IMMC 2024

22nd International Metallurgy and Materials Congress

22. Uluslararası Metalurji ve Malzeme Kongresi

CONGRESS PROCEEDINGS E-BOOK

KONGRE BİLDİRİLER E-KİTABI



19-21
Eylül/September
2024, ISTANBUL
Istanbul Expo Center
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The Role of Lithium-Ion Batteries in the Sustainable Green Energy Sector

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Keywords: Lithium-ion batteries, Energy efficiency, Sustainability

Abstract

The changing technological needs, driven by components such as the internet, computers, smartphones, software, cloud computing, artificial intelligence, virtual reality, and augmented reality, which form the main elements of digital technologies, have led to a demand for more environmentally friendly technologies. Lithium-ion batteries are rechargeable battery systems that constitute the foundation of modern technology. When compared to other secondary batteries (silver-zinc, nickel-zinc, nickel-metal hydride), lithium-ion batteries exhibit advantages such as not requiring maintenance of sealed cells, a wide operating temperature range, long shelf life, quick charging capability, strong discharge capacity, high energy efficiency, high specific energy, and absence of memory effect. However, they also come with disadvantages, including high cost, degradation at high temperatures, the need for protective circuits, capacity loss, or thermal degradation due to overcharging. As a clean energy source, lithium-ion batteries are preferred in various applications such as electric vehicles, electric toothbrushes, hearing aids, and wristwatches, where they can be recharged. The primary factor influencing the preference for lithium-ion batteries is lithium's status as a strategic raw material and its ability to provide sustainable green energy in vehicles. Due to the adverse environmental effects of vehicles consuming fossil fuels, there is a growing inclination towards vehicles developed using renewable technologies like lithium-ion batteries. Lithium-ion batteries are not only practical and recyclable but also contribute significantly to energy efficiency. This energy source is not only a sustainable environmental technology for people but also a valuable asset contributing to raw material recycling economically. As an important technological development with a significant role in reducing air pollution caused by fossil fuel-powered vehicles, lithium-ion batteries used in electric vehicles represent the future of technology. Comprehensive research is being conducted to improve the features of lithium-ion batteries, labelled as the technology of the future, and to address their disadvantages. This study discusses the position of lithium-ion battery systems in Turkey and the world, along with recent developments in the sustainable green energy field.

1. Introduction

With changing needs, there is an increasing demand for more eco-friendly technologies in the digital world. Lithium-ion batteries hold a significant position in eco-friendly technologies. The primary reasons for this are the strategic nature of lithium as a raw material and its ability to provide sustainable energy in vehicles. Its recyclable and recoverable properties also present a considerable potential in terms of energy efficiency. Besides being a sustainable environmental technology as an energy source, its raw material recycling feature holds economic value. Lithium-ion batteries have a wide range of applications in various electronic equipment, including cell phones, cameras, laptops, and many portable electronic devices. They boast several superior features such as excellent electrochemical performance, high voltage, high energy density, long cycle life, and absence of memory effect. With the renewal of electronic equipment and the rapid spread of clean energy vehicles, their more widespread use as a power source is increasing. Particularly, their use in electric vehicles has sparked a significant revolution in reducing air pollution caused by fossil fuel-powered vehicles [1,2].

With the continuous increase in energy demand today, the need for environmentally friendly and sustainable energy sources is becoming increasingly important. In this context, lithium-ion batteries have become one of the most widely used battery technologies in renewable energy storage systems and electric vehicles. Lithium-ion batteries play a significant role in the field of green energy by offering advantages such as high energy density, long lifespan, and low maintenance requirements. However, there are some environmental concerns associated with the production and use of lithium-ion batteries. One of the primary concerns is the environmental damage caused during the extraction and processing of raw materials used in battery component production. Therefore, it is crucial to implement sustainability measures in the production and use of lithium-ion batteries. The recycling of lithium-ion batteries is one of the most important issues in terms of sustainability. The recycling process involves the separation of used batteries' components, recovery of reusable materials, and environmentally friendly disposal of waste without causing harm to the environment. When recycling is done correctly, the environmental impacts of lithium-ion batteries can be significantly reduced. The separation of metallic and non-metallic materials in waste batteries is a challenging process. This separation or release of materials is one of the biggest obstacles in the recycling process. Used batteries are typically subjected to mechanical and physical separation processes. Lower operating costs and the use of more expensive sub-processes when applied appropriately allow for the creation of denser and higher-purity material feedstocks. Clean separation of materials requires fewer steps for the recovery of unwanted components, which can reduce CO_2 emissions, energy consumption, and the demand for new equipment. This study addresses the role of lithium-ion batteries in sustainable green energy and discusses research and development efforts in this field [2,3].

2. Lithium Ion Batteries and the Future

To effectively enhance the functionalities of today's extensively preferred portable electronic products and make them long-lasting, there is a need for a sustainable energy source that is high in energy density, safe, durable, easy to maintain, quickly rechargeable, and environmentally friendly. Rechargeable batteries, known as secondary batteries, such as lithium-ion batteries, are a type of rechargeable battery technology that converts chemical energy into electrical energy and is commonly used in portable electronic devices, electric vehicles, and renewable energy storage systems. They are electrochemical cells that can be recharged and reused after discharge. They consist of two main elements: anode and cathode. During charging, lithium ions move from the anode to the cathode, while electrons provide electrical energy by following an external circuit. During discharge, the process reverses; lithium ions move back from the cathode to the anode, releasing electrical energy in the process. The advantages and disadvantages of lithium-ion batteries compared to other secondary batteries (such as silver-zinc, nickel-zinc, and nickel-hydrogen) are provided in Table 1.

Table 1. Advantages and disadvantages of Lithium-ion Batteries

ADVANTAGES
Closed cell, maintenance-free
Long life-cycle
Wide operating range
Long shelf life
Quick charging ability
High powerful discharge capacity
High energy efficiency
High specific energy and energy density
Reaching high specific energy with power cells
Provide low internal resistance
DISADVANTAGES
Cost
Decomposition at high temperatures
The need for a protective circuit
Loss of capacity or thermal degradation as a result of overcharging
Fast charging not possible in freezing temperatures (<0°C)
Need for protection circuits to prevent misuse

In recent years, a series of innovations have been made regarding lithium-ion batteries. Among these innovations, materials with higher energy density, longer lifespan, and faster charging times are highlighted. Significant progress has also been made in the areas of safety and durability. For example, solid-state lithium-ion batteries, which use a solid electrolyte instead of a liquid electrolyte, offer higher safety and longer lifespan. Additionally, research continues on the more environmentally friendly approaches of lithium-ion batteries. Efforts are focused on improving the recyclability of batteries and reducing their environmental impact. Thanks to these innovations, lithium-ion batteries are expected to play an increasingly central role in renewable energy storage solutions.

3. Sustainability of Lithium Ion Batteries and Green Transformation

In the world of energy storage, sustainability and environmentally friendly practices have become not just a preference but a necessity. The evolution of eco-friendly battery technologies is being examined from a broad perspective, ranging from green innovations to recycling and waste management strategies. Global demand for batteries has seen a significant increase primarily due to the electrification of mobility and efforts to combat climate change. However, despite often surpassing initial forecasts, predictions for battery demand tend to underestimate the market size, necessitating frequent upward revisions. Next-generation battery technologies offer significantly higher energy density compared to traditional systems, along with longer lifespans and less environmental harm. Lithium-ion batteries stand as pioneers of this new era, being lightweight, high-capacity, and featuring notably short charging times. Moreover, they offer impressive energy efficiency and durability. When used in renewable energy systems, lithium-ion batteries provide a continuous and reliable energy storage solution [2,5].

The recycling of lithium-ion batteries enables reductions in energy consumption, carbon emissions, natural resource and raw material usage, environmental impact and damage, economic gains, as well as reductions in waste and waste management issues. However, currently, only about 3% of batteries are recycled. Electric vehicle manufacturers are exploring secondary uses of lithium-ion batteries, such as emergency generators, cleaning and agricultural machinery, industrial machinery, forklifts, and electric bicycles. Research is ongoing for other available areas. The reuse and production of lithium-ion batteries pose significant challenges because batteries must remain undamaged, and have operational efficiency, and the battery pack must be safely and harmlessly removed. While only Co, Cu, steel, Ni, and Al are recycled in recycling plants, many other materials are overlooked. However, as the process is refined, materials will be recycled, and these recycled materials will be marketed to production industries, creating new markets. The most significant challenge complicating recycling is the need for the safe recycling of lithium and electrodes in batteries [7].

With the increasing popularity of electric vehicles, manufacturers are constantly working to produce lithium-ion batteries. Industry analysts predict that more than 10 million tons of these batteries will reach the end of their service life

by 2030, resulting in a substantial lithium-ion battery waste issue in the future. Currently, less than 5% is recycled due to technical and economic barriers. Recovering valuable metals from battery electrodes and reusing them is challenging. Research is being conducted to develop and recycle battery electrodes without using organic solvents by reformulating materials used to produce lithium-ion batteries. The results of the research suggest that production and recycling costs, hazards, and environmental impacts of lithium-ion batteries can be reduced [8].

4. The Economic Dimension of the Sustainability of Lithium-Ion Batteries

The use of lithium-ion-based structures, an innovative technology, is rapidly increasing on a global scale. When looking at the areas where lithium is used in batteries in Turkiye in Figure 1, it is clear that progress in this field is also continuing in our country. Electric-based transportation systems, balancing renewable energy, improving grid factors, and meeting potential instantaneous demand are highly important. In recent years, efforts have been made to produce commercially competitive and environmentally friendly lithium iron phosphate ($LiFePO_4$) type battery cells for energy storage activities. Lithium iron phosphate technologies, which do not contain environmentally unfriendly elements such as cobalt, cadmium, nickel, or lead, are economically significant for obtaining electronic structures containing balancing and protection systems for battery cells, providing grid-scale storage, obtaining specialized energy storage systems, and ensuring the integration of necessary electronic converter structures and energy storage cells, electronic structures, and related software. However, the low reserves of lithium are one of the biggest obstacles to its use in new technologies. Nevertheless, the market share of lithium has continues to increase over the years. This situation is shown by country in Table 2 [3,9].

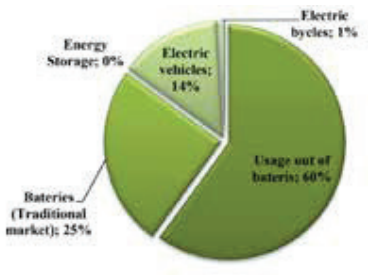

Figure 1. Usage areas of the lithium ion batteries in Turkiye [3]

Table 2. Lithium Production and Reserves [3].

Countries	Production		Reserve
	2019	2020	
USA	-	-	750.000
Argentina	3.600	5.700	1.900.000
Australia	14.000	14.300	4.700.000
Brazil	200	200	95.000
Canada	200	-	530.000
Chile	10.500	12.000	9.200.000
Chinese	2.000	2.000	1.500.000
Portugal	200	200	60.000
Zimbabwe	900	900	220.000
Other countries (7)	-	-	2.100.000
Total	31.500	35.000	21.000.000

5. Environmental Aspects of Sustainability of Lithium Ion Batteries

While the growth of the energy production industry promises numerous environmental and social benefits, it also brings significant challenges. Among these, battery manufacturers need to ensure a consistent supply of both raw materials and equipment, strategically allocate investments, and efficiently grow industrialization. Producer organizations must move beyond superficial environmental initiatives and adhere to comprehensive decarbonization and genuine sustainability efforts. To meet these imperatives, battery manufacturers need to offer proactive approaches in sustainability initiatives. Achieving sustainability in the sector will be possible through collaborative actions, standardized processes and regulations, and enhanced data transparency throughout the value chain. Sustainability, leading the way to circularity and flexibility, not only identifies leading battery manufacturers but also creates value while protecting the environment. In conclusion, the battery industry stands on the threshold of unique growth opportunities and substantial challenges. Battery manufacturers are not only obligated to meet increasing demand but also to pave the way for a greener, more resilient future by embracing sustainable practices, circular economy principles, and collaborative approaches [10]. Although technology related to lithium battery-powered vehicles has relatively matured, challenges persist, especially concerning adverse environmental impacts during the extraction process of critical metals and the particular dependence on China for these metals, which are among the issues that the European Union automotive sector must overcome.

The combustion of fossil fuels releases pollutants such as carbon monoxide (CO), particulate matter, sulfur oxides (SOx), nitrogen oxides (NOx), hydrocarbons (CxHy), and soot into the atmosphere. Efforts have been made to reduce these fossil fuels, which are the primary source of air pollution, through agreements like the Kyoto Protocol. Such agreements primarily bind developed countries. These countries, largely responsible for the existing high greenhouse gas emissions in the atmosphere, also play a significant role in the development and export of lithium-ion batteries as a consequence. It has been reported that carbon emissions per capita are increasing over the years both globally and in Turkiye. The increase in the number of vehicles in Turkey over the years, as shown in Figure 2, further emphasizes this situation. Rechargeable batteries such as lead-acid, nickel-cadmium, nickel-metal hydride, and lithium-ion are being developed for the storage of hydrogen in metal hydride form and for use in portable electronic devices. Alloys containing rare earth elements are used in rechargeable nickel-metal hydride batteries due to their hydrogen storage properties. For example, LaNi5 has a significant capacity to store hydrogen gas. The hydrogen density in LaNi5H6 is much higher than that in liquid hydrogen. Instead of pure lanthanum, an alloy containing light REEs (La, Ce, Pr, Nd) is used due to the high price of pure lanthanum. The NiMH battery consists of a metal hydride as the negative electrode, $Ni(OH)_2$ as the positive electrode, and an alkaline electrolyte (KOH) [3].



Figure 2. Increase in the Number of Vehicles in Turkey over the Years [3]

Sustainability in battery technologies extends beyond production to encompass the post-usage lifecycle as well. Recycling and waste management are among the most critical issues in this field. How to recycle or dispose of old or unused batteries without causing harm to the environment is of great importance to the industry [8,11,12].

- Effective Recycling Methods: Advanced recycling techniques render battery materials reusable safely and efficiently. This ensures that valuable materials are not wasted and reduces the environmental impact.
- Education and Awareness: Training and awareness campaigns are vital for users to manage battery waste correctly. Informing the public about the importance of battery recycling is critical to the success of the process.
- Legal Regulations: Standards and laws set by governments and international organizations for battery waste management play a crucial role in ensuring that the process operates correctly.

Green battery innovations refer to environmentally friendly developments in energy storage technologies aimed at contributing to a more livable world. Innovations are possible with some developments that aim to reduce the environmental impact of batteries from production processes to the end of their usage lifespan. These developments include:

- Eco-Friendly Materials: Some new battery technologies use less harmful and entirely renewable materials.
- Energy Efficiency: Batteries with higher energy efficiency consume less energy, thereby reducing both energy consumption and carbon footprint.
- Longevity: Extending battery life reduces waste. Long-lasting batteries alleviate pressure on the environment and can optimize resource usage.

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