ELECTRICITY STORAGE BY ELECTROCHEMICAL BATTERIES

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ABSTRACT: *The increasing integration of renewable energy sources into modern power systems has intensified the need for efficient and reliable electricity storage technologies. Electrochemical batteries have emerged as a leading solution due to their scalability, flexibility, and rapidly advancing performance characteristics. This paper provides an overview of the fundamental principles governing electrochemical energy storage, focusing on the conversion of chemical energy into electrical energy through redox reactions. Key battery technologies – including lithium-ion, lead-acid, and emerging solid-state systems – are examined in terms of energy density, efficiency, lifecycle, and environmental impact.*

Keywords: Electricity storage, Electrochemical batteries.

1. INTRODUCTION

Electrochemical batteries are devices that store electrical energy in the form of chemical energy and convert it back into electricity when needed. They are widely used in portable electronics, electric vehicles, backup power systems, and renewable energy storage. A battery consists of one or more electrochemical cells. Each cell contains two electrodes, an anode and a cathode, separated by an electrolyte. During discharge, chemical reactions occur at the electrodes, causing electrons to flow through an external circuit and produce electric current. During charging, an external power source reverses these reactions, restoring the battery's stored energy. Electrochemical battery storage plays an important role in modern energy systems because it helps balance electricity supply and demand. It is especially useful for renewable energy sources such as solar and wind, which produce electricity intermittently. By storing excess energy when production is high and releasing it when demand increases, batteries improve grid reliability and support the transition to cleaner energy. [1-5]

2. ELECTROCHEMICAL BATTERIES

2.1. Lithium-ion batteries

Lithium-ion rechargeable batteries (Li-ion) are an energy storage technology widely used in portable electronic devices (smartphones, laptops, tablets), electric vehicles and in renewable energy storage applications.

These work by moving lithium ions between a positive electrode (cathode) and a negative electrode (anode) through an electrolyte.

A. Structure and operation:

Main components: (fig. 1)

- *The anode*: is usually made of graphite or other carbon-based material, that can store lithium ions. The anode charges with lithium when the battery is charged;
- *The cathode*: made of a metal lithium compound such as lithium cobalt oxide ($LiCoO_2$) or other lithium oxides ($LiMn_2O_4$, $LiFePO_4$). This is the place where lithium ions move during the discharge of the battery;
- *The electrolyte*: is a liquid, gel or solid substance that contains lithium salts (e.g. $LiPF_6$). It facilitates the migration of lithium ions between the anode and the cathode, but is electrically isolated, preventing electrons from passing directly;
- *The separator*: is a microporous membrane that separates the anode from the cathode, allowing only lithium ions to pass through it, but blocking the electrons in order to prevent short circuit.

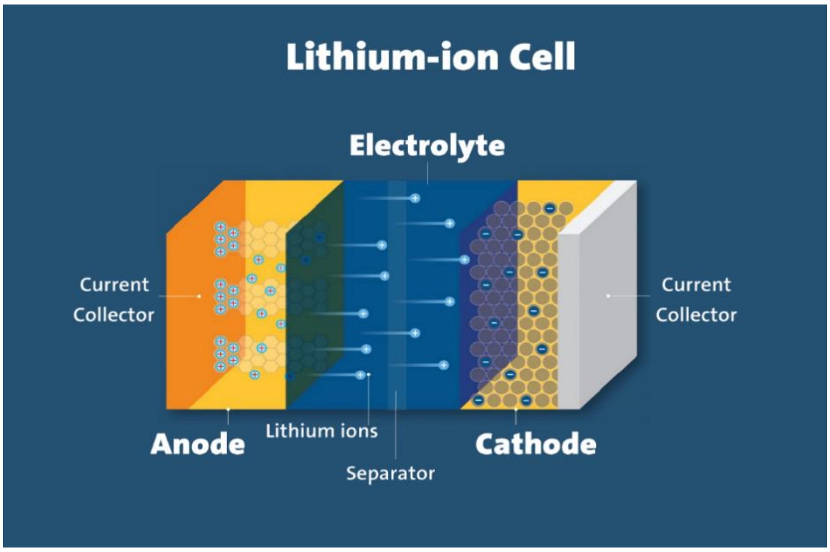

Fig. 1. Li-ion rechargeable battery components

Operating principle: [1-10]

The operating process of Lithium-ion batteries is carried out in two main stages:

Charging:

- when the battery is charging, an external electric current source applies a voltage between the anode and the cathode;
- this energy pushes lithium ions from the cathode through the electrolyte to the anode;
- lithium ions are incorporated into the material of the anode (usually graphite), a process called "intercalation";

- electrons travel through the external circuit from the cathode to the anode, generating electric current.

Discharging:

- when the battery discharging (when it is used to power a device), the process is reversed;
- lithium ions travel back from the anode to the cathode through the electrolyte;
- electrons travel through the external circuit from the anode to the cathode, generating electricity to power the device.
- lithium ions are "disintercalated" from graphite (anode) and return to the lithium-metal compound of the cathode.

Chemical reactions:

- *at the anode*: during charging, lithium ions are stored by $Li^+ + e^- \rightarrow LiC_6$ (in graphite) reaction, and during discharge these ions are released;
- *at the cathode*: during discharge, the chemical reaction involves the transformation of $LiCoO_2$ compound into Li^+ and the release of electrons and energy.

B. Advantages:

- *High energy density*: lithium-ion batteries can store a large amount of energy in relation to their mass, making them ideal for mobile devices and electric vehicles;
- *Long life cycle*: these batteries can be charged and discharged hundreds to thousands of times without significant performance degradation;
- *Charging time*: generally they charge faster compared to other types of batteries;
- *Memory effect*: does not suffer from memory effect, which means that it does not require full discharge before being recharged.

C. Disadvantages and limitations:

- *Risk of overheating*: if overworked, overcharged or damaged, lithium-ion batteries may overheat and, in extreme cases, may explode;
- *Degradation over time*: batteries lose their capacity as they are often charged and discharged. Normally, after a few hundred charge cycles, their capacity begins to decrease;
- *Costs*: their production involves relatively expensive resources (such as lithium and cobalt), which makes them more expensive compared to other types of batteries;
- *Temperature sensitivity*: they work less efficiently at extreme temperatures and can suffer damage in very high or very low temperatures.

D. Main applications:

- *Consumer electronic devices*: smartphones, laptops, tablets and other portable electronics, where light weight and small size are crucial;
- *Electric vehicles*: due to the high energy density, lithium-ion batteries are essential for electric cars, where the battery autonomy and weight are critical;
- *Energy storage for solar and wind systems*: the capacity to store energy produced by renewable sources makes them suitable for micro-grids and home energy systems.

E. Future trends and developments:

- *Solid-state batteries*: These replace the liquid electrolyte with a solid one, reducing the risk of fires and providing an even higher energy density;
- *Recycling and sustainability*: efforts are being made to develop efficient recycling methods, due to the importance of valuable components and environmental risk;

- *Lithium-Iron-Phosphate ($LiFePO_4$) batteries*: safer alternatives with longer lifespan, being especially popular in electric vehicles.

F. Safety and maintenance:

- In order to extend the battery lifespan, it is recommended not to expose them to extreme temperatures and avoid frequent full charge and discharge;
- Using an original charger also helps to avoid safety and performance problems.

Lithium-ion batteries are a key technology in the transition to renewable energy solutions and electric mobility, but they still require improvements in order to become more sustainable and affordable.

2.2. Flow type batteries (flow)

Flow type or *flux* type batteries are a renewable energy storage technology that works differently from traditional batteries (such as Lithium-ion).

In *flow* batteries, energy is stored in two liquid electrolytic solutions that circulate through an electrochemical cell where oxidation and reduction reactions occur.

This technology offers several important advantages, especially for large-scale applications such as renewable power plants or power grids.

A. Operating principle:

A flow battery consists of two electrolytic liquid tanks, one containing an electrolyte with a positive potential (cathode) and another with a negative potential (

The electrolyte in these two tanks is pumped through an electrochemical cell where a semi-permeable membrane separates the two solutions.

During the passage through this cell, a chemical reaction takes place between the two liquids, and the energy is released or stored depending on the direction of the flow. This allows the battery to be charged and discharged.

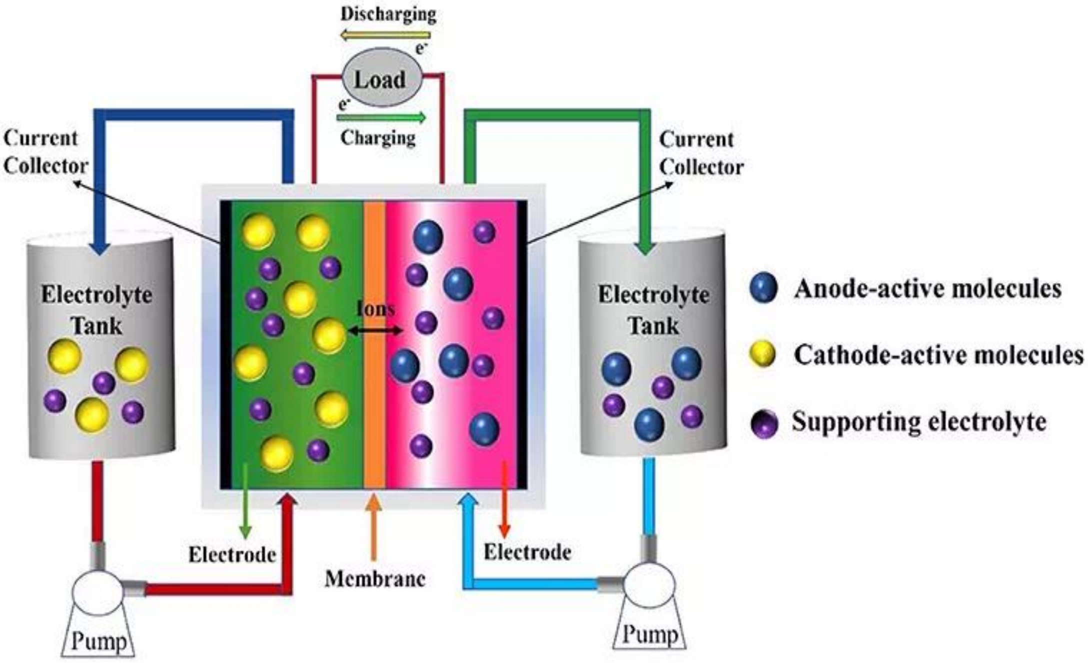

Fig. 2. Flow type or flux type battery

B. Types of flow batteries:

There are several types of *flow* batteries, including:

- *Vanadium-redox battery*: uses vanadium in both electrolyte compartments, having the advantages of sustainability and stability;
- *Bromine and zinc battery*: this battery has a more compact design and higher energy density than other types of flow batteries;
- *Iron-flow battery*: uses iron as the main material, being cheaper and greener, but with lower efficiency and energy density.

C. Advantages of flow type batteries:

- *Scalability:* the storage capacity depends on the volume of liquid in the tanks, which means that they can be easily extended to provide more energy;
- *Sustainability and long life cycle*: these batteries can withstand thousands of charge/discharge cycles without significantly losing capacity;
- *Safety:* compared to traditional batteries, the risk of fire is much lower because they use non-flammable solutions.

D. Disadvantages:

- *High initial costs:* flow battery installations require complex equipment and space, making them more expensive initially;
- *Energy efficiency:* the efficiency rate (about 70-80%) is lower than in other batteries such as lithium-based batteries;
- *Requires maintenance:* pumps and other mechanical components in the system need regular maintenance to prevent defects.

E. Usages:

Flow type batteries are suitable for applications involving long-term and large-scale energy storage, such as:

- *Renewable energy storage:* they are used to store energy from wind turbines and solar panels, providing a solution for the variability of these sources;
- *Long-term storage:* in cases where energy needs to be stored and used for extended periods, such as energy grids in remote islands or regions;
- *Grid balancing applications:* help to stabilise and balance energy demand across national grids.

F. The future of flow batteries:

Although not as widespread as lithium-ion batteries, *flow* batteries have great potential for development, especially for applications where long-term energy storage is required and where safety and sustainability are priorities.

Flow type batteries are considered a promising solution in the transition to a sustainable energy economy and a future based on renewable sources. [5-14]

2.3. Lead-acid batteries

Lead-acid batteries are among the oldest and most widely used types of rechargeable batteries.

Invented in the 1850s by Gaston Planté, these batteries are mainly used for automotive applications, energy storage systems, backup systems and other industrial applications.

A. Composition and operating principle

Lead-acid batteries consist of lead plates and lead dioxide (PbO_2), which act as electrodes (positive and negative). The electrolytes used are usually solutions of diluted sulfuric acid (H_2SO_4). When the battery discharges, the lead and lead dioxide react with sulfuric acid, forming lead sulfate ($PbSO_4$) and water (H_2O). When charging, this reaction is reversed, so that the compounds return to their original form. (fig. 3)

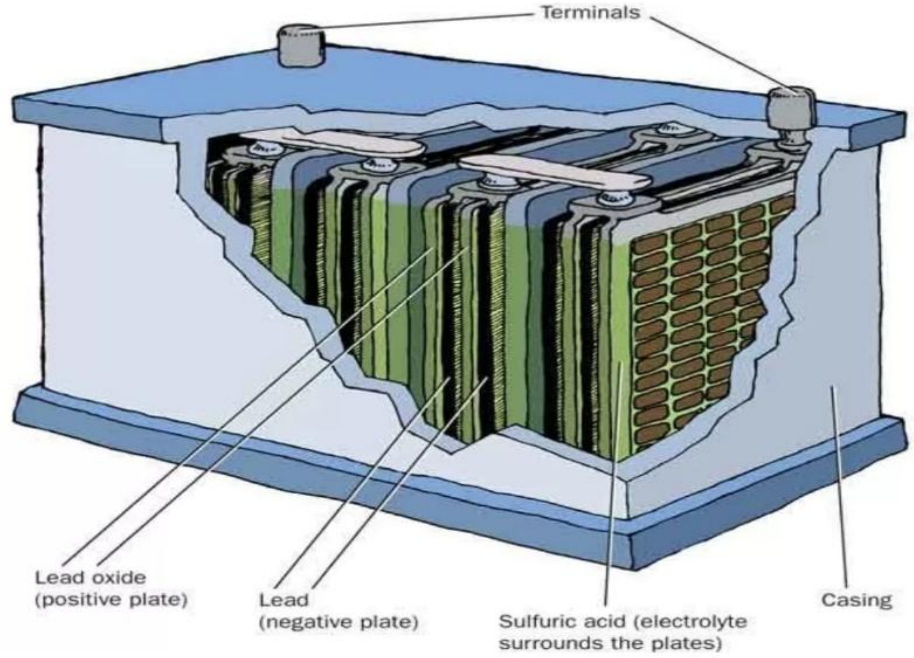

Fig. 3. Lead-acid batteries

B. Types of lead-acid batteries:

- *Conventional Lead-Acid batteries* – also known as maintenance batteries, require periodic replenishment with distilled water, since during operation water is lost through evaporation;
- *Maintenance free Lead-Acid batteries (VRLA)* – are sealed and do not require replenishment with water. These include:
    - Gel batteries – in which the electrolyte is in the form of a gel, reducing the risk of leakage;
    - AGM batteries (Absorbed Glass Mat) – in which the electrolyte is absorbed into a fiberglass separator, providing longer lifespan and higher vibration resistance.

C. Advantages:

- *Low cost* – are among the most affordable rechargeable batteries;
- *Overload tolerance* – can provide high current over short periods, being ideal for starting engines;
- *Robustness* – performs well in conditions of intense use and have a long lifespan;
- *High recyclability* – components are easy to recycle, helping to reduce toxic waste.

D. Disadvantages:

- *Heavy weight* – lead is a heavy metal, which makes these batteries to be massive;
- *Limited storage capacity* – compared to other modern batteries (Li-ion, NiMH), lead-acid batteries have lower energy density;
- *Maintenance* – some types require periodic replenishment with water;
- *Limited lifespan* – are sensitive to deep discharge cycles and have shorter lifespan than other types of rechargeable batteries.

E. Common usages:

- *Automobile* – are widely used for starting engines and powering basic electrical systems;
- *Energy storage in solar and wind systems* – due to low cost and stability;
- *Backup systems and UPS (Uninterruptible Power Supply)* – provides energy in case of supply interruption.

F. The future of Lead-acid batteries:

Although alternatives lighter and with higher energy densities (such as lithium batteries) are being developed, lead-acid batteries continue to be used due to low cost and mature technology.

In addition, there is research to improve their performance, such as increasing discharge cycles and the development of lead-carbon batteries, which combines the advantages of lead with rapid charging capabilities.

These batteries are an affordable and reliable solution for many applications, despite the limitations compared to other modern technologies. [10-14]

3. CONCLUSIONS

Electrochemical batteries play a crucial role in modern energy systems by enabling efficient storage and controlled release of electrical energy. Through reversible chemical reactions, they convert electrical energy into chemical energy during charging and back into electricity during discharge, making them essential for portable electronics, electric vehicles, and renewable energy integration.

Advancements in battery technologies – such as lithium-ion, solid-state, and flow batteries – have significantly improved energy density, efficiency, and lifespan. These improvements are key to supporting the transition toward sustainable energy, especially by stabilizing intermittent sources like solar and wind power.

However, challenges remain, including high production costs, limited raw material availability, environmental concerns related to disposal and recycling, and safety risks. Addressing these issues through innovation in materials science, recycling technologies, and battery design will be essential for long-term sustainability.

In conclusion, electrochemical batteries are indispensable for the future of energy storage, offering a bridge between energy generation and consumption. Continued research and development will further enhance their performance, affordability, and environmental compatibility, solidifying their role in a cleaner and more resilient energy landscape.

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