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GLOBAL DEVELOPMENT AND SUSTAINABILITY OF LITHIUM-ION BATTERIES IN ELECTRIC VEHICLES

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Review

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Abstract:
The aim of this review was to provide a comprehensive assessment of the global development and sustainability of lithium-ion batteries (LIBs) for electric vehicles. Production of various renewable energy sources has proven to be sustainable; however, with certain types of renewable energy sources, due to the cyclical nature of natural resources, energy production is not constant, and energy production needs to be more balanced with consumption needs. In the future, this problem could be alleviated if global energy storage capacity were improved and expanded. Today, batteries are an important but underutilized energy source for electric cars. LIBs have a long history behind them and currently play the most crucial role in the electric car industry. LIBs are primarily characterized by high energy and power density, which makes them incomparably competitive for use in electric cars. The research presents and processes in detail segments related to the development, principle of operation, and sustainability of LIBs, as well as the global manufacturing capacity of LIBs for electric vehicles.

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1. INTRODUCTION

Achieving CO_2 neutrality is currently the most important global activity in the fight against climate change. In order to meet the global goals of CO_2 neutrality, all countries are switching to cleaner energy. Furthermore, population growth on planet Earth, economic progress and technological development have triggered an accelerated demand for additional renewable energy sources. The biggest problem with using renewable sources is that they need constant energy production, and batteries are often needed to store that energy. Nowadays, great attention is paid to the use of batteries in all areas of society, especially in the transport system.

Modern batteries have made significant progress in the 21st century, and their performance and safety in use have been greatly improved over the past few years. Currently, we can only imagine the situation with these energy sources. We would be unable to make any wireless electronic devices and would have to rely only on a wired power source. Electric batteries of various types, designs and shapes are now available in large numbers for various purposes. Lithium-ion batteries (LIBs) were initially developed as portable electronics. However, their acceptance is now reflected in everyday life in increasingly diverse applications such as power tools, electric vehicles, satellites, drones, portable healthcare devices, smart watches, and stationary energy storage [1]. A particularly current application of these batteries is in electric vehicles (electric cars, motorcycles, bicycles, scooters, advanced wheelchairs, etc.) [2].

LIBs are primarily characterized by high energy and power density, making them incomparably competitive for all electric tools and devices, including electric and hybrid vehicles [3]. A battery is an electrochemical device composed of several components of different materials. The most important characteristics of a battery are its energy

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density, degradation rate, lifetime, safety, price and case type, etc. Depending on their technical design and properties, batteries are classified as primary or secondary. Primary cells are exclusively disposable, and their electrochemical process is irreversible. By discharging, the chemical compounds constantly change, releasing electrical energy until the original compound is fully depleted. Secondary cells are rechargeable, and the electrochemical process is reversible because the original chemical compound is renewable by applying an electric current from an external source.

2. DEVELOPMENT OF LITHIUM-ION BATTERIES

LIBs have a very long history behind them. Sony launched the first commercial LIBs in 1991, and they have since been used in various applications, from electronic devices to electric vehicles [4]. Nowadays, there has been an even greater boom in the research and development of better, more powerful and cheaper lithium batteries. Lithium batteries have several advantages over nickel-metal hydride batteries, lead-acid batteries and, last but not least, nickel-cadmium batteries. LIBs currently play the most crucial role in the electric car industry. Most common electric cars today use LIBs, which are currently the most available and practically the most technologically advanced. It is to be expected that with the growing demand for electric cars, their production will continue to grow in the coming period. These vehicles should have the best possible performance, such as the distance they can travel, charging speed, lifetime, etc. Unlike other batteries, LIBs have many advantages, such as high power density, high energy density, relatively long life, etc. [5].

Power performance, energy density, charge-discharge speed, cost, lifetime (number of cycles), safety, and environmental impact should be considered when adopting LIBs for electronic devices and electric vehicles. While energy density is the most important factor for portable electronics, price, lifetime, energy density (driving distance between charges), and safety are the most important factors for electric vehicles [6].

The application and sales growth of Li-ion batteries have expanded over the last 30 years, and their basic cell chemistry developed in the 1980s is still in use (i.e. intercalation chemistry based on graphite anodes and transition metal cathodes) [7,8]. What has improved and changed is increasing the effective energy density of commercial cells through various design modifications, such as reducing the thickness of components (e.g., current collectors, separators, cell housing, etc.) [9].

Evident progress in this area has been noted in the development of electrode materials for LIBs, with the aim of reducing production costs per unit by 90% and increasing gravimetric density. This ultimately resulted in an increased capacity, where state-of-the-art LIBs have high energy density (up to 750 Wh/l) and lifetimes (1,000 - 6,000 cycles) [10].

However, there are several types of LIBs, with the most used LIBs such as NCA (nickel, cobalt, aluminum). This abbreviation describes all the compounds found on the cathode, which are nickel, cobalt and aluminum. This combination has proven to be the most useful in many cases, as it provides high energy density and longevity [11]. The cells can accumulate 200-250 Wh/kg of energy, with a 1,000-1,500 cycle lifespan, which is enough to exploit for several years. A strong alternative to these batteries could be the NMC (Nickel, Manganese, Cobalt) battery, which bases its cathode on manganese, nickel and cobalt. This battery has a longer service life, but its energy density is considerably lower and ranges from 140 to 200 Wh.

An alternative to the use of LIBs can be lithium-sulfur batteries. The main feature of the element sulfur is its availability in abundance and its cost-effectiveness. Lithium-sulfur batteries have exceptional theoretical energy density compared to traditional LIBs, and they have the potential to pass 500 Wh/kg and may even approach 1,000 Wh/kg in theory [12]. These characteristics will make these batteries attractive for weight- and volume-sensitive applications such as electric aviation and portable electronics [13]. State-of-the-art Li-ion cells can accumulate about 250 Wh/kg (900 kJ/kg), while more advanced variants of Li-S and Li-air systems can accumulate about 650 Wh/kg (2.34 MJ/kg), that is about 950 Wh/kg (3.42 MJ/kg), respectively [14].

The production of LIBs is a very complex process consisting of several different activities in the production process. Fig. 1 shows an example of a modern LIB manufacturing process consisting of three main parts: electrode preparation, cell assembly, and battery electrochemistry activation. The formation is the last and most expensive activity in the production of LIB cells, which affects the quality of freshly assembled cells and significantly contributes to the total costs, making up to 33% of production costs [15,16]. The Forming process involves multiple cycles of charging and discharging, which slows down this activity significantly [17].

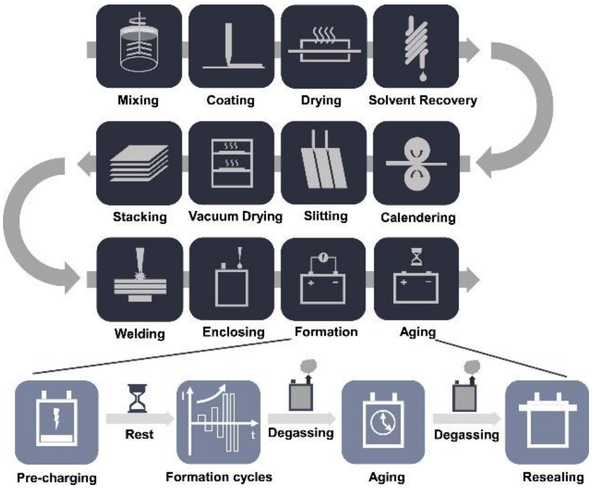

Fig. 1. Schematic representation of production activities in the production of LIBs [15]

3. PRINCIPLE OF OPERATION OF LITHIUM-ION BATTERIES

During discharge, lithium is oxidized to lithium ions, which are torn from the anode and move through the electrolyte into the crystal lattice of the cathode material, which leads to the reduction of this material [18]. To maintain the charge balance, the same number of electrons in the charging and discharging process should be transferred through the external circuit, and Li+ ions should move between the positive and negative electrodes simultaneously [19].

Cathode: $LiCoO_2 \leftrightarrow LixCoO_2 + xLi+ + xe-$

Anode: $6C + xLi+ + xe- \leftrightarrow LixC6$

In the charging process, Li+ ions deintercalated from the lithium metal oxide, pass through the conductive electrolyte and intercalate into the anode structure [20]. As mentioned, this process is the main difference between LIBs and other types of batteries.

In the production and development of batteries, a crucial aspect is the continuous monitoring of the condition of the prepared batteries. This process, known as battery characterization, introduces the terms state of charge (SOC) and state of health (SOH) of the battery. SOC, a relative quantity, describes the ratio of the remaining capacity to the current maximum available capacity of the battery and is given by:

$$SOC(t) = \frac{Q(t)}{Q_n}, \tag{1}$$

where are:

$Q(t)$ - the remaining capacity and

Q_n - the nominal capacity.

SOC is generally calculated proposed current integration to determine the change in battery capacity over time [21]:

$$SOC_t = SOC_0 - \int_0^t \frac{\eta_i \cdot I_{L,t} \cdot d_\tau}{C_a}, \tag{2}$$

where are:

SOC_t - the current SOC,

SOC_0 - the initial SOC value,

$I_{L,t}$ - the instantaneous load current (assumed positive for discharge, negative for charge),

η_i - the Coulombic efficiency (a function of current and temperature), and

C_a - the current maximum available capacity, which may differ from the nominal capacity.

The SOC value varies between 0% and 100%. If the SOC value is 100%, then the cell is considered fully charged; that is, if it is 0%, it means that the cell is completely discharged.

In practical applications, the SOC is not allowed to exceed 50%, so the cell is recharged when the SOC reaches 50% [22]. SOC is a key parameter for the correct control of an electric vehicle. Factors affecting SOC significantly in a short time are temperature and *C*-rate. The SOC level is related to the properties of the electrode active materials, and different active materials behave differently [23]. The health (SOH) of a lithium-ion cell is affected by cyclic aging due to use and aging due to storage time [24]. SOH, as a health index, is calculated based on capacity measurements during battery cycling to account for capacity loss. When the cell is fully charged, it has a maximum capacity of C_{max}. This capacity may vary from the start-of-life capacity, C_{bol}, which is assumed to be the maximum capacity of the cell when newly installed. C_{max} decreases with storage time and use of the cell [3]:

$$SOH = \frac{C_{max}}{C_{bol}} \cdot 100, \tag{3}$$

where are:

C_{max} - the value of the maximum capacity when the battery is fully charged and

C_{bol} - the capacity at the beginning of the battery life.

Aging processes that reduce SOH begin as soon as the batteries are assembled. As the battery ages, the SOC will decrease until the battery no longer meets the required performance and the end of life is reached. SOH is not a physical quantity, but depends on parameters such as the number of charge and discharge cycles, capacity and power drop, and internal resistance. The battery ageing process is complex and depends on various mechanisms such as temperature, SOC energy range performance conditions, and time, which are the basic parameters [21].

4. GLOBAL ELECTRIC VEHICLES LITHIUM-ION BATTERY MANUFACTURING CAPACITY

Over the next decade, the battery market is expected to experience substantial growth, surpassing fourfold from 2021 to 2030. The total revenue of the battery market in 2021 was approximately $112 million (US dollars), and by 2030, the annual revenue is projected to reach about $424 million. As illustrated in Fig. 2, the dominance of LIBs in production [25] is a testament to the stability and confidence in the industry.

For example, in China, the new energy industry is based on lithium raw material, that is, as a strategic emerging industry. In 2022 alone, China's lithium battery exports amounted to nearly CNY 342.7 billion [26].

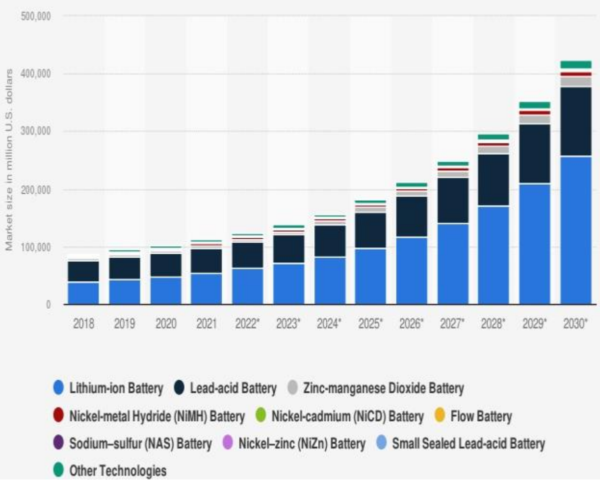

Fig. 2. Global battery market size from 2018 to 2021, with a forecast to 2030.

In 2021, China was the world's largest producer of electric vehicles from LIB; that year, it produced 79% of all-electric vehicles (Fig. 3). All predictions indicate that China will continue to be the leading country in the production of LIB electric vehicles, with an estimated share of 69% in 2025. On the other hand, large European countries need to increase their production capacities significantly. With the planned investments in production facilities, Germany will become the second producer of electric vehicles with LIB in the world by the end of 2025, with a share of about 11.3% of the global production capacity, Fig. 3 [27].

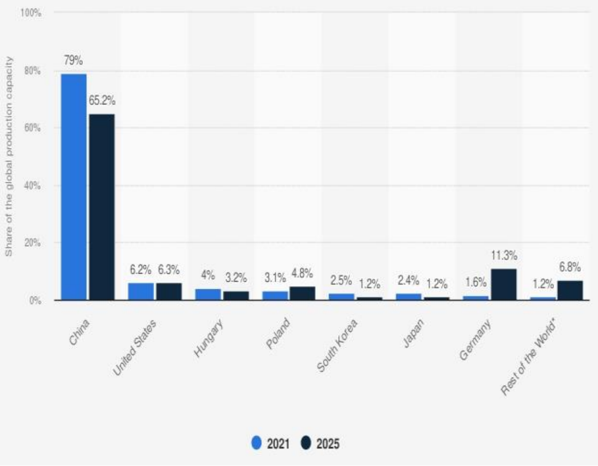

Fig. 3. Share of the global electric vehicles with LIBs manufacturing capacity in 2021. with a forecast for 2025

Forecasts show that global LIB production capacity will increase from 1.57 TWh in 2022 to 3.97 TWh by 2025., that is or to 6.79 TWh by 2030, Fig. 4.

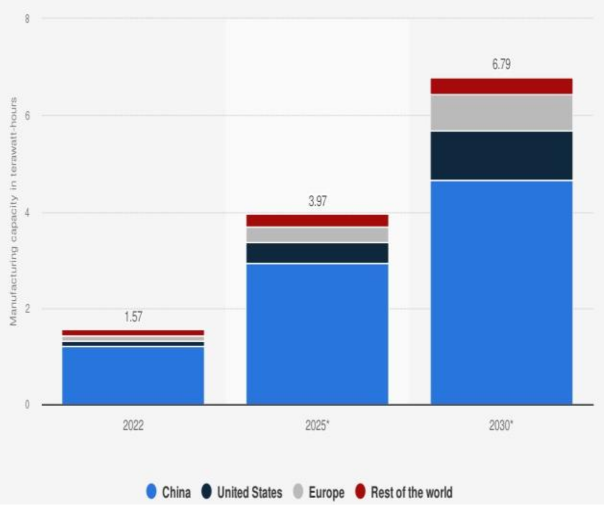

Fig. 4. LIBs battery manufacturing capacity worldwide in 2022, with a forecast to 2030.

In 2023, Japan's Hitachi Ltd. was the world's largest manufacturer of LIBs, with revenues of $91.36 billion. Johnson Corporation, headquartered in Ireland, with revenues of $25.3 billion, and Saft, headquartered in France, with revenues of $0.759 billion, were the largest European manufacturers of LIBs [28].

5. SUSTAINABILITY OF LITHIUM-ION BATTERIES IN ELECTRIC CARS

The European Union wants to reduce the carbon footprint of the transport sector to 200 g CO_2/km by 2030. and in order to achieve this goal, more electric cars must be on the roads. The main advantages of electric cars compared to internal combustion engines are potentially many times lower operating costs for maintenance, significantly higher efficiency, significantly lower operating noise and much better utilization of space.

Electric cars are becoming very popular worldwide due to environmental protection and bring significant benefits to transportation. Also, it should be noted that due to the absence of an internal combustion engine, electric cars have fewer working parts, there is no need to use oil to lubricate the moving parts of the piston-cylinder block, there is no need for service, etc. [29]. The absence of wear products, waste motor oils, or all tribological processes is also very important [30]. This means there is no danger of engine oils spilling onto the ground or further reaching waterways.

The market for recycled batteries is gradually growing as demand for electric vehicles grows worldwide. The rapidly growing use of LIBs in vehicles will produce many spent batteries that require proper handling after use and further recycling. Millions of tons of LIBs are expected to be decommissioned and stored worldwide in the coming decades. The battery life of an electric vehicle also depends on the use of the electric vehicle. The lifetime of LIB ranges from 3 to 10 years [31]. It was estimated that the amount of LIB waste generated annually by 2020 was between 200-500 million tons [32]. These data indicate that these are significant quantities of spent batteries, and further storage and recycling of this waste represents a danger to human health and the environment.

Today, people are concerned that electric car batteries will burden the environment, but fortunately, new technologies are gradually being developed for more environmentally friendly recycling of electric car batteries. Some advocates in the scientific community claim that the production of batteries alone has a more significant impact on the environment than internal combustion cars. At the same time, there is no research to confirm this.

All used and discharged batteries must be disposed of or recycled. Recycling batteries from electric vehicles at the end of their useful life is essential for many reasons. Recycling primarily stems from the effort to avoid unnecessary storage of materials, that is, using already used materials in new products after processing. Due to the cost and complexity of disassembling batteries, today's recycling methods are quite difficult. The recycling process works by draining the battery and removing the hard outer shell; the modules are often crushed and thrown into the oven. Lighter materials such as lithium and manganese burn, leaving behind an alloy slurry that contains higher-value metals such as copper, nickel and cobalt.

In spent LIBs there are a large number of flammable organic substances (electrolytes and separators) [33] and toxic substances (cobalt), which means that the disposal of these batteries can cause serious health and environmental problems. Spent LIBs contain many beneficial metals, such as aluminum, copper, nickel, cobalt, and lithium [34]. Recycling technologies should be sustainable, i.e. clean and efficient. Direct recycling methods are still in the early stages of development; this approach could one day allow recyclers to put more recycled materials back into the manufacturing process, which should result in a higher-value final product.

By 2030, LIBs reuse and recycling is expected to be approximately US$13 billion worldwide, with China accounting for half of the global value. China will have the largest revenues from recycled LIBs, with 6 billion dollars, followed by the European Union countries with 3 billion dollars, the USA with 2 billion dollars, and the rest of the world with around 2 billion dollars (Fig. 5).

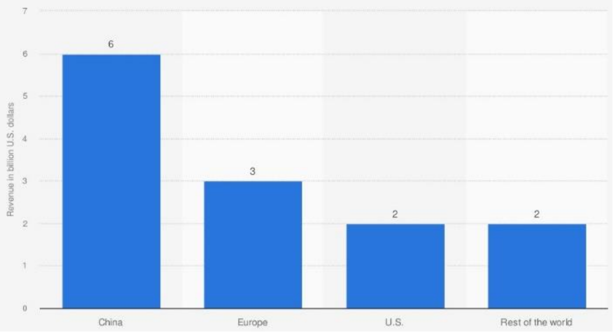

Fig. 5. Revenue opportunities in LIBs reuse and recycling in 2030.

The global LIB recycling market value is estimated at US$9.37 billion in 2023, up from US$8.19 billion in 2021. This number is expected to rise to over $18 billion by 2031 (Fig. 6). LIB recycling capacities will also need to increase significantly to be able to process the entire supply of spent batteries in the next decade.

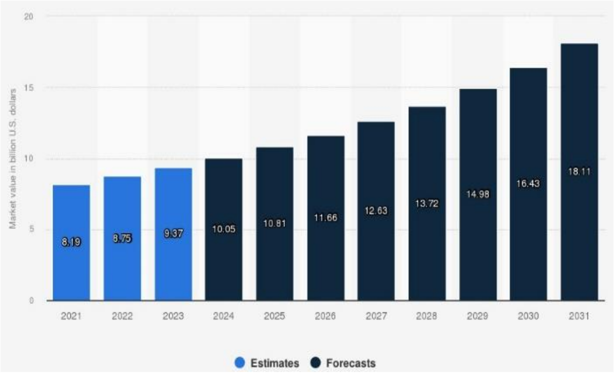

Fig. 6. Market value of LIBs recycling sector worldwide from 2021 to 2023, with projections through 2031.

The rapid deployment of new energy technologies as part of the transition to sustainable clean energy implies a rapidly growing demand for critical minerals [35,36]. The use of mineral raw materials varies depending on the availability of raw materials and new energy technologies. Earlier observations of the scientific and wider social community were focused on the availability of lithium. However, recent research has shown that the cobalt raw material may pose the greatest concern in terms of sustainability and long-term availability due to the fact that it is primarily sourced from the Democratic Republic of Congo, since the political situation in this country is unstable [37].

Circumstances related to the safety and health of people stand out as limiting restrictions on the use of LIBs. Due to inadequate maintenance and use of these batteries, chemical energy can be suddenly released in the form of fire or explosion. These accidents have been recorded worldwide as fires and LIB explosions in devices and machines such as mobile phones, laptops, electric vehicles, aeroplanes, etc. [38]. These negative phenomena also caused serious threats to the safety and health of people, which ultimately resulted in numerous withdrawals of devices and machines by the manufacturer.

4. CONCLUSION

The world depends on energy; therefore we need resources that will ensure the sustainable development of any society. Around the world today there is great support for renewable energy sources as one of the key pillars of energy. Global warming and climate change have drawn much attention to the use of primary renewable energy sources and the need to store this energy in systems such as batteries. LIBs dominate the secondary energy storage market due to their unmatched combination of energy density, power performance and cycle stability, along with lower costs that have contributed to the growth of global production capacity.

The use of LIBs due to their energy content and multifunctional use has a huge potential and great perspective for the future of every country in the world. In the future, in the production of LIBs, the most important thing will be the price, and it is assumed that it will be cheaper. People are concerned that electric car batteries will burden the environment, but fortunately, new technologies are gradually being developed for more environmentally friendly recycling of electric car batteries. What will certainly be a problem in the further global development of the battery is the limitation and access to rare raw materials necessary for the production of batteries of materials such as lithium and cobalt.

Conflicts of Interest

The author declares no conflict of interest.

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