- $LiNiMnCoO_2$ (NMC);
- $LiNiCoAIO_2$ (NCA).

2. Factors influencing the operation of a battery

2.1. How weight and volume of a battery affect suitability for transport applications

The Lithium-ion batteries have earned their position in transport applications due to some advantages. One of them is the very advantageous ratio of energy to volume or weight. This parameter is referred to as energy density and it informs, how much energy can be stored in 1 kilogram or litre. Cell manufacturers specify this value, which is important information to evaluate suitability of a given technology for a solution to design. It is important to remember, that the energy density is different for the cells alone, and different for finished battery pack that includes the cells. This is caused by presence of additional electrical, mechanical and measuring systems in the battery pack. However, this information is a good reference point to evaluate how required energy affect weight and volume of a vehicle.

Table 1. Comparison of energy densities for three types of lithium-ion cells.

Cell type	Energy density per weight [Wh/kg]	Energy density per volume [Wh/l]
LTO	90	200
LFP	130	247
NMC	150	300
NCA	240	670

Table 1 presents energy densities for four lithium-ion cell types. LTO cells are the worst in this comparison, LFP and NMC cells are on the similar level, while the NCA technology features definitely the greatest energy density.

Energy density is an important factor when selecting a battery type for a given type of vehicle. For example, passenger cars require small and high capacity batteries, which is caused by small available space and restrictions on the vehicle weight. Buses have much more space and the battery volume is not that important, but weight still can be an important factor after reaching certain level, due to limitation of gross vehicle weight allowed by regulations. Heavier battery may put limit on allowed number of passengers that can travel by the vehicle.

2.2. How climate conditions can affect operation of traction batteries

All lithium-ion battery manufacturers define how performance depends on the temperature. The restrictions are safety related and affect charging and discharging current. Exceeding such limitations may damage the battery or cause much faster aging.

Table 2 presents exemplary temperature ranges for battery operation at discharging and charging. Data in table 2 for the temperatures of cell types LTO, LFP, NMC were set at a safe level suggested by the manufacturers of the battery packs while from data sheet for NCA.

Table 2. Exemplary temperature ranges for battery operation at discharging and charging.

Cell type	Operating temperature range (discharging)	Operating temperature range (charging)
LTO	-30 to 55 ℃	-20 to 55 ℃
LFP	-30 to 55 ℃	-20 to 55 ℃
NMC	-20 to 55 ℃	-0 to 55 ℃
NCA	-20 to 60 ℃ [3]	-0 to 45 ℃ [3]

The table 2 data shows that the temperature ranges for charging currents are narrower than for discharge currents. This means that charging process is more electrochemically demanding, hence higher requirements for temperature parameters to meet for the process.

It is necessary to remember that besides the limit on the temperature range of cell operation, there is also relation between the temperature and allowed charging and discharging current. Figure 1 presents an example for LFP batteries charging.

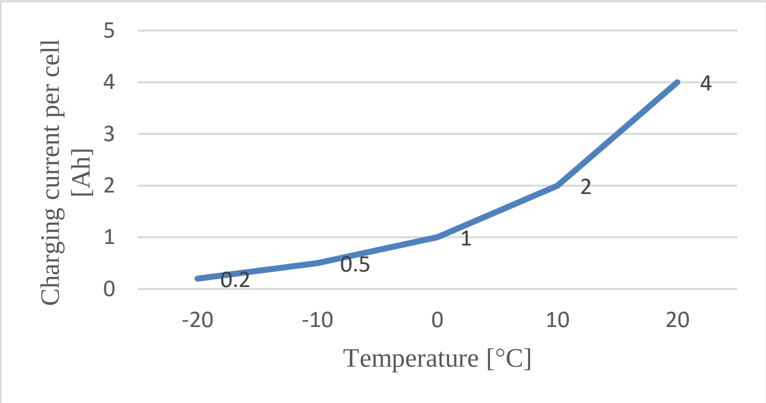

Figure 1. Exemplary relation between charging current and the cell temperature. [4]

Figure 1 reveals that charging currents for the lowest temperatures are the lowest, and increase towards temperature values close to 20 ℃. This means longer charging times. It is easy to imagine a situation. When a vehicle is equipped with fast-charging batteries but the temperature does not allow to take advantage of that feature, this in turn can cause delays in carrying out transport activities.

Such situation may also happen when the battery pack is too warm, then charging current is reduced. This allows to limit further heating of the battery.

Another relationship to consider is how the temperature affects available battery capacity. Unfortunately this phenomenon can be observed even in temperature range allowed by the manufacturer, and it is caused by increase of internal cell resistance with cooling of the cell. Figure 2 presents such exemplary relationship, where decrease of available capacity as a function of the cell temperature reached over 35%. There are technologies that such reduction may exceed even 50% within temperature range allowed by the manufacturer.

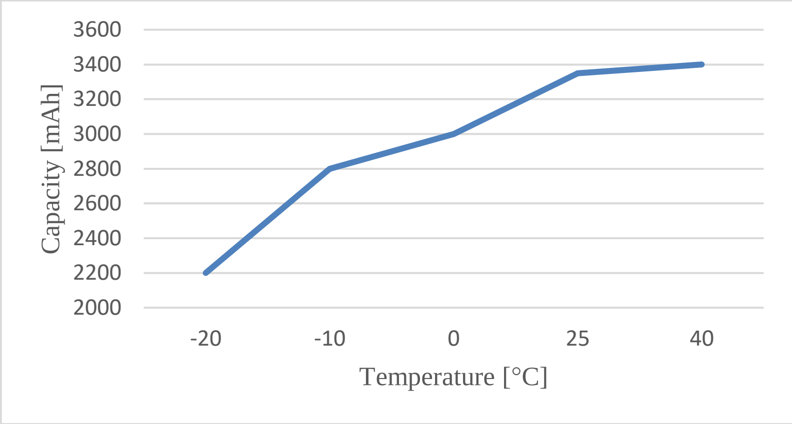

Figure 2. Relationship between available cell capacity and the cell temperature. [5]

Battery operation in too low or too high temperature contributes to faster wear. The most recommended operating temperature is as close to 20–25 ℃ as possible.

To counteract against the above mentioned situations, it is possible to integrate passive or active systems for thermal conditioning with the battery packs. This can be a system for heating, cooling or both, according to the needs. Depending on specification of such system, it uses heated or cooled air, ventilation with ambient air, liquid heating and cooling.

Apart from obvious functionality that protects the battery pack from over-heating and over-cooling, the thermal conditioning systems aim to provide uniform temperature inside. This is important, because cells operating at different temperatures have different operating specifications, which has already been discussed in this paper. Such differences in one battery pack may cause faster wear and limit operating functionality.

2.3. Use of heating and cooling systems for a traction battery

Average temperature in Poland falls in between 7 and 9 ℃. In Warsaw extreme temperatures can be observed, from very high up to approximately 35 ℃, to very low, less than -15 ℃. Selection of battery for an electrically powered vehicle requires consideration of these conditions.

Considering very high charging currents for LTO batteries, and great amounts of heat generated in the process, they always have cooling systems with liquid coolant medium. They also allow to heat the battery in case of significant temperature fall. This guarantees that LTO battery packs are fully protected from ambient temperature variations.

This is different for LFP batteries. Due to allowable working currents and the battery size, there is no need to include liquid cooling systems, and heating is not available either. The exception are battery packs for cold climate countries, like Sweden and Norway, which have additional heating mats installed. Such mats can be included with the battery packs for Polish market on client request, but this is not a common practice. In accordance with the data from cell manufacturers, operating temperature range is between -30 to +55 ℃ for discharging and -20 to +55 ℃ for charging. It is clear, that fault free operation is possible down to -20 ℃, which will result in reduced charging current, but will not put the vehicle to a halt caused by no possibility to recharge. Adjustment of charging current to the temperature of the battery pack is governed by the BMS, Battery Management System.

It should be noted, that the remaining cell types installed in electrically powered vehicles, namely NMC and NCA, require heating systems. This is due to the operating temperatures allowed by manufacturers, and they are -20 to +55 ℃ for discharge and 0 to +55 ℃ for charging in case of NMC, and -20 to +60 ℃ for discharge and only 0 to +45 ℃ for charging in case of NCA.

2.4. Battery working currents in electric vehicles

This parameter defines allowed currents for charging and discharging, specified for temperature ~20 ℃. The working current is specified as a multiplier of C number, for example 5C. C current (1C) is one-hour current, which would allow to charge the battery from 0 to 100% of its capacity in one hour, or discharge the battery from 100 to 0% of capacity in one hour. In the given example, 5C is the current that exceeds one-hour current five-fold, i.e. will discharge the battery completely in one fifth of an hour, which is 12 minutes.

Table 3. Exemplary working current ranges for discharging and charging batteries.

Cell type	operating current (discharging)	operating current (charging)
LTO	5 to 10 C	5 to 10 C
LFP	3 C	1 C
NMC	2 to 3 C	1 C
NCA	2 C	0.5 C

It is shown that LTO battery offers the greatest allowed working currents. LFP and NMC technologies are comparable by this parameter, and NCA technology have greater requirements on charging.

Depending on the technology, some batteries require charging stations with sufficient power available for quick charging, and other batteries must be used in vehicles, where few hours charging does not hinder vehicle operation.

When considering working current, we must also look at the relationship between charging current intensity and the battery charge level as compared to the total capacity. This greatly affects possible selection of battery capacity, because a vehicle leaving a charging station does not have the full battery capacity. The only way to obtain full working capacity is shifting from the CC charging (Continuous Current) to CV charging (Continuous Voltage) [6].

Figure 3 shows exemplary relationship between charging current intensity and charge level for an exemplary cell. The data are collected by the authors [7].

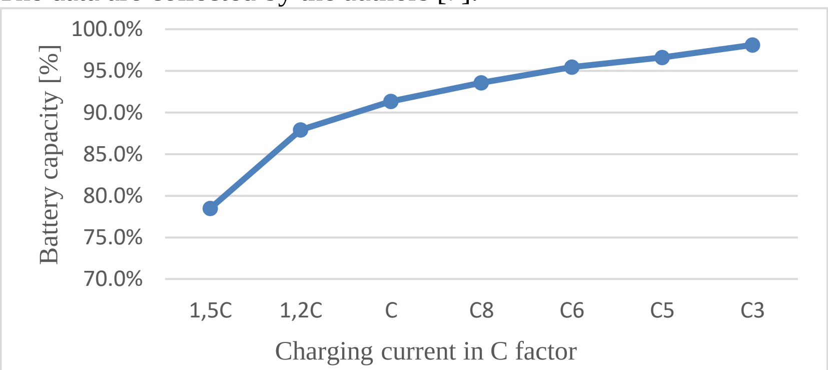

Figure 3. Sample relationship between charging current intensity and charge level of a Li-Ion cell. C factor (1C) is one-hour current, which would allow to charge the battery from 0 to 100% of its capacity in one hour, or discharge the battery from 100 to 0% of capacity in one hour.

3. Factors influencing the selection of a battery

3.1. The required number of traction battery working cycles

Manufacturer's data do not always allow to compare the numbers of work cycles. This is because the number depends on many factors: charging and discharging currents and the process depth. Therefore, comparison requires data specific for exactly the same values of the mentioned parameters.

Below is the collection of exemplary number of cycles obtained from a battery packs manufacturer. All pertain to 100% discharge depth and working currents falling in range allowed by the cell manufacturer. Getting reliable data on possible number of work cycles in a wide range of currents and discharge depths often requires performing a private study.

Table 4. Comparison of possible number of work cycles before capacity drops to 80% of rated capacity for LTO, LFP, NMC and NCA cells.

Cell type	Number of life cycles for 100% Depth of Discharge (DoD)
LTO	15000
LFP	3600
NMC	3000
NCA	500

This list shows that LTO technology has considerable advantage over other technologies, LFP and NMC are comparable again, and NCA shows much worse results. We need to notice that 15,000 full cycles with 3C current at 25 ℃ and full discharge depth is a confirmed value that has been achieved experimentally by the LTO cells manufacturer. The tests are still in progress and carrying more such cycles is possible before the capacity drops to 80% of the rated capacity.

The questions arises, how a battery capable of going for only 500 cycles has found its use for automotive applications. Solution to this issue is the right use of the battery capacity. It is important that depth of discharge is related to the loss of capacity caused by number of work cycles. It turns out that the smaller the cycling range, for example 30–70%, the longer its service life can be. So the battery type and capacity should be selected also with consideration of the discharge depth. Cell manufacturers sometimes provide such data, and if not, they need to be obtained by making measurements. Figure 4 presents an exemplary relation for LiFePo4 battery [8].

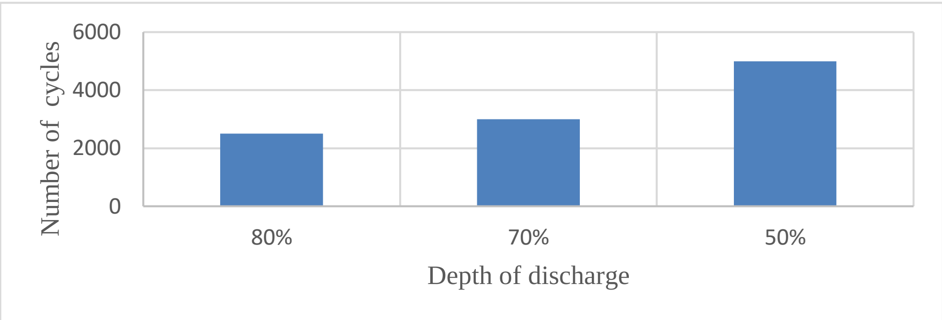

Figure 4. Relation between depth of discharge and loss of capacity caused by number of work cycles. [8]

3.2. Economic aspect of traction batteries selection

The decision making process on the traction battery selection heavily depends on economic aspect. Figure 5 shows price relations for specific lithium technologies.

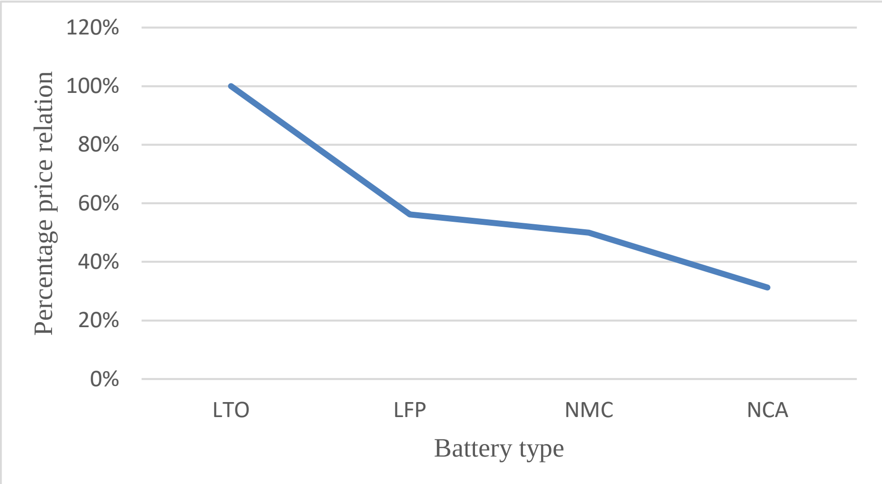

Figure 5. Price relations for specific lithium technologies for the same capacity.

Prices for lithium-ion batteries remain at high level, roughly at USD 250–900 per kWh. This is the reason for limitations in development of electrically powered communication. The abovementioned features and restrictions must be considered when deciding about investment in electrical vehicles. Appropriate operation conditions can significantly extend the lifetime. Drop of capacity by 20% of the rated capacity is assumed as the right moment for decommissioning. However, operating the batteries below 80% of initially available capacity is also considered. LFP cells aging is greatly related to change of structure (porosity) of the negative electrode, loss of material and damages in positive electrode structure, and oxidation processes. If the inner impedance increases, amount of reactive lithium and active material changes, which in turn reduces available energy and power. With loss of capacity caused by aging, the charging current reduces and amount of produced heat increases. For 60% of maximum capacity, the halt times required to replenish energy increase by over 40%. That is because the battery capacity reduction causes drop of respective charging current. Continued use of the traction batteries below recommended level of 80% capacity must be agreed and approved by the manufacturer.

When choosing the batteries it is also better to consider planned battery replacement during the vehicle life time. For example, when the planned life time of the vehicle is 12 years and whenever technical conditions allow, a LTO battery can be replaced with NMC cells battery. It is cheaper by approximately 55%, so potential replacement will not be an economical burden to the investment, and considering drop of prices and technology development it may turn out that after 6 years the savings can be even greater.

3.3. Exemplary selection of a battery with consideration of factors weights

In the "Renewable Energy Powered Hybrid Innovative Sailing Yacht" project the battery was selected by looking at the weighting sum of specific factors for each of the considered technologies. The following section describes criteria used to select parameters and weights.

Battery capacity is related to the characteristic daily specifications handed over by the project partner:

- work mode during port docking, without connected on shore power supply,
- work mode for going under sails,

- work mode for going with electric motor only.

The third specified mode was the hardest in terms of loading the battery, and required nearly 40 kWh of energy. So the selected battery must cover that need and work range must not reach 100% Depth of Discharge (DoD). Therefore, the capacity is not included in the table of weights.

Volume and weight are important, considering the planned place of batteries installation. The room will be small, and carrying the battery in will require going along steep stairs with narrow passages. The battery will be divided into battery packs maximum 50 kg each to allow carrying; the number of packs should be possibly the lowest, because the container cost increases with each additional battery pack.

Climate effect is important for operation, which has been explained in this paper. All analysed batteries can be used in the project, but they differ by allowed working temperatures in higher ranges, which may appear in Turkey, where the yacht may be operated. It is reflected with assigned points.
Cooling system is not required considering the working currents, nevertheless LTO batteries are equipped with such system in accordance with the manufacturer recommendations.

The part on charging current shows that the assigned weight is 0% and scoring is skipped. This is caused by assumption that the battery will be charged during planned, few hours long docking at port, so there is no requirement for quick charging with high current.

Number of cycles is an important factor, and in this case NCA score was lifted from 1 to 3, because replacement of cells is possible after 5 years, which still does not exceed the assumed cost.
The last criterion is the price, which is a significant factor overall, and decisive in this particular case. This is because US dollar price increased during the project, and the energy required by the project partner allowed to purchase NCA battery, which allows for required 5 years of the unit operation according to simulations. Table 5 presents exemplary selection of a battery with consideration of factors weights.

Table 5. Exemplary selection of a battery with consideration of factors weights for LTO, LFP, NMC and NCA cells.

	Volume	Weight	Climate effect	No cooling system	Level of charging currents	Number of work cycles	Price	Total
percentage distribution	5%	10%	15%	10%	0%	30%	30%	100%
LTO	1	1	10	5	0	10	1	5.45
LFP	4	4	5	10	0	5	5	5.35
NMC	5	5	3	10	0	4	6	5.2
NCA	10	10	2	10	0	1	10	6.1

4. Conclusion

This paper discusses the issues of batteries selection for electric vehicle, taking into account many operation criteria. This problem is obviously a complex one. Selection of a battery for an electrically powered vehicle requires detailed analysis of many factors, such as: weight and volume, charging currents, route characteristics, depth of discharge, operating temperatures related to seasons of the year in the given area, potential integration of conditioning and heating. Selection method of the suitable technical solution is described, using comparison of the weighting sum of specific factors for each considered option. Correct selection of the battery and appropriate operation can extend the service life between replacements, thus reducing operating costs of the electrically powered vehicle.

References

[1] Linden D and Reddy T (ed.) 2002 McGraw Hill chapter 2 Electrochemical Principles and

Reactions *Handbook of Batteries Third Edition* p 229

[2] Sierszyński M, PikulaM, Fuć P, Lijewski P, Siedlecki M and Galant M 2016 Overview of solutions for lithium-ion batteries used in electric vehicles *International journal of energy and environment* pp 105-11

[3] 2012 Lithium-ion Battery Overview (PDF) *Lighting Global* **10**

[4] 2012 *A123 Systems ALM 12V7 User's Guide*

[5] Panasonic Datasheet for NCR18650b 3400 mAh [http://na.industrial.panasonic.com/sites/default/pidsa/files/ncr18650b.pdf]

[6] Al-Haj Hussein A and Batarseh I 2011 IEEE Transactions on Vehicular Technology *A Review of Charging Algorithms for Nickel and Lithium Battery Chargers* **60** 3 pp 830-8

[7] Koniak M, Czerepicki A and Tomczuk P 2016 Test bench for battery energy storage selection for use on solar powered motor yachts *Scientific Journals of the Maritime University of Szczecin* **46** pp 197-202

[8] Victron Energy Datasheet 12,8 Volt Lithium-Iron-Phosphate Batteries Victron Energy 2017 [https://www.victronenergy.com/upload/documents/Datasheet-12,8-Volt-lithium-iron-phosphate-batteries-Smart-EN.pdf]

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