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COMPARATIVE ANALYSIS OF NOVEL ELECTRIC ENERGY STORAGE TECHNOLOGIES FOR VEHICLES

The article aims to highlight the desirable and undesirable properties and characteristics of different energy storage technologies. It focuses on the comparison between the different specific battery technologies and supercapacitors currently available on the market, as well as novel technologies that are still in development. Assessment is made for these technologies based on their strong and weak points. Due to the dynamic nature of the developments made in this technology sector, such assessment of beneficial properties allows for an easier consideration of which technologies have the most desirable properties for automotive use. The current trends and technological solutions used in newest electric and hybrid vehicles is discussed, and predictions are made for the future development for batteries and supercapacitors, as well as their possible hybridization. An assessment of the market share of different powertrain technologies is also presented with commentary on how research trends are likely to change the popularity and viability of electric and hybrid vehicles.

Keywords: LTO batteries, supercapacitors, electric vehicles, hybrid vehicles

1. INTRODUCTION

With the development of new vehicle propulsion technologies focused on alternative technologies, as well as hybrid vehicles, supporting technologies are being developed in parallel to meet their growing demands. New road vehicles, both hybrid and electric, require a reliable high capacity battery technology to allow for their

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effective operation. The battery capacity determines the range of the vehicle, but it is also tied to its weight and energy efficiency. Unfortunately modern battery technologies tend to produce very heavy energy storage units. As a result battery types are usually described using the parameter of power or energy per kilogram of mass, which underlines the fact that usually it is the mass, not the volume, that is the limiting factor. Among the core parameters of automotive battery technologies are: energy density, power density, lifespan (number of load-discharge cycles), storage efficiency, reliability and maintenance required.

Batteries used in current passenger vehicles normally rely on lead-acid compound for electro-chemical energy storage. But there are new emerging technologies for energy storage that may soon offer competitive parameters. Due to the wide differences in storage technology the alternatives compared to modern batteries tend to excel in some aspects while being inferior in others. As a result the choice of the most suitable technology to be used depends heavily on the intended purpose and operating parameters. Which indicates that even technologies that are clearly inferior to currently available products in some aspects may still find applications in a specific section of the market, where their particular properties hold the most significance.

2. BATTERY TECHNOLOGIES

The currently most commonly used battery types are the lithium-ion batteries (Li-Ion) after they replaced the older technologies of nickel-metal hydride batteries (NiMH). The common problem with this technology is the battery weight and cost. Among the older technologies were the rechargeable nickel-cadmium batteries (NiCd), but due to their poor energy density and the memory effect, where recharging the battery before completely discharging it caused it to lose capacity, they were replaced by NiMH batteries. This improved the battery performance and decreased the memory effect. NiMH batteries are an important starting point for electric car battery technologies as this was the battery types used in the first commercially successful hybrid vehicles manufactured, such as Toyota Prius and Honda Insight. But due to the low voltage of a single cell for battery technologies, purely electric vehicles needed to wait a little longer before making a proper debut on the market.

The use of lithium, which is a very light metal, was a breakthrough step allowing a significant improvement in battery performance as well as removing the memory effect. This was achieved by using the movement of lithium ions for charging and discharging the battery (Fig. 1). Although Li-Ion batteries also have certain disadvantages, the main problem being the heat they generate during charging and quick discharging. This phenomenon was what forced the makers of the first hybrid vehicle, the Mercedes S500 Hybrid, to use these batteries to add an additional cooling system for the battery [Mercedes-Benz]. When smaller in size the heating of Li-Ion batteries is not too significant, which is why they are commonly used in a number of applications, such as cellphone and laptop batteries. However, at higher capacities the heat becomes a problem. This is even more significant when trying to find a well-performing battery solution that would function with its full potential in different environments around the world. Although the manufacturers can adjust the vehicle and its battery supporting systems depending on the country and climate the vehicle is to be used in, most customers tend to prefer universal solutions that are equally reliable in hot and cold regions. This is significant since the Li-Ion batteries have a wider operational temperature range than charging temperature range, and prolonged exposure to excess heat reduces the battery life.

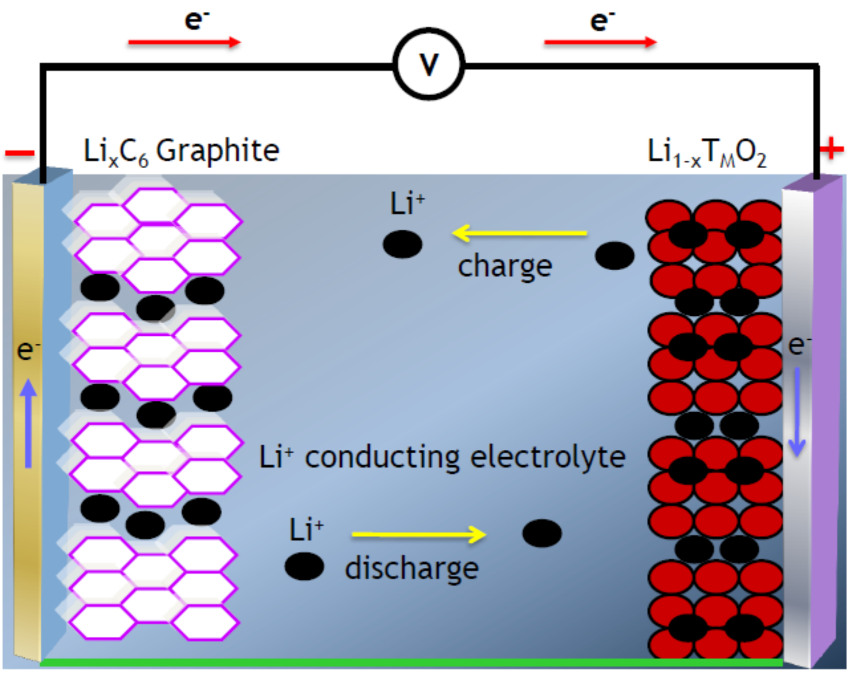

Fig. 1. Structure of a Li-Ion battery [Rohan et al. 2014]

While Li-Ion batteries are currently one of the most commonly used energy storage technologies, many research units and companies have been trying to find an alternative solution. It is also important to note that theoretical assessment and calculations [Rohan et al. 2014] indicate that the Li-Ion battery technology can potentially achieve power density multiple times of what it currently offers. Additionally, the new concept of a Lithium-air battery has the potential to achieve 5–15 times the limit of today's Li-Ion batteries [Jurgen, Besenhard 1999].

But the technologies that are, in some capacity, available for testing today that could compete for vehicle applications would include:

- lithium-titanate batteries (LTO),
- lithium ferrophosphate batteries (LFP),
- lithium nickel manganese cobalt oxide batteries (NMC),
- lithium manganese batteries (LMO),
- nanophosphate LTO batteries (A123),
- lithium-air batteries (Li-air).

While LTO batteries are currently leading the electric and hybrid vehicle market, and boast a number of beneficial properties. They can operate in temperature range between –46°C and 70°C, making them much more versatile in different regional climates and conditions. The battery life is also notable, retaining 80% of its capacity after 7000 charge-discharge cycles according to [GWL Power]. Their main downside is the small single-cell voltage of only about 2.4 V.

This is less than the competing LFP batteries, which can have a voltage of 3.2 V on a single cell. Additionally LFP batteries are highly resistant to self-discharge or charge leaking. Although the temperature range is lower (only 0–60°C) the battery life is comparable to LTO technology, showing 70% charge capacity after 10 000 charge-discharge cycles. An even higher single-cell voltage is offered by NMC batteries, reaching 4.1 V. But their vulnerability to overheating (operating temperature range of –20°C to 55°C), as well as their capacity loss on charge-discharge cycles, only 1000 of which can reduce the battery capacity to 80% of original cause this technology to be considered insufficient for most automotive applications. Similarly for LMO batteries where the 80% mark is reached at merely 1800 cycles.

On the other hand the Nanophosphate A123 batteries have a single cell voltage of 3.3 V and an operational temperature range of –30°C to 55°C. They also hold about 90% of their original capacity after 3000 cycles. The A123 batteries are also considered safer to use, although they are also more expensive than their competition. But their key feature is the fact that the battery power seems to be independent of the battery charge level, which is not the case for the other available battery technologies. This allows for an easier control over the power distribution, which means a less complex battery management system (BMS) can be used. The Li-air batteries have a superior capacity and charge density to most battery types, their specific energy is about 5 times what current Li-Ion batteries offer. Their main disadvantage is the power output and the relatively quick capacity loss with charge-discharge cycles. One of the researched variants has shown a 5% capacity loss after only 100 cycles [Service 2012]. Which is why the main focus of current research for these types of batteries is on improving the battery life.

3. SUPERCAPACITOR TECHNOLOGIES

There exists a wide range of available energy storage technologies, and capacitors are one of them. Due to the performance shortcomings of the ordinary electrolytic capacitors they were not considered as potential energy storage devices for automotive use outside of integrated circuits. But a newer technology that bridges the gap between electrolytic capacitors and rechargeable batteries could prove useful in this field either way. Supercapacitors, or ultracapacitors, are fundamentally different in the technical solutions used for energy storage, and thus they display widely different properties in comparison to the batteries discussed previously. Among their advantages are an almost unchanged capacity over a very large number of charge-recharge cycles, as well as their ability to take in and give out power much more quickly, which makes the peak power output higher, and most importantly their recharge times are much shorter. These properties allowed them to be used in some vehicles where their rapid charge and discharge ability was a key factor. These uses include: regenerative braking, short-term energy storage, and burst power delivery. This is achieved by eliminating the solid dielectric used in conventional capacitors. Two types of modern supercapacitors are currently in wide use, and they utilize slightly different technologies for charge storage, which are either the electrostatic double-layer capacitance, or the electrochemical pseudocapacitance. The extended life of supercapacitors despite numerous charge-discharge cycles comes as a result of these capacitors not using chemical changes to the electrodes to store or release their charge. Despite the charge absorption and release being a quick process for supercapacitors, meaning that their power density is much higher than in modern battery technologies, their energy density, so the amount of energy stored per kilogram of the device weight, is at least about ten times lower. One of the main weaknesses of supercapacitors has been a substantial leak current compared to the current battery technology. Although there have been improvements done for this technology supercapacitors still leak charge faster than batteries, which in electric vehicles can lead to increased energy losses and a decreased vehicle range.

The inherent differences between battery and supercapacitor technologies mean that they both have desirable properties in terms of their automotive applications (Fig. 2). Thus a possibility exists that a combination of both these technologies could greatly improve the performance of electric vehicles. While batteries could still store the charge for long periods with their high energy density, keeping some of that energy in supercapacitors would allow for power bursts and a more efficient energy recovery from the brakes. An alternative to using both technologies would be to attempt and hybridize them with each other. Works are currently underway to develop new capacitors with a much higher energy density than other supercapacitors while retaining their useful features, such as high power density and fast charge and discharge.

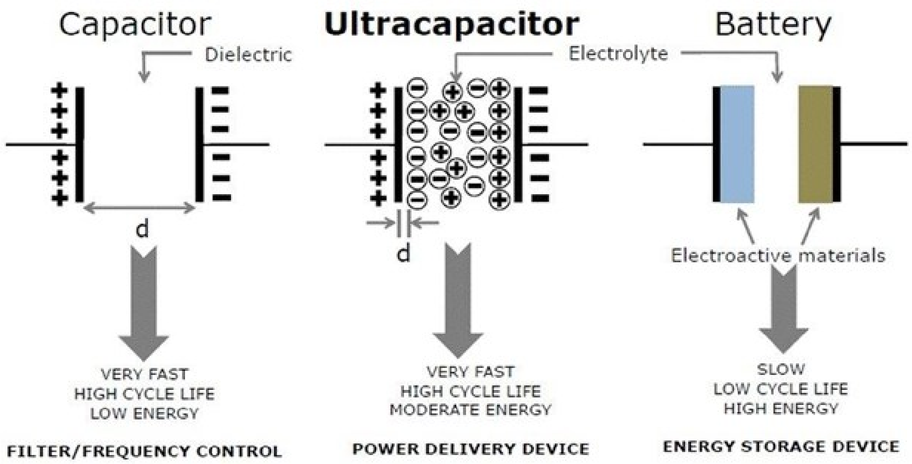

Fig. 2. Comparison of basic differences between capacitors and batteries [Leiber 2011]

In order to properly manage the cooperation between batteries and supercapacitors an appropriate Battery Management System (BMS) needs to be developed. It is possible to use the quick response of supercapacitors to regulate power and charge levels of integrated battery systems, as well as offer more effective methods of preventing over-current, over-voltage, under-voltage, over-temperature or under-temperature. A better control over the operating conditions of batteries, by using supercapacitors that can generally have a larger voltage and temperature operating range, could potentially further improve the overall efficiency of charge storage and use. Supercapacitors can help a BMS to better balance the charge of batteries allowing for safer exploitation.

Supercapacitors have been used in electric vehicles on their own already, despite their significantly lower energy density and thus operational range. An example of such a solution is the supercapacitor-powered minibus presented by Sinautec Automobile Technologies [Sinautec US]. Similar solutions for inner-city buses, both purely electric and hybrid, are increasingly more commonly tested in many countries. In the case of city buses the vehicle makes regular stops, each of which can be used to recharge the supercapacitors and, because of the technology used, the charging happens very quickly, meaning that the vehicle does not need to store much charge at any given time. Additionally the constant improvements in supercapacitor technology allowed for Toyota to use them in their TS040 race car.

4. COMPARISON

The key advantages of each of these technologies are valuable for vehicle applications. As a result efforts to further develop the solutions discussed will continue. Since the ideal solution would be a device that combines the main features offered by either batteries and supercapacitors work towards their hybridization will continue, as it shows much promise. Combining the number of stable charge-discharge cycles and the long lifespan of double-layer capacitors with the energy density and cell voltage of LTO batteries could potentially provide a breakthrough in making electric vehicles significantly more competitive in the market. No longer needing to fill a niche market of heavily urban transport but also making them a reasonable option for day to day transit of people and goods even over medium distances. Figure 3 shows a graphical comparison of three chosen technologies available in terms of the main characteristics demanded from these types of devices for use in electric vehicles.

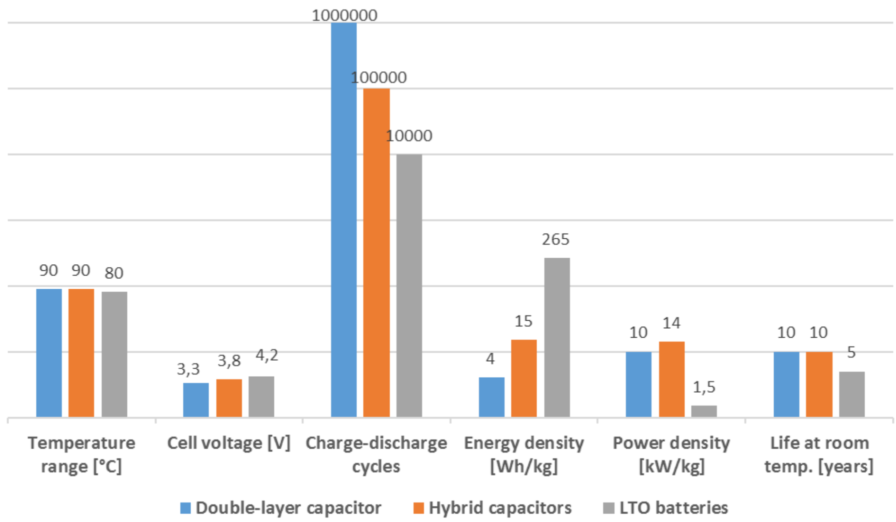

Fig. 3. Comparison of hybrid capacitors and double-layer capacitors with LTO batteries in terms of the most important characteristics of energy storage devices (data combined from various sources)

Ultimately the choice of technology will depends on all of these parameters, as well as the overall cost of the device. But as is the nature of developing technologies the costs for production and maintenance of such devices, despite their increasing technological and structural complexity, will inevitably continue to fall. This, combined with the ever increasing emission limits that combustion vehicles are subject to, will be the forces driving the upcoming change in the whole transportation market. Although these technologies are still new, and electric vehicles still have a fairly small share of the market (Fig. 4) their influence and reach continue to grow much faster than that of combustion engine powered vehicles.

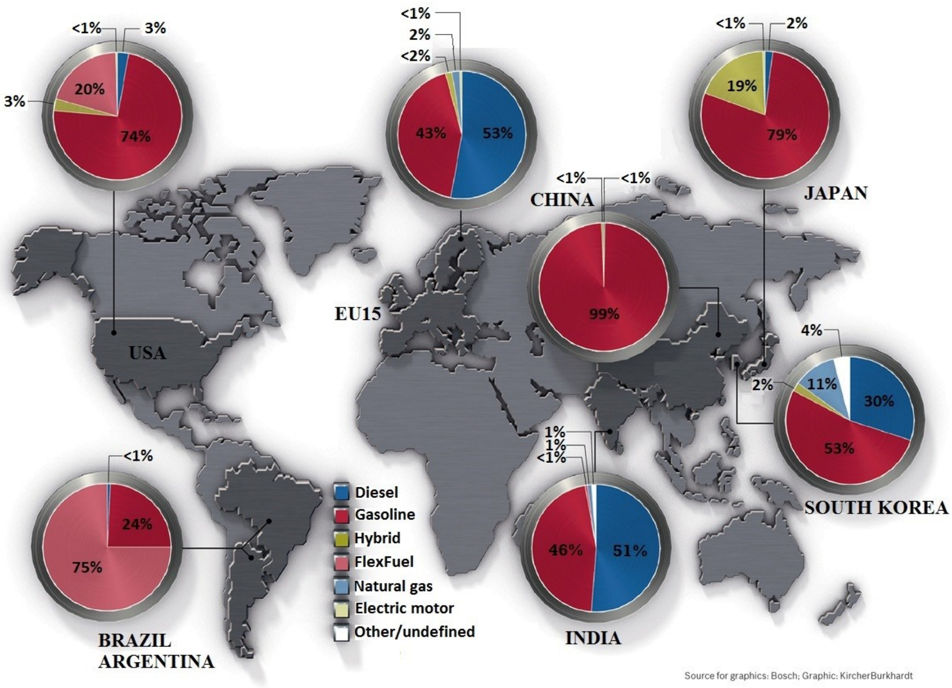

Fig. 4. World market share of gasoline, diesel, electric, hybrid and other vehicle types [Burkhardt 2014]

5. CONCLUSIONS

While at this point in time most of the technologies used for electric vehicles seem to be a novelty, they are in a position to take to the market in a more considerable scale over time. The rising share of hybrid and electric vehicles in the world will drive massive changes in world transport solutions. It should be noted that much of the cost of exploitation and maintenance of such vehicles requires specific infrastructure, which creates a significant initial hurdle for the emerging technologies to overcome as they try to enter the market in any wider capacity. But this trend will undoubtedly continue, so while the gap between the applicability of these technologies is still visible this gap will only get smaller. It is thus not a matter of if, but a matter of when electric and hybrid solutions overtake combustion engines as the main powertrain technologies on the world market.

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PORÓWNANIE NAJNOWSZYCH TECHNOLOGII PRZECHOWYWANIA ENERGII ELEKTRYCZNEJ STOSOWANYCH W POJAZDACH

Streszczenie

W artykule zawarto informacje na temat obecnych kierunków rozwoju technologii służących przechowywaniu energii, z uwzględnieniem możliwości wykorzystania ich w przemyśle samochodowym. Przedstawiono i opisano różne rozwiązania, wykorzystywane obecnie w samochodach osobowych oraz pojazdach transportu publicznego, omówiono ich słabe i mocne strony i możliwe zastosowania. Rozpatrzono możliwości połączenia i hybrydyzacji omawianych technologii oraz potencjalną popularność i opłacalność ich stosowania. Przedstawiono obecne oraz planowane badania naukowe w tej dziedzinie i cele dalszego rozwoju tych technologii w aspekcie możliwych zastosowań w motoryzacji. Artykuł zawiera również omówienie obecnej sytuacji na rynku motoryzacyjnym oraz stopień wykorzystania różnych rozwiązań technologicznych. Ponadto odniesiono się również do współczesnych tendencji rozwoju rynków samochodowych na całym świecie.