# Overview of solutions for lithium-ion batteries used in electric vehicles

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***Abstract* —** The development of civilization brings a continuous increase in energy demand. Fuel consumption increases, which causes an increase in environmental pollution with harmful exhaust gas components such as carbon monoxide (CO), carbon dioxide ($CO_2$), hydrocarbons (HC), nitrogen oxides ($NO_x$) and particulate matter (PM). The development of vehicle propulsion systems so focused on the search for alternative drivetrains, which include primarily hybrid and electric. Such drives are characterized by a favorable ecological and economical performances. The problem is the performance of used batteries, which differ significantly from the large-scale use of fossil fuels such as petrol and diesel.

The subject of this study concerns the analysis of the concept of the world's existing lithium-ion batteries used in electric vehicles. The study contains a presentation of innovative solutions that can improve the performance characteristics of alternative drives. The article presents 8 latest solution for lithium-ion batteries: LTO batteries, LFP batteries, NMC batteries, LMO batteries, Lithium-ion KOKAM batteries, A123 batteries, Li-Tec lithium-ion batteries, Nano-Li4Ti5O12 batteries from Altairnano.

Also presented is a case study in the use of batteries as a storage of energy for an electric bus. In view of their favorable properties LFP and LTO type batteries were analyzed. Simulations were carried out using an 18 meter bus on the selected route. Use of different chargers was simulated on the actual travel route for a city bus. The entire route of the bus covered more than 150 km.

***Keywords* –** battery, alternative vehicle drives, lithium-ion technology, case study

## I. Introduction

THE development of vehicle propulsion systems is focused on the use of alternative technologies, which include primarily hybrid and electric motors. Due to their environmental, functional and economical characteristics, exploitation of vehicles equipped with these kinds of drives is especially beneficial in urban conditions. In the cities, vehicles often start and stop moving. Often, these phases are separated by the vehicle being idle. Under these conditions, a classic vehicle drive the combustion engine is running in a large range of power, speed and efficiency. The overall energy efficiency of classical drive vehicles are also degraded by the irreversible conversion of kinetic energy into heat during frequent deceleration. Another aspect promoting the electrification of powertrains is regulations requiring the reduction of emission limits of harmful exhaust emission components. The main performance parameters of energy storages include: energy density, power density, storage efficiency, conversion efficiency, lifetime, overload resistance, reliability and no need for maintenance. Table 1 shows a comparison of these parameters for basic types of energy storages [8]. The kinetic energy storages stores energy in the mechanical form, typically using a rotating flywheel. The hydropneumatic equivalent of energy storage accumulates elastic energy in the form of elasticity of solid or gas, or in the form of potential energy of the load, using the phenomenon of increasing pressure of the medium.

Table 1 Basic properties of different types of energy storages [developed based on 6, 7]

| Property | Energy storage type | | |
|---|---|---|---|
| | kinetic | hydropneumatic | electro-chemical |
| Energy density [kJ/kg] | up to 10 (360) | up to 3,2 | up to 400 |
| Power density [W/kg] | unlimited | up to 300 | up to 200 |
| Storage efficiency: | | | |
| Short-term | (+) | (+) | (+ +) |
| Long-term | (– –) | (+) | (o) |
| Conversion efficiency | (+) | (–) | (–) |
| Lifetime | (+ +) | (+ +) | (– –) |
| Overload resistance | (+) | (+) | (– –) |
| Reliability | (+) | (+) | (–) |
| No need for maintenance | (+) | (+) | (– –) |
| Overall cost (+ = low) | (+) | (–) | (– –) |

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Legend: (+ +) – great, (+) – good, (o) – average, (–) – poor, (– –) – very poor

Electrochemical batteries are characterized by the best indicators of power and energy density compared with other battery types and for this reason, despite the highest cost, gained the most popularity. In order for electric vehicles to achieve the range approaching that of the hydrocarbon fuel vehicles it is necessary to use large and heavy electrochemical batteries [8]. This results in a significant increase in vehicle weight affecting the amount of energy required to move, and thus also the cost of its operation. For several years the lithium-ion (Li-Ion) batteries are increasingly used, replacing the older technologies of nickel-metal hydride (NiMH) batteries.

## II. LITHIUM-ION TECHNOLOGY

The ability to charge batteries makes them different from galvanic cells, where the principle is the same, but its function is fulfilled once. The chemical energy stored in the galvanic cell can only be used once. Electrodes originally used in batteries were made of basic nickel oxide (III) NiO(OH) (cathode) and metallic cadmium (anode). So they were called rechargeable nickel-cadmium batteries (NiCd) [9]. This solution was characterized by low density capacity values and above all, the occurrence of the memory effect, i.e. Recharging before the full cycle discharge is complete will decrease the capacity of the battery. The next generation of batteries used nickel in combination with metal and hydrogen (NiMH). The change had a positive effect on battery performance and reduced the memory effect. This technology was used in the first hybrid vehicles like the Toyota Prius in the years 1997-2010 [21]. Both solutions were characterized by a low voltage of a single cell of 1.2 V.

An opportunity to improve the battery performance was to use the lightest metal - lithium. The main advantage of this solution was the lack of the memory effect, and higher values of energy and power density than in previous solutions. Lithium-ion batteries are currently used in electric and hybrid vehicles. The charging and discharging is associated with the transfer of lithium ions through the electrolyte. During charging, they collect electrons from the negative electrode while simultaneously being fixed in its structure as neutral atoms. During discharge they pass the electron to the electrode and move into the electrolyte as lithium ions. A similar but reverse process occurs at the positive electrode. The first vehicle, which used this technology was the Mercedes S500 Hybrid unveiled in 2010. The main obstacle in the earlier introduction of this technology have been problems with the overheating of the batteries. The Mercedes-Benz S500 Hybrid uses an additional air flow for battery cooling [3,10].

The main trend in the development of electric drives is associated with the search for technology that would enable increased energy density per unit volume and mass of the battery. Theoretical calculations indicate that the battery energy capacity of a Li-Ion battery can be increased to 2 700 Wh/kg which is approximately 20 times higher than the currently used solutions. It is envisaged that this will be achieved by the use of fullerene nanotubes [15]. This publication provides an overview of modern lithium-ion batteries together with an indication of their main characteristics.

## III. OVERVIEW OF THE LATEST SOLUTIONS FOR LITHIUM-ION BATTERIES

### A. LTO batteries

In LTO batteries (Lithium-titanate) the anode is made of titanium oxide ($Li_4Ti_5O_{12}$). These batteries are increasingly used in the automotive industry. Due to their properties they are used in hybrid and electric vehicles. They can operate in temperatures as low as -46°C (charging and discharging) at which other batteries have very low capacity [14]. At -30°C the batteries have over 80% of their base capacity in the ambient temperature of 20°C [17]. The result is that they have proved themselves applicable in many climate zones, as well as in extreme temperatures (maximum operating temperature is approx. 70°C) [4]. The current parameters of batteries of this type are a capacitance of maximum 90 Wh/kg and 250 Wh/dm$^3$ [20]. In addition, this type of battery can be charged with high voltages.

Tests showed that after 7 000 cycles of full charging and discharging, the battery capacity has changed in relation to the original by less than 20%. The relationship between the number of cycles of discharge/charge and the battery capacity is shown in Figure 1.

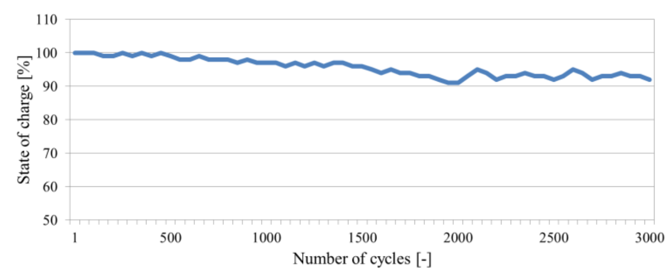


Fig. 1 The relation between the number of discharge/charge cycles and the LTO battery capacity [17]

Unused batteries self-discharge by a small amount. Due to its properties batteries can be used in applications in which the rapid charging is needed. For example: fast charging of 125kWh battery in the bus at the ends of lines with the power up to 450kW. The disadvantages of the LTO battery is the voltage produced by one cell, it is only approx. 2.4 V, but this value is still higher than for lead-acid batteries (2 V).

### B. LFP batteries

LFP batteries (Lithium ferrophosphate) are characterized by the cathode being made of lithium compound, iron, phosphorus and oxygen ($LiFePO_4$). These batteries, like the LTO variety, are suitable for automotive applications. This type of a battery is characterized by high resistance to self-discharge when charging cycles are incomplete, which is desirable in hybrid vehicles. In the case of LFP battery voltage of a single cell is up to 3.2V, however, it should not be allowed to discharge below 2.5V, or the charging voltage to reach more than 4.2V, as this may damage the battery [12]. The batteries respectively recharged could gives over 2000 full cycles while retaining 80% of original capacity. The dependence of the capacity on the number of full discharge/charge cycles is shown in Figure 2.

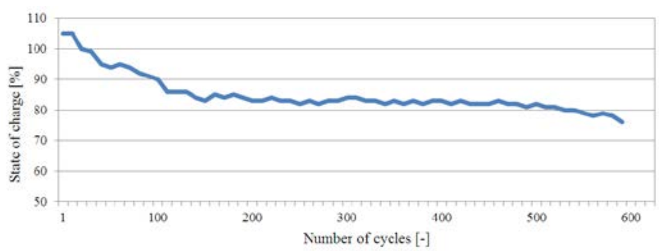


Fig. 2 The change of LFP battery capacity with the number of discharge/charge cycles [19]

The compound used for the cathode is environmentally safe and non-flammable. Operating temperature range is 0 to 60°C, and the energy density reaches over 120 Wh/kg, which is a high and desirable value. LFP batteries, due to higher specific energy than LTO batteries, are typically used in electric vehicles with extended range required on a single charge.

## C. *NMC batteries*

NMC battery type (Lithium Nickel Manganese Cobalt Oxide) is characterized by the use of a $LiNiMnCoO_2$ compound with the cobalt content of 10-20% as a cathode. These batteries use nickel, which has been used on a large scale in NiMH and NiCd batteries, later replaced by lithium-ion batteries. Maximum voltage is 4.1V, and the minimum operating voltage is 2.7V [13]. Batteries of this type are characterized by high energy density reaching up to 250-270 Wh/kg, and in combination with SiC even more than 300 Wh/kg. At the same time the danger of overheating or damage compared to LTO and LFP solutions is higher. Operating temperature range is -20 to 55°C [13]. This value results from the instability of nickel at higher temperatures. Number of complete cycles of discharge/charge while maintaining 80% of the original capacity is 1 000, so less than the aforementioned solutions.

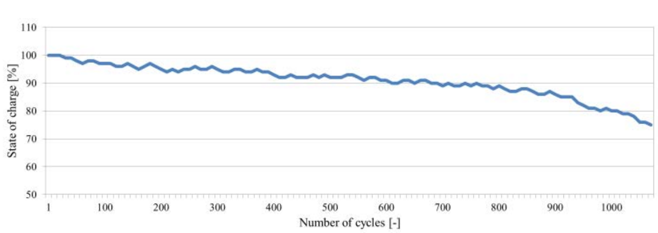


Fig. 3 The change of NMC battery capacity with the number of discharge/charge cycles [11]

This type of battery is not as popular as the LFP and LTO batteries for electric vehicles due to higher danger of overheating or damage compared to LTO and LFP solutions.

## D. *LMO batteries*

LMO batteries (Lithium manganese spinel) are characterized by the use of manganese oxide in combination with lithium as the cathode ($LiMn_2O_4$). They have the possibility of storing large amounts of energy (up to 240 Wh/kg), while maintaining better safety in the case of overheating than NMC batteries [16]. This type of batteries are still in the testing phase, but they are considered a viable prospect for energy recovery systems in Formula One vehicles. LMO-type battery manufacturers do not publish data of the number of cycles of discharge/charge and how it affects the battery capacity. There is only the information that the batteries are characterized by a number of full cycles of discharging and recharging while maintaining 80% of the original capacity stated as 1 800 [16].

## E. *Lithium-ion KOKAM batteries*

KOKAM batteries are batteries made with lithium-ion technology and patented by Dow Kokam. Their primary objective was to increase the operational parameters of lithium-ion technology, especially energy density. Dow Kokam received a grant for a new technology in 2009, and already in 2012 started mass production of a new battery. One of the objectives was to organically produce the batteries in a way that does not use fossil fuels, but rather energy from natural sources. The cathode is made of nickel, magnesium and cobalt. At the time of launching on the market KOKAM batteries were characterized by an energy density of 143 mAh/g (130 – 200 Wh/kg), and a large number of cycles of full discharge and charge while maintaining 80% of the initial capacity (2 500), as illustrated in Figure 4.

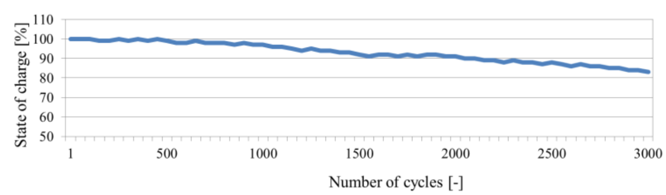


Fig. 4 The change of KOKAM battery capacity with the number of discharge/charge cycles [2]

In addition, KOKAM-type batteries have the ability to be charged with a higher current when compared to other battery solutions. All of these are the key parameters in terms of the use of batteries for automotive applications. In addition, they offer less heating during operation and greater safety for the environment in case of damage. Charging temperature ranges from 0 to 40°C, and discharging from -20 to 60°C. The batteries are characterized by low rate of self-discharging and no memory effect. Figure 5 shows the percentage of battery capacity KOKAM after 2 weeks.

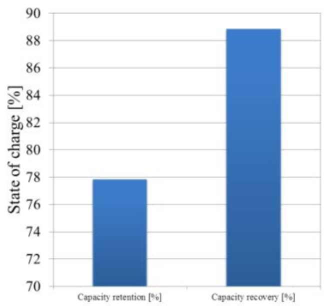


Fig. 5. Percentage of battery capacity of a KOKAM battery after 2 weeks [2]

### F. *A123 batteries*

The overall performance and reliability of the battery depends largely on the chemical compounds used in the construction of a single cell. For example, lithium-ion technology is used both in electric vehicles, network storage systems and a variety of industrial applications. The company A123 Systems announced Nanophosphate® technology. This technology was developed by a team of professor Yet-Ming Chiang at the Massachusetts Institute of Technology. It utilises lithium-ion batteries constructed at the nanoscale level with specific structural and chemical properties, allowing for maximization of performance. Figure 6 shows schematically the structure of Nanophosphate®.

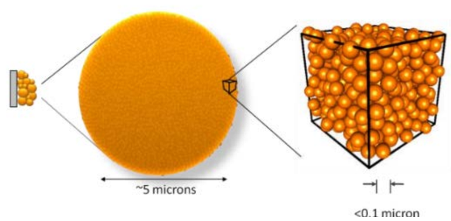


Fig. 6 Schematic visualisation of the Nanophosphate structure used in lithium-ion battery produced by A123 [2]

The main advantages of A123 batteries include: high energy value useful in a wide range of SOC (state of charge) and extended maintenance interval achieved through the use of specialized patented nanostructure. Single cell voltage is 3.3 V [18]. The batteries allow to have high power values per mass (2 400 W/kg), volume (500 W/dm3), and capacity (up to 300 Wh/dm3 and 165 Wh/kg) [17]. The value of the operating temperature range (from -30 to 55°C) and storage (-40 to 60°C) should also be noted. A123 batteries also feature a very low watt-hour cost.

A particularly important indicator when using this type of battery in vehicles is the unusual, when compared to other technological solutions used, independence of the battery power from the battery charge level. Typically, this involves a significant voltage drop along with the discharging of the battery, in this case the character of the curve is closer to flat (Fig. 7).

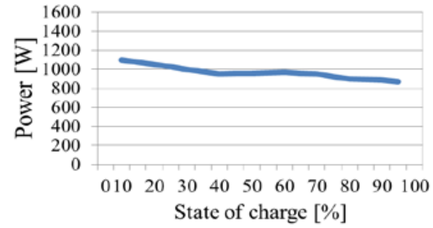


Fig. 7 The relation between battery power and the level of charge held [1]

A very important aspect of battery usage is safety. A123 batteries, although this is not currently required, have passed crash tests assessing their ability to maintain the required level of safety in the event of deformation. Such tests will be mandatory for batteries in vehicles only since 2016. This ensures their applicability in future vehicles. The last mentioned advantage applies to retention of the original capacity depending on the number of cycles (Figure 8).

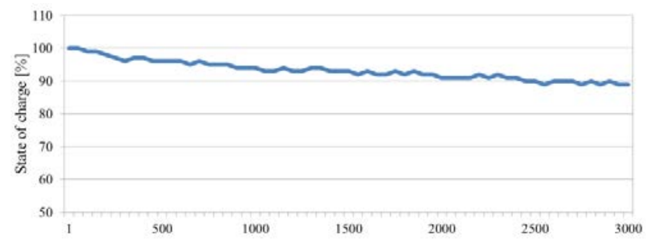


Fig. 8 The relation between the A123 battery capacity and the number of discharge/charge cycles [1]

A123 batteries continue to hold approx. 90% of the original capacity after 3 000 cycles. This distinguishes them from other solutions available on the market. Comparable battery solutions after the same number of cycles have only approx. 80% of their original capacity.

### G. *Li-Tec batteries*

CERIO® technology is based on a specific combination of ceramic materials and conductors of ions of high molecular weight. It has been developed for Formula 1 and is based on a ceramic separator SEPARION®. The compact design of the Li-Tec cell, enables high energy density and low weight. The construction of a single cell is shown in Fig. 9.

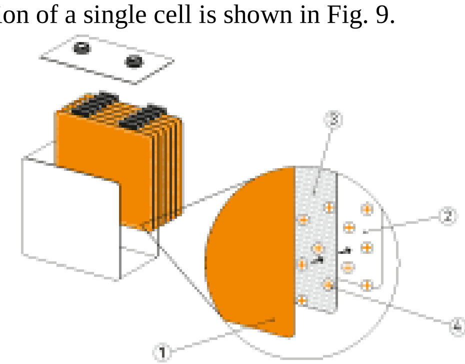


Fig 9. Construction of a single-cell lithium-ion battery, Li-Tec: 1- cathode, 2- anode, 3- ion conductor of high molecular weight with a ceramic membrane SEPARION®, 4- lithium

ions during charging [11]

Cell Li-Tec CERIO® are made of three parts:

- positive electrode with a layer of metal oxide of lithium in an aluminum collector (cathode),
- negative electrode with a graphite coating on a copper collector (anode),
- a high molecular weight conductor with an ionic ceramic membrane SEPARION® that effectively separates the cathode from the anode, and prevents internal short circuit.

When charging the lithium ions move from the cathode through the conductor with membrane SEPARION® until they reach the cathode. After discharge lithium ions return to the cathode to provide electricity. It is possible because of the porous structure of SEPARION®.

Compared to conventional lead acid, nickel-cadmium or nickel-metal hydride batteries, the lithium-ion Li-Tec batteries have many advantages:

- much higher voltage
- high capacity and performance with low weight and volume
- low self-discharge
- no memory effect
- maintenance-free.

### *H. Akumulatory Nano-Li4Ti5O12 firmy Altairnano*

Altairnano is the first company to replace the traditional graphite structure in lithium-ion batteries with nano lithium-titanium (fig. 10 and 11, Tab. 2). Thanks to the new structure the manufacturer extended the battery life, increased safety, reduced the time to load and enabled the use of batteries in extreme conditions.

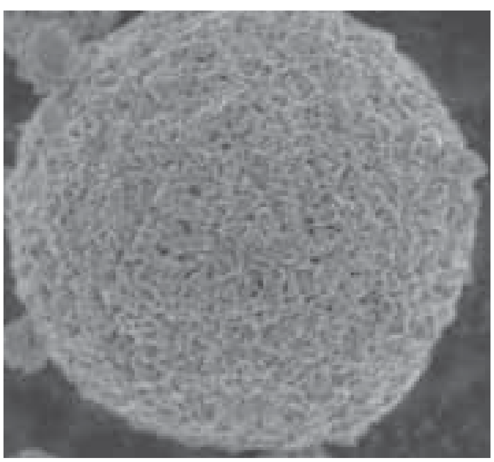

Fig. 10. Nano-Li4Ti5O12 structure [11]

Manufacturer's offer includes a nano lithium-titanium module 24 V, 50 Ah, characterized by:

☐high power without loss of stored energy,
☐long service life,
☐they are virtually maintenance free,
☐symmetry of charge/discharge advantageous when regenerative braking is applied.

Table 2 Basic properties of different types of energy storages [11]

| | |
|---|---|
| Napięcie nominalne | 23 V |
| Pojemność nominalna | 50 Ah |
| Waga | 25,3 kg |
| Wymiary (dł. szer. wys.) | 279x155x304mm |
| Gęstość energii | 45,8 Wh/kg |
| Czas ładowania | 10 min |

a) b) c)

Fig. 11. Connecting a single battery (a) into one module (b), then into an energy storage system (c)

## IV. CASE STUDY

Simulations were carried out taking into account the possibility of using LFP and LTO batteries in an 18 meter bus on the selected route. The daily distance for the bus on this route is 152.17 kilometers travelled in the time span of 12:30:00 (hh:mm:ss). The amount of energy consumed during operation was estimated and referred to a 1 km drive distance. The number of times the battery needed charging, the average time of a single charging and the time needed to recharge after completing the tour were determined based on the battery capacity. Two of the most popular and most commonly used technologies were selected for simulation. LFP and LTO technologies used in the construction of lithium-ion batteries have characteristics which make them particularly preferential for use in electric buses. The main feature of the LTO technology is the fast charging ability with a power of up to 4 times the nominal power of the battery, which allows for maintaining operational capability of the vehicle practically all day long.

LFP technology is characterized by a high voltage obtained from a single cell, which makes it possible to minimize their volume and mass while maintaining similar operating parameters. This feature is desirable in electric vehicles as the weight decrease can have a positive effect on the vehicle range. The main characteristics of the test route are shown in Table 3.

Table 3 Basic properties of different types of energy storages

| Parameter | Value |
|---|---|
| Energy consumption | 3,45kWh/km |
| Amount of energy consumed | 525,6kWh |
| Daily distance travelled | 152 172 m |
| Time spent stationary after stopping at the depot | 11:30:00 hh:mm:ss |
| Driving time | 12:30:00 hh:mm:ss |

| | |
|---|---|
| Energy consumed by on-board equipment (air conditioning, lighting etc.) | 24,4kW |

In the simulation a solution was proposed in which the depot was equipped with a stationary charger of 32 kW [5]. Depending on the type of technology used and the capacity of the battery differences were found in the number of charge cycles along the route and time spent charging after traveling the route. The selection of the data used in the simulation is shown in Table 4.

Table 4 Basic properties of different types of energy storages

| Parameter | Battery 1 | Battery 2 | Battery 3 |
|---|---|---|---|
| Battery capacity | 200kWh | 120kWh | 240kWh |
| Technology | LFP | LTO | LFP |
| Number of bus stop chargers | 2 | 1 | 1 |
| Power of bus stop chargers | 200kW | 400kW | 240kW |
| Number of chargings on route | 11 | 6 | 6 |

The battery charge level during operation was also simulated. Charging was included. Chargers were selected so that, in accordance with the battery manufacturer's instructions, the charge on the battery during operation never dropped below 20% SOC. Figures 12-14 show the change in battery charge level in time for selected batteries.

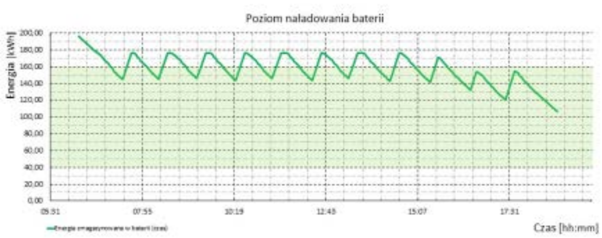


Figure 12. The charge level of an LFP battery with a capacity of 200 kWh over time

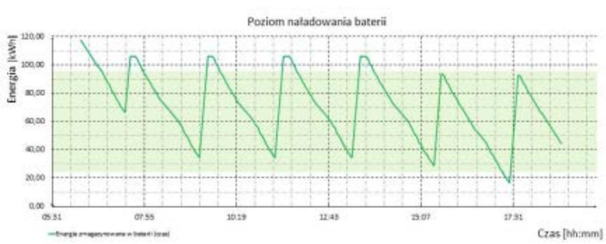


Figure 13. The charge level of an LTO battery with a capacity of 120 kWh over time

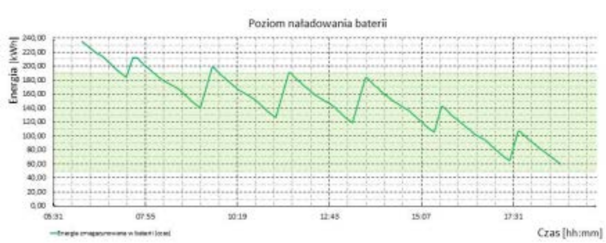


Figure 14. The charge level of an LFP battery with a capacity of 240 kWh over time

The curves of the battery charge levels during operation for an 18-meter bus presented in Figures 9-11 vary significantly. This is mainly due to the different capacities of the batteries used. Fluctuations in the charge level in Figure 9 are the smallest, which is the result of a large battery capacity and using two chargers (more peaks in the graph). Solution #3 presented in figure 11 is a very high capacity battery, but used with only one charger. It is clear that at the end of the working time the battery charge is low which in the case of a road event occurring (e.g. congestion) may prove to be insufficient. Figure 10 shows the use of a low capacity LTO battery with a single high power charger. This solution seems to be the best, because the battery is the lightest, there is only one charger on the route, and the battery remains in the manufacturer's recommended charge level range throughout its operation. For all of the considered solutions, a single low-power depot charger is more than sufficient to charge the batteries before taking the bus for another route.

## V. Conclusion

The development of lithium-ion technology leads to the creation of newer and newer types of batteries. The main goal of battery designers is to achieve the greatest energy and power density. Currently, the achieved values are significantly lower than those available in hydrocarbon fuels that are used on a large scale. The review of the technologies used in batteries shows that there is no such solution, which would facilitate the best indicators in all relevant aspects of use; some form of a compromise has to be made. Batteries with high energy and power density typically have a limited number of charge cycles to a specified loss of capacity. The operating temperature range, which depends on local conditions in which the vehicle will be utilized, is also important.

Solaris Bus & Coach in their vehicles, which required the use of electrochemical batteries and fast charging decided to use the LTO technology. Such batteries are characterized by relatively small values of voltage across a single cell (2.4 V) and small energy density. However, they have the largest operating temperature range (-50°C to 70°C) and the largest number of full charge and discharge cycles to the agreed capacity loss value - reducing the initial capacity to 80% of the initial value. The performed simulation of the bus drive cycle on the bus line proves that despite the disadvantages of this solution, these batteries with a capacity close to the LFP battery technology work in the charge range recommended by the manufacturer.

These aspects are very important for the Solaris Bus & Coach company, which offers its products in many countries with different climate conditions. The operating conditions of urban buses, for example frequent starting and braking phases requiring the use of substantial torque, depending on the used battery charging method can significantly affect the deterioration of batteries, so it is important to keep it at the highest level. The maximum theoretical gravimetric (or volumetric) energy density for LTO batteries is quite small compared to competing solutions, but in the case of city buses the latter aspect is not as important. The batteries can be placed for example on the roof of the vehicle and by solutions in which they are often recharged (at the ends of the line), their capacity could be much smaller in comparison to the LFP batteries, which are used in buses with extended range on a single charge.

## V. SUMMARY

The development of civilization brings with it a continuous increase in energy demand. Fuel consumption increases, which causes an increase in environmental pollution harmful exhaust gas components such as carbon monoxide (CO), carbon dioxide ($CO_2$), hydrocarbons (HC), nitrogen oxides ($NO_x$), and particulate matter (PM). The development of vehicle propulsion systems is therefore directed to the search for alternatives, which include primarily hybrid and electric drives. Such drives are characterized by favorable environmental and economic performance. The problem is caused by the properties of utilized batteries, which differ significantly from those of fossil fuels used on a large scale.

The subject of this study concerns the analysis of the existing concepts of lithium-ion batteries used in electric vehicles around the world. The development includes a presentation of innovative solutions that can improve the performance characteristics of alternative drives. In conclusion, the choice of LTO batteries as the main solution used by SBC has been justified.

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