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Overview of Battery Systems

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1.1 Introduction

The challenge of how to store energy is greater than ever due to current technological advances and the increasing mobility of society. Solar, wave, wind, and other energy sources are the main sources of renewable energy [1]. Before reaching the user, energy must go through several stages, including production, transport, and storage, regardless of its origin. For energy to be transported and used where and when required, efficient energy storage systems are mandatory [2]. One of the main energy storage systems, based on the transformation of chemical energy into electrical energy, is batteries [3].

A battery is an electrochemical device that uses reversible oxidation–reduction reactions to store and supply energy, transforming chemical energy into electrical energy and vice versa [4]. Batteries are typically classified into primary and secondary batteries. Primary batteries are devices that cannot be recharged when their energy runs out. On the other hand, secondary batteries can be recharged several times [5]. The basic components of a typical battery are the anode, the cathode, and an electrolyte, and its operation is based on reversible electrochemical reactions through the process of charging and discharging, as shown schematically in Figure 1.1 for a graphite-based anode and a lithium-based cathode [6].

Alessandro Volta created the first battery in 1800, commonly referred to as a voltaic cell. It was based on electrodes composed off zinc and copper and a cloth soaked in saline was used as a separator [7]. Significant progress has been achieved in battery technology since the voltaic cell's creation, including improved electrode materials, cell designs, and electrolyte formulation improvement, among others [8, 9].

Lead-acid (Pb-Ac), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), lithium-ion (Li-ion), and sodium-ion (Na-ion) batteries are the most widely used types in toys, smartphones, and other portable smart devices, including electric and hybrid vehicles, and renewable energy storage systems [10]. The specific energy and energy density values

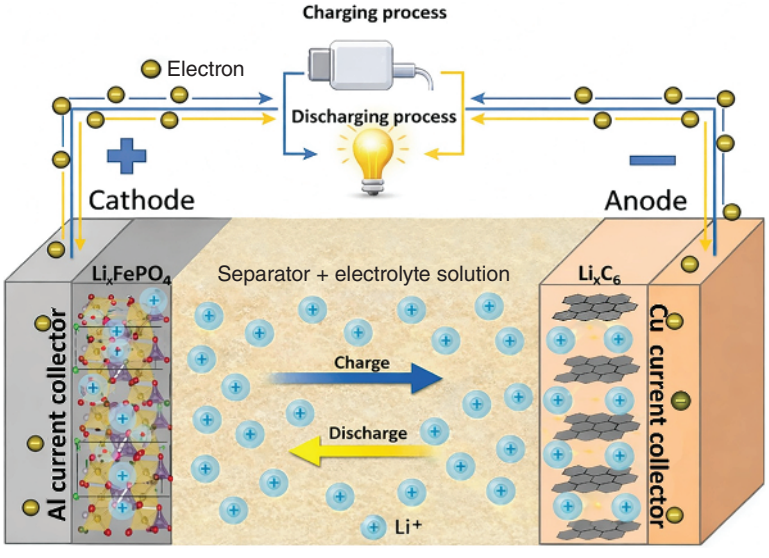


Figure 1.1 Schematic representation of the battery components and the corresponding charging and discharging processes.

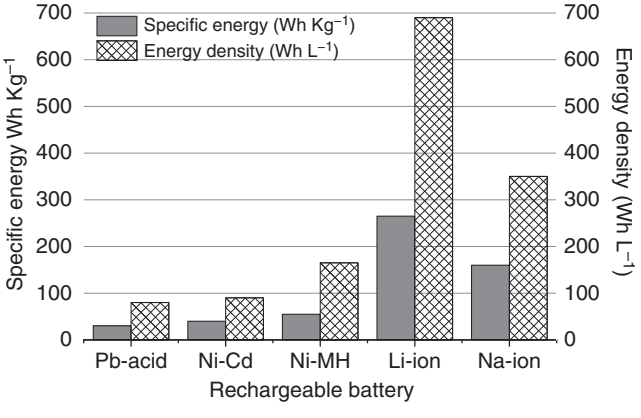


Figure 1.2 Specific energy and energy density values for different rechargeable battery systems.

for the different battery systems, which determine performance and, therefore, potential applications, are shown in Figure 1.2. It is shown that the highest performance parameter values are obtained for lithium-ion batteries (LIBs), a technology developed in the 20th century [11].

Because of its unique electrochemical properties, Li-ion technology currently dominates the market. LIBs offer a higher cell voltage of about 3.7 V, whereas Pb-Ac batteries often run at a nominal voltage of about 2.0 V, and Ni-MH and Ni-Cd systems produce about 1.2 V [12]. The high gravimetric and volumetric energy densities needed for current mobile applications are made possible by the high voltage capabilities, which directly lead to increased power output and efficiency. The main characteristics of the different battery systems are presented in the following section.

1.2 Key Performance Metrics and Types of Batteries

Regardless of the battery type, Figure 1.3 shows some of the main required attributes, the most important being energy density and power density. Energy density or capacity is defined by the energy per cell weight or volume, whereas specific power (or power density) is described by power per cell mass.

The capacity is the total charge that can be discharged from a fully charged battery under specified conditions and represents the product of current and time. Its unit of measurement is Ah (ampere-hour).

The power (P) can be calculated as $P = VI$, where V = cell voltage and I = cell current (or rate), since $V = IR$, $P = I^2R$, and $P = V^2/R$.

Beyond these essential battery parameters, there are others, such as state of charge (SoC), state of health (SoH), and state of temperature (SoT), which are crucial in battery management technologies, in which monitoring SoC and SoH are relevant for improving reliability and ensuring the safety of the battery system [13]. The relationship between the remaining capacity and the maximum capacity of a battery is known as SoC [14]. The SoC value ranges from 0 to 100%. A battery is fully charged when its SoC is at 100% and completely discharged when its SoC is at 0%. Ideally, batteries should operate in the SoC range of 20–80% to avoid overdischarge [15].

Additionally, the ratio of the current maximum capacity to the nominal (or initial) capacity can be used to quantify the battery's SoH. In order to identify battery failures, SoH monitoring must be assessed and examined over an extended period of time [16, 17].

Pb-Ac, Ni-Cd, Ni-MH, Li-ion, and Na-ion batteries are among the battery types in which these properties are relevant and can be evaluated. Considering Pb-Ac batteries, they are composed of lead dioxide at the anode and a matrix lead at the cathode. The electrolyte may be a gel with a pressure-regulating valve or a liquid (distilled water and sulfuric acid) [18]. In general, this battery type is used in power grid stabilization, starting systems in internal combustion engine vehicles, energy management, and other applications. Pb-Ac batteries represent a well-studied, low-cost, recyclable technology that allows for deep charging, tolerates intensive use, and has a low self-discharge rate. However, it has some disadvantages, such as being heavy, having low power density, a short lifespan, and not allowing for fast recharging [19].

A potassium hydroxide electrolyte, a nickel hydroxide cathode, and a cadmium anode constitute Ni-Cd batteries. These batteries show good performance at different temperatures, have a long lifespan, tolerate peak power loads and deep discharges, and are

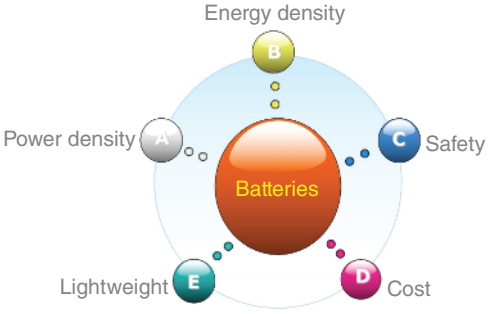


Figure 1.3 Key attributes of batteries.

characterized by minimal internal resistance, among other advantages. However, it is an expensive technology with a high environmental impact due to the usage of cadmium and severe self-discharge, and it presents a significant memory effect, among other issues [20]. Generally associated with energy storage and management, portable devices, and backup systems, Ni-MH batteries consist of a metal hydride cathode and a nickel hydroxide anode. They can be considered an advancement over Ni-Cd batteries. They do not use cadmium, show better energy density, and do not exhibit memory effect. However, they show longer charging times, shorter lifespan, higher self-discharge rates, and less tolerance for extreme operating conditions [21].

Finally, Li-ion technology, which presents the greatest potential and widespread use in a wide range of applications, has a relatively low self-discharge rate, typically less than 5% per month, allowing for effective energy retention over extended periods of inactivity, a distinct advantage over nickel-based predecessors [22, 23]. The fundamental operation of these systems relies on the "rocking-chair" or "shuttle" principle, where lithium ions act as the primary charge carriers, reversibly migrating between two intercalation electrodes during charge and discharge cycles [24].

In a standard cell architecture, the positive electrode (cathode) typically comprises lithium-hosting transition-metal oxides, such as lithium cobalt oxide ($LiCoO_2$; LCO) or lithium iron phosphate ($LiFePO_4$; LFP), while the negative electrode (anode) is predominantly composed of graphitic carbon. During the charging process, an applied voltage drives the migration of Li^+ ions from the cathode, through an electrolyte, to the anode where they are stored, while electrons flow through the external circuit. Conversely, during discharge, the stored ions are released back to the cathode, generating the electron flow that powers external devices [25]. Critical to this operation is the electrolyte, which in conventional batteries is typically a liquid solution comprising lithium salts, such as $LiPF_6$, dissolved in a mixture of organic carbonate solvents like ethylene carbonate (EC), dimethyl carbonate (DMC), and diethyl carbonate (DEC) [26]. These solvents are selected to balance high dielectric constants, necessary for salt dissociation, with low viscosity to facilitate ion mobility [27]. Additionally, the separator plays an essential role in physically isolating the anode from the cathode to prevent short circuits while maintaining porosity for ion transport, often relying on polymers such as polyethylene (PE) and polypropylene (PP) [28].

Despite the prevalence and success of LIBs, conventional architectures face inherent physicochemical limitations and safety challenges that drive ongoing research. A primary concern is the flammability of liquid organic electrolytes, which renders these batteries susceptible to thermal runaway, fire, and potential explosion if exposed to mechanical, electrical, or thermal abuse [29–31], with strong efforts being devoted to the development of solid electrolytes to successfully address those issues. Furthermore, the energy density of conventional LIBs is approaching its theoretical ceiling. The specific capacity of the standard graphite anode is limited to approximately 372 mAh g^{-1}, which is insufficient to meet the escalating demands for extended driving ranges in electric vehicles and high-capacity grid storage [32–34]. Consequently, the field is actively exploring alternative chemistries and configurations. This includes the development of lithium-metal batteries (LMBs), which utilize metallic lithium anodes to achieve theoretical capacities exceeding 3860 mAh g^{-1} [35, 36], and lithium-sulfur (Li-S) batteries, which promise high gravimetric energy densities through conversion reaction mechanisms rather than simple intercalation [37].

LIBs offer several notable advantages, such as high operating voltage, long cycle life, and superior energy density. Owing to these characteristics, they have become the dominant energy storage technology for a wide range of applications, including portable electronics, electric vehicles, and large-scale energy storage systems. Nonetheless, the scope of battery technology is expanding beyond lithium. Concerns regarding the scarcity and cost of critical raw materials like cobalt and lithium have catalyzed research into post-lithium systems, utilizing earth-abundant elements such as sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), and aluminum (Al) [25]. These alternative ion batteries share similar working principles with established intercalation technologies but rely on different charge carriers, offering potential pathways toward more sustainable and cost-effective energy storage solutions [38]. Simultaneously, structural innovations are emerging, such as solid-state electrolytes (SSEs), which replace flammable liquids with nonflammable ceramics or polymers to enhance safety and enable the use of high-capacity metal anodes [25, 39]. To establish a foundation for understanding SSEs in LMBs, it is first essential to examine the general electrolyte requirements for these systems. Subsequently, the discussion can focus on the specific types of SSEs used in LMBs. In the design of all-solid-state lithium metal batteries (ASSLMBs), *performance* and *safety* remain the primary evaluation criteria. Therefore, to fulfill these objectives, the electrolyte must exhibit high ionic conductivity (σ), an elevated Li-ion transference number (t^+), excellent interfacial contact with the electrodes, and robust mechanical strength to suppress lithium dendrite growth. Additionally, cost-effective manufacturing and wide electrochemical stability window are required.

The evolution of battery technology also covers innovative form factors or paper-based batteries for disposable diagnostics and flexible electronics, highlighting the versatility of electrochemical storage [40]. As the demand for energy storage continues to diversify, understanding the fundamental principles, operational mechanisms, and limitations of conventional batteries remains essential for contextualizing the transition toward these advanced, next-generation energy storage landscapes.

The most stable and commercially available technology besides lithium is Na-ion batteries, since sodium, the fourth most abundant element on Earth, shares chemistry with lithium, offering high stability and low toxicity, and is found in many low-cost minerals around the world [41]. In 2025, sodium carbonate was priced at ~180–188$/ton, compared to 9000–12 000$/ton for lithium carbonate [42–44]. Hence, sodium has emerged as the most promising element for next-generation ion batteries (Na-ion batteries) in efficient stationary applications for renewable energy storage, as well as in electrical cars, aiming to reduce fossil fuel dependency [45].

Na-ion batteries were developed alongside LIBs in the 1970s and 1980s, but were eclipsed by the commercial success and energy/power ratings of the latter [46]. Although substantial gains have been made since the first investigations, especially since 2010, as indicated by the exponential growth in research papers [47, 48], the implementation of Na-ion batteries in large-scale electrical energy storage (EES) systems still requires further developments, particularly in terms of energy cost and performance. Research has concentrated on identifying appropriate materials (electrodes, electrolytes) for this battery technology while taking cost, associated impacts (toxicity, recyclability, environmental impact), and efficiency into account [49–52].

Electrolytes are critical for battery safety, lifetime, and performance, as well as for sustainability of Na-ion batteries, impacting the solid/electrolyte interface (SEI) layer and the

stability of the active material. Organic electrolytes offer a large stability window (1.5–4.25 V vs. 1.0–1.5 V) and higher energy densities (150–300 Wh kg^{-1} vs. ≤100 Wh kg^{-1}), and for these types of batteries, the issue is the replacement of liquid electrolytes with solid electrolytes [50]. Even higher energy density can be attained by utilizing SSEs [53], demonstrating a wide range of working voltages, higher safety, and excellent mechanical qualities. However, few studies on Na-ion batteries have been reported with this focus, and various challenges remain before their widespread adoption [54]. The environmental impact of the electrode materials and their production methods is another important factor in the development of sustainable battery technologies.

Overall, Na-ion technology has already started to enter the market, showing great promise with a variety of technological potential improvements, and may be the way of the future for a number of applications [55].

1.3 Battery System Components and Battery Management System

The architecture of a battery system depends on the cells, modules, and battery packs, as shown in Figure 1.4. A battery module is a collection of several cells connected in parallel or series and frequently enclosed in a protective casing, whereas a cell is a single electrochemical unit [56]. Furthermore, a battery pack is an assembly of battery modules along with additional parts like thermal management and a battery management system (BMS) [57]. Furthermore, in a battery module or pack, the capacity and voltage values can be tailored by connecting the cells in parallel and in series, respectively. Furthermore, inhomogeneities in batteries are a known concern that impacts performance and safety. Variations and inhomogeneities between cells occur prior to module assembly due to differences in chemical composition, materials, processing, cell form, connectors, and aging circumstances. This necessitates a variety of tests at different scales to confirm inhomogeneous deterioration [58, 59].

In addition to the cell, module, or pack, the BMS, the thermal management system, and the power electronics are key elements in battery systems.

Power, energy density, and reliability are directly impacted by battery aging, and thermal cooling in battery module design is essential for safety and delay aging [60]. Battery module design can also improve performance. Thus, a battery module with cell supports at various heights helps to properly address thermal runaway and improve lifespan. These supports work as a tray to accept the battery cells and act as fins, enhancing the consistent distribution of temperature within the module [61].

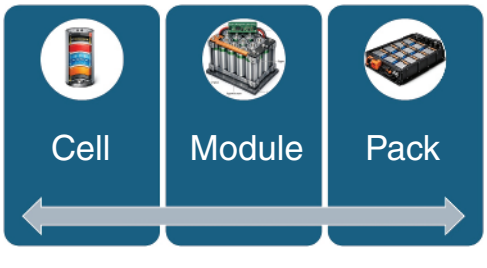


Figure 1.4 Key components of a battery system.

An ideal battery design should be able to maintain cell temperatures within the most favorable range, i.e., 25–40 °C, with a temperature difference in each cell of no more than 5 °C [62].

The BMS, which is made up of various blocks, including control unit, communication, battery status assessment, data collecting, safety protection, and thermal management, is essential to guarantee efficiency, longevity, and safety of batteries [63]. A correctly operating BMS is crucial as it manages different aspects of the battery, such as SoC and SoH, assuring battery safety.

The BMS can be configured in a variety of ways based on the application and how it responds to both internal and external events.

To enhance performance with operational and protective capabilities, the BMS's behavior needs to be thoroughly evaluated in the overload/overdischarge test procedure. During this phase, the BMS automatically disconnects the primary contactors to stop the overload/overdischarge current and inhibits its active load control function [64].

The BMS gives battery packs protection, optimal operating conditions, and precise battery status prediction, including lifespan and charge [65].

Finally, real-time optimization might be made possible by integrating machine learning into balancing procedures, which would further increase system dependability, efficiency, and battery life [66].

In order to alter balancing priorities in real time based on operational conditions, future balancing techniques could make use of multiparameter frameworks that combine critical states like SoC, SoH, state of power (SoP), and SoT [67].

1.4 Applications and Life Cycle Assessment

Battery devices are an essential component of a wide range of current applications, each with specific needs for power, energy density, and safety, as represented in Figure 1.5. The most popular applications, based on different battery systems, are depicted in Figure 1.5.

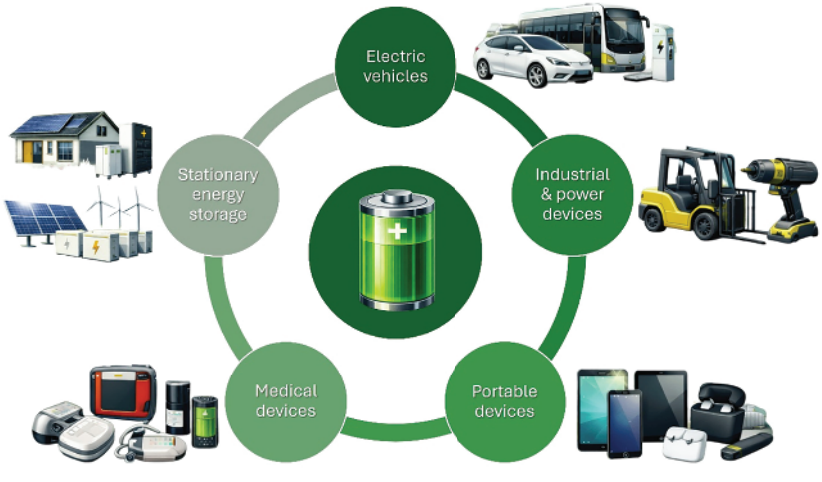


Figure 1.5 Applications of battery systems.

Electric vehicles, which require high power and energy density to ensure range and acceleration, are among the most relevant applications. Depending on the vehicle type, current capacity ranges from approximately 20 kWh to over 100 kWh, focusing also on improved safety and thermal management [68].

In industrial and power devices, batteries are implemented in wireless tools, specialized equipment, forklifts, and heavy machinery, which require high power for short periods of time [69].

With typical capacities ranging from a few watt-hours (Wh) to 100 Wh, battery systems are also used in wearable and portable electronics like smartphones, laptops, and smartwatches. In these cases, lightweight design and high energy density are given priority [70]. Furthermore, wearable and medical devices that need a high degree of flexibility, biocompatibility, and dependability also rely on battery systems [71].

Furthermore, stationary energy storage also relies on batteries to assist the integration of renewable energies, such as solar and wind, allowing frequency management, peak demand reduction, and backup power supply. Batteries are also used to supply backup power and stabilize the electrical system. These systems are measured in kilowatt-hours (kWh), megawatt-hours (MWh), or even gigawatt-hours (GWh) and prioritize longevity and safety over gravity energy density considerations [72].

From a sustainability viewpoint, life cycle assessment (LCA) represents a relevant method for analyzing the environmental impact of battery technologies, being divided into three stages, as shown in Figure 1.6 [73]. As illustrated in Figure 1.6, LCA considers materials extraction and processing, manufacturing emissions, operational efficiency, and end-of-life treatment, among other relevant parameters.

Recycling and reuse strategies are essential to boost sustainability and cut expenses. While sophisticated recycling techniques seek to recover valuable materials with the least amount of environmental impact, reusing batteries from a variety of applications can increase their lifespan [74, 75].

It is essential to incorporate the circular economy's principles from battery design, with a focus on recyclability, modularity, and the use of easily recoverable and nontoxic materials.

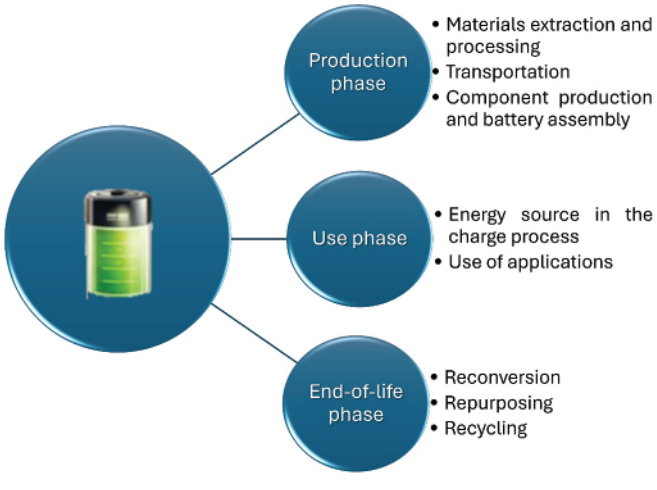


Figure 1.6 Different phases of battery life cycle assessment.

Direct and electrochemical recovery are examples of scalable recycling techniques that should be developed concurrently with battery innovation, backed by industrial-scale demonstrations, and tailored to the unique difficulties of each chemistry [76]. Future battery systems will continue to be developed and will include, from the outset, material recovery, adaptability, and technological transparency.

1.5 Conclusions and Future Directions

Nowadays, the most effective energy storage systems are battery systems, which can range from single cells to arrays based on several battery types with advanced thermal and management systems.

An overview of battery systems has been provided in this chapter, addressing different battery types, relevant functional characteristics, materials, and applications, together with the relevant issue of sustainability.

Despite the advances this area has achieved in recent years, battery systems still confront some major hurdles that limit their performance and cost-effectiveness. This field takes advantage of ongoing developments in electronics and materials research to broaden its scope and address the energy issue. Increasing energy density through the development of novel materials and the resolution of safety issues by reducing the possibility of thermal runaway are just two of the issues that require improvement. To enhance battery performance, a deeper comprehension of electrode cracking, lithium metal deposition, and degradation mechanisms is also required.

Reducing the production cost of batteries, especially for large-scale and electric vehicles applications, is also critical for wider acceptance, as is the development of new technologies to minimize the time necessary to fully charge a battery without degrading the materials, which is essential for many applications.

Considering resource and sustainability concerns, particularly the dependence on crucial elements such as lithium, cobalt, and nickel, it is necessary to design more sustainable battery systems.

Furthermore, the improvement of and further studies on advanced batteries, such as Li-S batteries, are crucial to improve energy density, presenting promise for electric vehicles with better range. Further, solid-state batteries are crucial to boosting safety by reducing the possibility of heat leakage by substituting liquid electrolytes with solid electrolytes, which also promise higher energy densities and faster charging times.

Additionally, given the abundance of sodium, Na-ion batteries should be used in place of LIBs whenever possible to improve sustainability. For grid-scale storage, when weight and volume are less of an issue, this chemical composition provides a viable and less expensive substitute for Li-ion.

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