Rechargeable Batteries for Renewable Energy: Current Status, Technical Challenges, and Future Directions

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Abstract. With the increasing severity of climate change and the threat of global warming, countries are boosting the development and promotion of renewable energy sources like solar and wind to bring about the energy transition and reduce carbon emissions. However, because these energy sources are unreliable in supply, efficient energy storage technologies are required to balance energy output to satisfy daily electricity demand. Among numerous energy storage alternatives, rechargeable battery technology has received a lot of interest due to its high energy density, efficiency, and reusable nature. Currently, lithium-ion batteries, nickel-metal hydride batteries, lead-acid batteries, and other rechargeable battery types are widely utilized in consumer electronics, transportation, renewable energy storage, medical equipment, and other industries. This paper examines the basic working principle, structure, and important chemical reactions of rechargeable batteries, as well as their performance indicators such as capacity, energy density, cycle life, and so on. Furthermore, this paper addresses the technology's global application cases, as well as the status of its development and the major problems, such as safety, cost, longevity, environmental impact, and other issues. Finally, this article examines probable future technology breakthroughs, market trends, and the possibility of suitable policy support in this field.

1 Introduction

Every society depends on electrical power to meet its fundamental requirements, meanwhile, carbon dioxide emissions have drastically increased and brought about global warming. The current situation has jeopardized the environment in which people reside, leading to abnormal rainstorms, prolonged droughts, and an accelerated expansion of desert areas. Long-term variations in weather and temperature conditions, including differences in solar activity and significant volcanic eruptions, are referred to as changing the climate. Human activity has served as the primary cause of global warming since the beginning of the 19th century [1].

Carbon emissions must be reduced by nearly fifty percent by 2030 and reach net-zero levels by 2050 to avert the worst effects of climate change [2]. The creation of diverse renewable energy sources is one potential course of action. According to predictions from

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the International Renewable Energies Agency (IRENA) By 2050, 90% of the world's electricity could and ought to originate from renewable sources [3]. Utilizing renewable energy sources to the fullest can help reduce air pollution and related health problems [4]. By using the force of nature to create electricity, marine energy, wind energy, and solar energy are significant types of renewable energy that reduce carbon dioxide emissions and reduce global warming. These technologies provide energy security, lessen the negative effects on the environment and human health, and lessen reliance on fossil fuels. Renewable Energy power lead to inconsistent power output and compromise grid security. The energy storage battery system can react rapidly to variations in frequency and voltage, keeping the grid stable. The primary benefit of rechargeable battery technology is the capacity to effectively store and release electrical energy, making it appropriate for a range of applications, particularly in electric vehicle and grid regulation. Because of its adaptability, broad range of applications, and capacity to sustain power stability in an environment of significant changes in renewable energy sources, this technology is garnering attention. Rechargeable batteries are multipurpose power sources that can be repeatedly utilized and charged by an external voltage. Lead-acid batteries, nickel-metal hydride batteries, batteries with lithium ion (including lithium cobaltite and manganate), and nickel-cadmium batteries are common varieties. Rechargeable batteries have become a cost-effective and environmentally responsible choice because of their high energy density, safety, dependability, protection against the environment, and longer cycle life. They are extensively utilized in high-power, continuous-use gadgets including electric toys, power tools, and mobile phones.

Rechargeable battery power is not without its issues, though. Rechargeable batteries, for instance, may overheat when being charged or discharged, which could lead to leakage and short circuit. The battery's performance can also be lowered by erroneous operation, overcharging or draining, particularly when using a power battery, as well as by improperly timing the charging process or committing errors during operation. In this paper, principle, technical characteristics, application scenarios, problems and solutions of rechargeable battery are analyzed to elucidate how rechargeable batteries might mitigate environmental damage and significantly contribute to sustainable development.,.

2 Working principle

2.1 Definition of rechargeable battery

Rechargeable batteries are devices that can store and release electrical energy after multiple charging and draining cycles. The functioning principle is based on electrochemical processes. It stores electrical energy when charging and releases it during discharging using electrodes and electrolytes. Batteries usually consist of a positive electrode, a negative electrode, and an electrolyte. Metal oxides or phosphates are common positive electrode materials. Graphite and lithium metal are common materials for negative electrodes. Electrolytes are liquids, gels, or solids that allow ions to travel among electrodes. When a battery is charged, electrons and ions flow from the negative electrode to the positive electrode, and the reverse happens when it is discharged. This process can be repeated on multiple occasions, and it is the irreversible electrochemical reaction that enables the battery to both charge and discharge.

Rechargeable batteries use electrochemical reactions to transfer chemical energy to electrical energy. During the discharge process, an oxidation reaction happens at the anode (negative electrode), releasing electrons and delivering power over an external circuit; a reduction reaction occurs at the cathode (positive electrode), taking electrons. When charging, an external power source enables electrons to flow back, restoring these chemical processes and restoring the battery's capacity. The comparison of rechargeable battery and ordinary battery are summarized in table 1.

Table 1. The difference between rechargeable batteries and ordinary batteries [5]

Items	Rechargeable batteries	Ordinary batteries
Component	Lithium dioxide as positive platform, spongy pure lead as negative platform	Positive substance (Oxygen or hydrogen), negative substance (zinc or lead)
Application	High-energy-consuming electronic devices including digital cameras, laptop computers, and mobile phones.	Devices demanding consistent voltage and current, including torches, clocks, and others.
Rechargeable or not	Rechargeable	Nonchargeable
Strengths	Large capacity, proper for heavy energy requirements, minimizing the frequency of battery change.	Stable current and voltage, easy to transport, reliable performance, unaffected by the environment.
Weakness	Considerable cost, restricted number of charge and discharge cycles, and self-discharge.	It may not be replenished and must be replaced after usage.
Environmental impact	Reusable, minimizing the environmental impact of waste.	It must be discarded all at once, generating a vast amount of waste with protentional environmental contamination.

2.2 Types of rechargeable batteries

Nickel metal hydride batteries, lithium-ion batteries, lithium manganese oxide batteries, lithium cobalt oxide batteries, nickel cadmium batteries, and lead-acid batteries are some of the most common types of rechargeable batteries available today. Their characteristics are summarized in Table 2.

Table 2. Characteristics of various rechargeable batteries [5]

Types	Characteristics	Strengths	Weakness	Application
Lithium-ion Battery	High energy density, light weight, and high voltage	Long life, high single charge voltage, and lightweight.	Higher expense, fire risk.	Electric vehicles, such as smartphones, and laptops.
Lithium Manganate Battery	Hot temperature stability and safety, capable of sustaining higher current discharges.	Excellent safety and great temperature resistance.	Lower energy density compared to other lithium batteries.	Power tools, electric cars.
Lithium Cobalt Oxide Battery	High energy density.	High energy density and light weight.	Poor safety, high costs, and limited lifespan.	Laptops, smartphones.

Nickel Metal Hydride Batteries	Environmentally friendly, sturdy structure.	Lower cost and fewer hazardous metals.	Rapid self-discharge and limited lifespan.	Hybrid vehicles, digital cameras.
Nickel Cadmium Batteries	Low density of energy and high deep discharge capacity.	Can handle many charging and releasing cycles; suited for harsh temperatures.	Holds poisonous cadmium and has a "recall effect".	Power tools, emergency lighting.
Lead-acid Battery	Low energy density, large and bulky.	Low-cost, capable of supplying enormous amounts of current.	Heavy and short service life.	Car batteries, UPS backup power, and solar energy storage.

2.3 Main performance parameters

2.3.1 Energy density

Lithium-ion batteries typically have a power density of 150 to 200 Wh/kg, making them excellent for use in products that demand reducing weight. These products include electric vehicles (EVs), smartphones, and laptops [6]. Due to their high energy density, lithium-ion batteries keep more energy per unit weight, making them excellent for portable gadgets or applications that require a longer period of operation.

2.3.2 Charge and discharge efficiency

Lithium-ion batteries have a charge and discharge efficiency of more than 90%, which is why they are commonly employed in electronic products and electric cars. The excellent charge and discharge performance minimizes energy loss throughout the conversion process, making it perfect for systems that operate for a long amount of time or require efficient energy leadership, including solar energy storage systems and electric automobiles. Its great efficiency enables more energy to be used on each charge, extending the device's life.

2.3.3 Energy storage cost

The cost of producing lithium-ion batteries has decreased dramatically in recent years, with a current cost of approximately $137 per kilowatt-hour. With advancements in manufacturing techniques and savings of production, this cost is predicted to continue to fall in the next few years, approaching $100/kWh [7].

2.3.4 Cycle life

Lithium-ion batteries typically have 500 to 1,500 charge and drain cycles, and in some outstanding performance applications, optimized batteries can have a cycle life of over 3,000 times [8].

2.3.5 Charge and discharge speed

The charging as well as discharge speed of lithium-ion batteries can be measured using C-rate. Its rapid charge and discharge rate enables it to finish charging quickly, which is critical for everyday electronics like mobile phones and laptop computers. Furthermore, with the adoption of fast charging technology, the speed of charging of lithium-ion batteries is constantly improving, lowering users' wait times. However, high charge and discharge rates can shorten battery life, thus they are typically managed by battery management software (BMS).

2.3.6 Cost

The cost of lithium-ion batteries has been decreasing over time and is now around US$100 per kWh. As global demand for sustainable energy and electric vehicles grows, lithium-ion battery production expands, resulting in lower unit costs [8].

2.4 Applicable scenarios

2.4.1 Aerospace field

Rechargeable battery systems are essential for providing energy support in satellites, unmanned aerial vehicles （UAVs）, and other aerospace applications. In harsh settings, this sort of battery must be exceptionally reliable, long-lasting, and lightweight. Lithium-ion batteries and their new versions, among them lithium-sulfur batteries and solid- state batteries, are gaining considerable interest [9].

2.4.2 Consumer electronics

Lithium-ion batteries are commonly utilized in handheld electronics that include smartphones, laptop computers, and smart watches. Research focuses on increasing energy density, extending battery life, lowering self-discharge rates, and investigating alternate electrolyte to improve safety. Lithium-ion batteries are the chosen power source for these gadgets due to their high density of energy, lightweight design, and long service life [10].

2.4.3 Medical Equipment

Rechargeable batteries are widely used in medical devices such as pacemakers, hearing aids, and insulin units. These batteries are often compact, powerful, and long-lasting, and must operate reliably inside the bodies of people or in medical settings. The medical profession requires extremely exact standards for the safety and stability of batteries that are rechargeable. As a result, academic circles are researching the usage of solid-state batteries and bio-batteries in place of typical lithium-ion batteries to reduce dangers and increase service life [11].

2.5 Project Cases

Massive lithium-ion battery arrays are currently being used for storing wind and solar energy and offer power aid to the national grid [12]. These projects, which use the Powerwall and Powerpack storage systems for energy to provide clean energy solutions for homes and businesses, represent the commercialization of rechargeable battery technology. Tesla's

Powerwall is a popular energy storage solution for households and businesses that employs lithium-ion battery technology. Each device has 13.5 kWh of energy storage capacity, allowing users to store solar energy for use during grid disruptions or peak hours. This project demonstrates the successful integration of rechargeable batteries and renewable energy systems [13].

3 Technical challenges

3.1 Security Issues

A major safety risk for batteries made with lithium-ion is "thermal runaway," which occurs when the battery is subjected to high temperatures, charging too much, or physical damage, and the chemical reactions inside the battery become uncontrollable, causing the internal temperature to rapidly rise and cause a fire or explosion. Because of the enormous quantity of energy accumulated in high-energy-density packs of batteries, such as those used in electric vehicles, the risk of thermal runaway is very great. When the temperature within the battery exceeds a particular point, the electrolyte may dissolve and emit flammable gases, increasing the risk of a fire.

3.2 Longevity

Lithium-ion batteries have a limited life cycle, and when they are charged and discharged repeatedly, their ability steadily declines. This phenomenon is commonly known as "capacity fading" or "battery aging." After several hundred cycles, a battery may only deliver a percent of its first capacity, reducing the device's longevity.

3.3 Environmental impact issues

Lithium-ion batteries require a considerable number of rare metals, including lithium, cobalt, and nickel. The extraction of these metals has a significant impact on the environment. For example, cobalt mining is mostly centered in the Democratic Republic of Congo, which includes issues that include environmental pollution, ecological degradation, and human rights violations.

3.4 Cost challenge

Although the cost of batteries made from lithium-ion has been falling year after year in recent years, production costs stay high, particularly in large-scale applications such as electric vehicles and energy storage systems on a massive scale. Manufacturing lithium-ion batteries needs the use of high-purity elements such as cobalt, lithium, and nickel, as well as sophisticated production procedures and stringent quality control, all of which raise manufacturing costs.

4 Solutions and further trends for technical challenges

4.1 Security

4.1.1 Security Issues

Solid electrolytes provide stronger thermal stability than standard liquid electrolytes, which can considerably lower the danger of thermal runaway within the battery. Solid-state batteries not only lower the combustible gases emitted during electrolyte decomposition, but they also boost the battery's energy density.

4.1.2 New Diaphragm Technology

Higher-temperature stable separating materials can improve the reliability of the battery's inner workings and keep it from short-circuiting or failing at elevated temperatures. Ceramic separators, for example, have gradually gained popularity as a safety upgrade for lithium-ion batteries because to their exceptional thermal stability.

4.1.3 Battery Management System (BMS)

Sophisticated BMS system may track the temperature, current, voltage, and other battery characteristics in real time to prevent overcharging, over-discharging, and overheating, lowering the risk of thermal runaway. By intelligently changing the charging and discharging rates, BMS can delay the onset of thermal runaway.

4.1.4 Development trend

Solid-state batteries are seen as the future of lithium-ion battery safety. Solid-state battery technology is predicted to enter commercial production over the next ten years, with widespread use in electric vehicles, systems for storing energy, and other applications. In addition, innovative nanomaterials, coating technologies, and automated monitoring systems will improve the safety of lithium batteries.

4.2 **Lifespan Challenge**

4.2.1 Type Electrode Material

Researchers are aiming to create new silicon-based or lithium metal anodes with increased ability and cycle stability. By enhancing the structure of the materials used for electrodes, mechanical stress generated by the intercalation and deintercalation of the lithium ions can be decreased, extending the battery's service life.

4.2.2 Electrolyte improvements

High-stability electrolyte additions can prevent electrolyte decomposition under high-pressure, high-temperature circumstances while avoiding adverse reactions. The inclusion of additives (for instance, fluorinated electrolyte) can considerably increase the battery's cycle stability and delay capacity degradation.

4.2.3 Smart charging technology

Optimizing the process of charging algorithm and using advanced charging technology can help to reduce battery damage during charging and discharging. For example, several manufacturers of electric cars have begun to use rapid charging technologies and segmented recharging algorithms to alleviate battery stress during deep drain and quick charging.

4.2.4 Development trend

The life of batteries made with lithium-ion will be extended further as battery material research advances, and the battery's cycle life may eventually exceed 3,000 times [14]. At the same time, solid-state batteries are projected to play an important role in prolonging battery life due to their superior electrochemical stability. Since the need for long-life batteries in electric automobiles and energy storage increases, research into battery life improvement will become more important.

4.3 Environmental Impact Issues

4.3.1 Material Recycling Technology

To lessen dependency on rare metals, batteries recycling equipment is fast evolving. Recycling lithium, cobalt, nickel, and other metals in old batteries reduces the demand for new natural resources while also reducing the environmental impact of mining. Closed-loop recycling technology may significantly boost metal recycling efficiency while lowering the environmental impact of battery production.

4.3.2 Material Substitution

Some research aims to build cobalt-free batteries with lithium ion or replace rare elements with more abundant minerals like iron and sodium. Because of the abundance of sodium supplies, sodium-ion batteries have appeared as a potentially practical alternative to lithium batteries. In addition, the use of cobalt-free battery packs, such as iron phosphate lithium power sources, is growing, particularly in sectors where great energy density is not required.

4.3.3 Environmentally Friendly Material Development

The study and development of some novel materials is geared to minimizing environmental pollution. Water-based electrolytes, for example, are thought to be more environmentally benign than standard organic solvents. Furthermore, the research of compostable battery materials is steadily progressing to prevent environmental contamination following battery disposal.

4.3.4 Development Trend

As global environmental restrictions tighten; battery longevity will become a major focus for future improvements. Battery recycling technology is likely to advance significantly in the next years, and closed-loop logistics systems will become more widespread in the battery manufacturing industry. At the same time, the creation of green manufacturing processes and alternative resources will become a priority for the sector.

4.4 Cost Challenge

4.4.1 Scale effect and production process optimization

As the volume of lithium-ion batteries produced grows, manufacturers can save costs by improving efficiency in production and perfecting procedures. For example, automated lines of production, modern manufacturing technologies (including 3D printed electrodes), and optimized production procedures can all help to cut production costs on a big scale.

4.4.2 Material substitution and reducing dependence on rare metals

One important strategy for lowering battery prices is to limit the consumption of rare metals like cobalt and nickel. Lithium iron phosphate (LFP) batteries have appeared as the preferred low-cost batteries due to their lack of cobalt and nickel content and low material costs. Future material developments, like sodium-ion batteries, are predicted to dramatically cut battery production costs.

4.4.3 Government Subsidies and Policy Support

Some countries and regions encourage the use of electric motor vehicles and systems to store energy through government funding or tax breaks, hence boosting the growth of the lithium battery industrial chain. Furthermore, the National Strategy Reserve Program may help stabilize price variations in essential metals such as cobalt and lithium, thereby lowering the long-term expense of batteries.

4.4.4 Development Trend

The cost of producing lithium-ion batteries is likely to reduce further in the future years, driven mostly by worldwide demand for electric motor vehicles and renewable energy storage devices. With material innovation, improved production efficiency, and greater economies of scale, the cost of lithium-ion batteries is predicted to approach the critical threshold of $100/kWh, further pushing their use in a variety of situations [9].

5 Conclusion

The future growth of lithium-ion batteries confronts many hurdles, including safety, longevity, environmental impact, and cost. However, with advances in materials science, the implementation of modern technologies, and the improvement of the worldwide industrial chain, lithium battery performance and sustainability are likely to increase dramatically in the future. Innovative advancements such as solid-state batteries, renewable resources, and smart charging technology will encourage the widespread use of batteries made of lithium in electric vehicles, batteries for energy storage, and personal gadgets.

References

1. IPCC. IPCC Sixth Assessment Report. Retrieved on 5th November, 2024, retrieved from https://www.ipcc.ch/report/ar6/wg1/
2. IEA. Net Zero by 2050. Retrieved on 5th November, 2024, retrieved from https://www.iea.org/reports/net-zero-by-2050A.

3. United Nations. Renewable energy – powering a safer future. Retrieved on 5th November, 2024, retrieved from https://www.un.org/en/climatechange/raising-ambition/renewable-energy
4. World Health Organization. Billions of people still breathe unhealthy air: new WHO data. Retrieved on 5th November, 2024, retrieved from https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data
5. Siriyala Trilochana, C.N. Sangeetha. A Comparative study and Recent Research of Battery Technologies. The International journal of analytical and experimental modal analysis, **8**, 1183-1189 (2021)
6. Shuvajit Ghosh, Udita Bhattacharjee, Subhajit Bhowmik, et al. A Review on High-Capacity and High-Voltage Cathodes for Next-Generation Lithium-ion Batteries. Journal of Energy and Power Technology, **1**: 002 (2022)
7. China Energy Storage Network. Analysis and prospect of new energy storage technology route. Retrieved on 5th November, 2024, retrieved from https://www.escn.com.cn/20240129/18ea85be891d4a7dbd554a9c3b540624/c.html
8. NREL. Electric Vehicle Lithium-Ion Battery Life Cycle Management. Retrieved on 5th November, 2024, retrieved from https://www.nrel.gov/docs/fy23osti/84520.pdf
9. Energy Storage. Bloomberg NEF: Average battery pack prices to drop below US$100/kWh by 2024 despite near-term spikes. Retrieved on 5th November, 2024, retrieved from https://www.energy-storage.news/bloombergnef-average-battery-pack-prices-to-drop-below-us100-kwh-by-2024-despite-near-term-spikes/
10. M. Stanley Whittingham. Lithium Batteries and Cathode Materials. Chemical Review, 104:4271-4301(2004)
11. J.M. Tarascon, M. Armand. Issues and challenges facing rechargeable lithium batteries. Nature, 414: 359-367 (2001)
12. John, A.T., Nair, M. G., Morrow, M. R. Rechargeable batteries for medical implants https://pubs.acs.org/doi/10.1021/cr020731c. Journal of Power Sources, 493:229730 (2021)
13. Tesla. Tesla Power Everything. Retrieved on 5th November, 2024, retrieved from https://www.tesla.com/energy
14. Battery University. BU-808: How to Prolong Lithium-based Batteries. Retrieved on 5th November, 2024, retrieved from https://batteryuniversity.com/article/bu-808-how-to-prolong-lithium-based-batteries