# Introduction to Batteries and Energy Storage

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***Abstract***

In an era marked by escalating energy demands and a growing emphasis on sustainable solutions, the role of batteries and energy storage has emerged as pivotal. This introductory chapter delves into the fundamental concepts of batteries and energy storage systems, elucidating their significance in modern society. The chapter commences by elucidating the underpinnings of energy storage and its relevance across various sectors, from portable electronics to renewable energy integration. A comprehensive overview of battery types, encompassing chemical composition, working principles, and common applications, is presented. This foundational exploration encompasses primary and secondary batteries, lithium-ion batteries, lead-acid batteries, and emerging technologies like solid-state batteries. Furthermore, the chapter discusses key considerations in battery design, such as capacity, voltage, and efficiency, along with the challenges posed by factors like self-discharge and cycle life. The discourse extends to energy storage systems beyond batteries, including supercapacitors, flywheels, and compressed air systems, elucidating their unique attributes and deployment scenarios. Throughout the chapter, an emphasis on the evolving landscape of energy storage, characterized by innovations and sustainability imperatives, serves as a guiding thread. As the global pursuit of efficient, reliable, and eco-conscious energy solutions escalates, this chapter sets the stage for an in-depth exploration of batteries and energy storage systems, setting the tone for the subsequent chapters' deeper analyses and applications.

## 1. Introduction

The integration of renewable energy sources, increasing electrification, and sustainable energy solutions have led to a growing need for efficient energy storage systems. These systems play a crucial role in bridging the gap between energy generation and demand, facilitating grid stability, enhancing the utilization of intermittent renewable sources, and ensuring a reliable power supply. As the world grapples with reducing greenhouse gas emissions, transitioning to cleaner energy sources, and mitigating climate change impacts, energy storage systems play a vital role in shaping the future of sustainable energy. This review explores the principles, applications, challenges, and recent advancements of energy storage systems, focusing on established technologies and emerging innovations. It also addresses the environmental impact, resource availability, and economic feasibility of energy storage systems, examining factors such as material sourcing, manufacturing processes, and end-of-life disposal. The insights provided in this review can inform decision-makers, researchers, and practitioners, fostering the development and deployment of energy storage systems that contribute to a resilient and cleaner energy future [1].

The rapid growth of global electricity generation over the past three decades has predominantly relied on conventional sources such as fossil fuels, contributing to approximately 76% of the total global electricity production in 2016. In India, during the fiscal year 2016-17, both utilities and non-utilities contributed to a total electricity generation of 1433.4 TWh, prompting a need for more sustainable energy generation methods due to environmental concerns. The adoption of renewable energy sources like solar and wind energy addresses these environmental issues, but their intermittent nature poses challenges for maintaining a stable and reliable energy supply. To address these challenges, Electrical Energy Storage (EES) technology has emerged as a promising solution. EES involves converting electrical energy into a storable form and then converting it back into electrical energy as needed. This technology plays several crucial roles within power systems, including meeting peak load demands, managing time-varying energy requirements, enhancing the intermittence of renewable energy generation, improving power quality and reliability, addressing remote area and vehicle load demands, contributing to the development of smart grids, and aiding in power distribution and standby power generation management. Researchers and scientists have extensively studied EES technology, offering various reviews and experimental reports on its development and application across industries. Notable papers have discussed energy storage for power system enhancement, progress in electrical energy storage technology, actively controlled battery-capacitor hybrid models, superconducting magnetic energy storage, and large-scale electrical energy storage systems. However, despite technological advancements in EES, challenges remain in deploying and installing these techniques effectively. These challenges include selecting the most suitable EES system for specific power system requirements, accurately evaluating the technical and economic benefits of EES systems, and reducing installation costs to an acceptable level [2].

## 2. Role of batteries as a key energy storage solution.

Batteries are essential for maintaining power backup systems and ensuring grid stability. They possess flexibility and can be adjusted in terms of location and scale as needed. Batteries can also absorb energy and function as a fast-acting load, which helps manage the balance between power supply and demand.

Battery Energy Storage System is generally installed to improve reliability in the power grid system, to increase the integration of various energy resources to the grid and to match between power generation supply and load demand in order to enable power operating system more stable and reliable. In power system network, Battery Energy Storage System has ability to do a quick response for regulating the grid frequency caused by some interference. For dealing with such interferences the utilities have applied a defiance scheme mechanism to prevent the gird blackout due to a rapid change of the frequency for a while. Some defence Scheme indicators within Battery Energy Storage System at a substation has been assessed through a software modelling. The results show that Battery Energy Storage System at Substation is able to increase the reliability of grid by such frequency regulation.

Battery energy storage systems have been broadly accepted as one of the potential solutions, with advantages such as fast response capability, sustained power delivery, and geographical independence. During the implementation of battery energy storage systems, one of the most crucial issues is to optimally determine the size of the battery for balancing the trade-off between the technical improvements brought by the battery and the additional overall cost. Numerous studies have been performed to optimise battery sizing for different renewable energy systems using a range of criteria and methods.

Requirements for automotive batteries have been increasing significantly for a number of years, particularly due to the integration of more and larger loads into vehicle electrical systems. In addition, fuel saving measures is being considered that actively utilize the battery. The battery is used as a buffer, and continuous overcharge is avoided. On the other hand, such measures involve different levels of power train hybridization, including micro, mild/medium, and power-assist/full hybrid electric vehicles (HEV). The requirements associated with any of these HEV system configurations necessarily involves a fundamental shift in the nature of the energy storage system requirements away from those traditionally considered for lead/acid SLI battery application usage.

## 3. Types of Batteries

### 3.1 Lithium-ion batteries for portable electronics and electric vehicles.

Batteries are crucial components in consumer goods such as phones and laptops, in essential medical and industrial applications needing mobile and backup power supplies, the storage of renewable energy such as solar, and in Electric Vehicles (EVs).

Improved energy density, discharge tolerance, cycle life, re-charge times with a low memory effect are some of the key advantages that make Lithium-ion batteries a favourite for use in EV applications. Figure 3.1 shows a volumetric versus gravimetric energy density comparison of lithium-ion batteries compared to some other rechargeable batteries. Advantages in both of these metrics permit use of smaller and lighter battery packs and hence improve the driving range. The most favourable battery technologies which can closely fulfil the minimum goals of the United States Advanced Battery Consortium (USABC) for commercialisation of EVs are the lithium-ion batteries. Although there are various types of lithium-ion batteries have been widely used to power the EVs, the performance characteristics of these batteries are not clearly specified in a more comparable way.


Figure 3.1 Lithium-ion Battery

The rechargeable lithium-ion batteries have transformed portable electronics and are the technology of choice for electric vehicles. They also have a key role to play in enabling deeper penetration of intermittent renewable energy sources in power systems for a more sustainable future. A modern lithium-ion battery consists of two electrodes, typically lithium cobalt oxide (LiCoO2) cathode and graphite (C6) anode, separated by a porous separator immersed in a nonaqueous liquid electrolyte using LiPF6 in a mixture of ethylene carbonate (EC) and at least one linear carbonate selected from dimethyl carbonate (DMC), diethyl carbonate (DEC), ethyl methyl carbonate (EMC) and many additives. During charging, Li-ions move from the LiCoO2 lattice structure to the anode side to form lithiated graphite (LiC6). During discharging, these ions move back to the CoO2 host framework, while electrons are released to the external circuit. It is this shuttling process or what is called rocking-chair chemistry that has revolutionized our modern life.

To avoid safety issues of lithium metal, Armand suggested to construct Li-ion batteries using two different intercalation hosts. The first Li-ion intercalation-based graphite electrode was reported by Besnard showing that graphite can intercalate several alkali-metal ions including Li-ions4. Graphite intercalates Li-ions based on a layered structure with half-filled pz orbitals perpendicular to the planes that can interact with the Li 2s orbitals to limit volume expansion and dendrite growth[2].

Lithium-ion batteries as a power source are dominating in portable electronics, penetrating the electric vehicle market, and on the verge of entering the utility market for grid-energy storage. Depending on the application, trade-offs among the various performance parameters—energy, power, cycle life, cost, safety, and environmental impact—are often needed, which are linked to severe materials chemistry challenges. The current lithium-ion battery technology is based on insertion-reaction electrodes and organic liquid electrolytes. With an aim to increase the energy density or optimize the other performance parameters, new electrode materials based on both insertion reaction and dominantly conversion reaction along with solid electrolytes and lithium metal anode are being intensively pursued. The cell produces electrical energy through a chemical electrolysis process. It can constitute around 70% of the total cost of a battery back. A liquid electrolyte, such as one based on LiPF6, is commonly used.

Lithium-ion battery fast charging is critical to save time and minimize its impact on the utility grid. The goal of this paper is twofold: first, to create a proof-of-concept Simulink model for EV fast chargers; second, to highlight several shortcomings in present fast charger technology. The suggested technique employs PWM rectifiers on the grid side to provide a near-unity power factor with sinusoidal voltage and current. A buck DC-DC converter on the battery side provides the necessary charging voltage to the Lithium-ion battery.

**3.1.1 Design of Lithium-ion Battery:**

Generally, the negative electrode of a conventional lithium-ion cell is graphite made from carbon. The positive electrode is typically a metal oxide. The electrolyte is a lithium salt in an organic solvent. The anode (negative electrode) and cathode (positive electrode) are prevented from shorting by a separator. The anode and cathode are separated from external electronics with a piece of metal called a current collector. The electrochemical roles of the electrodes reverse between anode and cathode, depending on the direction of current flow through the cell. The most common commercially used anode is graphite, which in its fully lithiated state of $LiC_6$ correlates to a maximal capacity of 1339 C/g (372 mAh/g). The cathode is generally one of three materials: a layered oxide (such as lithium cobalt oxide), a polyamine (such as lithium iron phosphate) or a spinal (such as lithium manganese oxide). More experimental materials include grapheme-containing electrodes, although these remain far from commercially viable due to their high cost.

Lithium reacts vigorously with water to form lithium hydroxide (LiOH) and hydrogen gas. Thus, a non-aqueous electrolyte is typically used, and a sealed container rigidly excludes moisture from the battery pack. The non-aqueous electrolyte is typically a mixture of organic carbonates such as ethylene carbonate and propylene carbonate containing complexes of lithium ions. Ethylene carbonate is essential for making solid electrolyte interphase on the carbon anode, but since it is solid at room temperature, a propylene carbonate solvent is added [3].

## 3.2 Lead-acid batteries for automotive and backup power

The lead–acid battery is a type of rechargeable battery first invented in 1859 by French physicist. It is the first type of rechargeable battery ever created. Compared to modern rechargeable batteries, lead–acid batteries have relatively low energy density. Despite this, their ability to supply high surge currents means that the cells have a relatively large power-to-weight ratio. These features, along with their low cost, make them attractive for use in motor vehicles to provide the high current required by starter motors. Lead-acid batteries suffer from relatively short cycle lifespan (usually less than 500 deep cycles) and overall lifespan (due to the "double sulfation" in the discharged state), as well as slow or long charging time.

As they are inexpensive compared to newer technologies, lead–acid batteries are widely used even when surge current is not important and other designs could provide higher energy densities. In 1999, lead–acid battery sales accounted for 40–50% of the value from batteries sold worldwide (excluding China and Russia), equivalent to a manufacturing market value of about US$15 billion. Large-format lead–acid designs are widely used for storage in backup power supplies in cell phone towers, high-availability emergency power systems like hospitals, and stand-alone power systems. For these roles, modified versions of the standard cell may be used to improve storage times and reduce maintenance requirements. *Gel-cells* and *absorbed glass-mat* batteries are common in these roles, collectively known as VRLA (valve-regulated lead–acid) batteries. In the charged state, the chemical energy of the battery is stored in the potential difference between metallic lead at the negative side and $PbO_2$ on the positive side. Most of the world's lead–acid batteries are automobile starting, lighting, and ignition (SLI) batteries, with an estimated 320 million units shipped in 1999. In 1992 about 3 million tons of leads were used in the manufacture of batteries. Wet cell stand-by (stationary) batteries designed for deep discharge are commonly used in large backup power supplies for telephone and computer centres, grid energy storage, and off-grid household electric power systems. Lead–acid batteries are used in emergency lighting and to power sump pumps in case of power failure.

Traction (propulsion) batteries are used in golf carts and other battery electric vehicles. Large lead–acid batteries are also used to power the electric motors in diesel-electric (conventional) submarines when submerged, and are used as emergency power on nuclear submarines as well. Valve-regulated lead–acid batteries cannot spill their electrolyte. They are used in back-up power supplies for alarm and smaller computer systems (particularly in uninterruptible power supplies; UPS) and for electric scooters, electric wheelchairs, electrified bicycles, marine applications, battery electric vehicles or micro hybrid vehicles, and motorcycles. Many electric forklifts use lead–acid batteries, where the weight is used as part of a counterweight. Lead–acid batteries were used to supply the filament (heater) voltage, with 2 V common in early vacuum tube (valve) radio receivers.

Lead–acid batteries shown in figure 3.2 are designed for starting automotive engines are not designed for deep discharge. They have a large number of thin plates designed for maximum surface area, and therefore maximum current output, which can easily be damaged by deep discharge. Repeated deep discharges will result in capacity loss and ultimately in premature failure, as the electrodes disintegrate due to mechanical stresses that arise from cycling. Starting batteries kept on a continuous float charge will suffer corrosion of the electrodes which will also result in premature failure. Starting batteries should therefore be kept open circuit but charged regularly (at least once every two weeks) to prevent sulfation. Starting batteries are of lighter weight than deep-cycle batteries of the same size, because the thinner and lighter cell plates do not extend all the way to the bottom of the battery case. This allows loose disintegrated material to fall off the plates and collect at the bottom of the cell, prolonging the service life of the battery. If this loose debris rises enough it may touch the bottom of the plates and cause failure of a cell, resulting in loss of battery voltage and capacity.


Fig 3.2 Lead Acid Battery

## 4. Emerging technologies like solid-state and sodium-ion batteries.

Solid-State Batteries: Solid-state batteries are a promising next-generation battery technology that replaces the traditional liquid electrolyte found in lithium-ion batteries with a

### 4.1 solid-state electrolyte.

They offer several advantages, including:

- **Improved Safety**: Solid-state batteries are less prone to thermal runaway and fire risks compared to conventional lithium-ion batteries with liquid electrolytes.
- **Higher Energy Density**: Solid-state batteries have the potential to provide higher energy density, allowing for longer driving ranges in electric vehicles.
- **Longer Cycle Life**: They tend to have longer cycle life and improved durability, making them suitable for various applications [9].

**4.2 Sodium-Ion Batteries**: Sodium-ion batteries are another emerging battery technology that uses sodium ions instead of lithium ions for energy storage. Key attributes include:

- **Abundant Resources**: Sodium is more abundant and widely available than lithium, potentially reducing supply chain concerns.
- **Cost-Effective**: Sodium-ion batteries have the potential to be cost-effective, making them suitable for grid storage and large-scale energy applications.
- **Similar Chemistry**: They share some similarities in chemistry with lithium-ion batteries, making it easier to adapt existing technologies [10].

## 5. Battery Performance Metrics:

- **Energy Density:**

Energy Density is the amount of energy a battery contains relative to its size. Energy Density is typically measured in watt-hours per liter. Specific Energy is the amount of energy a battery contains relative to its weight and is typically measured in watt-hours per kilogram.

- **Battery Power:**

Battery power refers to the rate at which an electrical current can be moved through a battery, and it's measured in watts, or more often C-rate. The higher the power, the faster a battery can deliver its stored energy (or store incoming energy). C-rates are commonly used to describe battery power. For example, a 1C discharge rate describes the current at which the battery will discharge in 1 hour, while a battery with a 5C discharge rate, being 5 times faster, will discharge in 12 minutes (60 minutes divided by 5). The higher the C-rate, the more of a punch the battery can deliver.

- **Cycle Life:**

Battery cycle life is the number of full charge and discharge cycles a battery can achieve before its capacity level drops below 80%, which is considered a typical "end of life" for most applications. This is around the time consumers may begin to experience a difference in their battery performance. The cycle life of a battery has a direct impact on a product's performance and the consumer's perceived value of that product over time. To use an electric car as an example, if your battery is projected to last for 1,000 cycles and your driving range is 200 miles, then the life of your vehicle battery will be 200,000 miles (or longer based on the rate of performance drop off). With that said, the better the cycle life, the better the consumer experience.

- **Charge Rate Or Charge Speed:**

Charge rate or speed is how long it takes a lithium-ion battery to be recharged after use. This is often measured in time and capacity range (i.e. 20 min to charge from 10-80% capacity) or measured in C-rate, same as discharge (i.e. a 6C capable battery would charge in roughly 10 minutes). Whether powering a phone or an electric vehicle, consumers value convenience and want a battery that charges quickly. And the faster the charge rate, the faster a product will be able to get you back on the road.

## 6. Energy storage systems

Energy storage systems beyond traditional batteries represent a frontier of innovation in the quest for efficient and versatile energy storage solutions. Super capacitors, known for their high power density and rapid charge/discharge capabilities, are gaining traction in applications requiring quick bursts of energy, such as hybrid electric vehicles (HEVs) [5]. Flywheel energy storage systems, leveraging the principle of kinetic energy storage, offer remarkable reliability and longevity, making them suitable for uninterruptible power supplies (UPS) in data centers and grid stabilization [6]. Compressed air energy storage (CAES) systems are a promising solution for large-scale energy storage, with the ability to mitigate intermittent renewable energy generation and enhance grid stability [7]. These alternative technologies, as highlighted in various research papers, exemplify the diverse attributes and deployment scenarios that contribute to the resilience and sustainability of modern energy systems.

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