# Comparative analysis of battery technologies in energy systems

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**Subject**: Literary review of Battery storages for energy systems: Comparison of battery technologies

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**Abstract:**

This thesis presents a comprehensive comparison of different battery technologies from both electrochemical and automation engineering perspectives. The expanding use of renewable energy sources and the electrification of transportation have created a demand for efficient energy storage. The study covers conventional batteries like nickel-based, lead-acid, and lithium-ion, as well as new technologies including solid-state and betavoltaic batteries. Key performance parameters, like energy density, lifecycle, efficiency, and cost, are studied to evaluate their suitability for different applications. In addition, the role of automation is examined, with specific focus on battery management systems, state estimation, and thermal control.

**Key words**: Energy density, Power density, Energy storage systems

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# 1 Introduction

The structure of energy production and consumption has changed significantly over the last two decades. Traditional power generation has been centralized and is being progressively complemented by renewable and clean power sources, like wind and solar power. While these technologies do reduce pollution and greenhouse gas emissions, they introduce volatility into the power system. Wind and solar generation are inherently fitful and weather-dependent, which can create challenges for balancing supply and demand while maintaining grid stability. Electrical grids require constant balance between production and consumption, which leaves large scale integration of renewables in an increasing need for flexible energy storage solutions [1].

Energy storage systems provide a way to store surplus energy during periods of high production and release it when power generation cannot meet demand. On this basis, batteries have become one of the most widely used pieces of energy storage technologies due to their fast response times and scalability [2]. Electrification in other sectors, such as transportation, has increased the need for high-performance battery systems.

Lithium-ion batteries dominate applications like storage and electric vehicles due to their high energy density and long cycle life [3]. The widespread use and success of lithium-ion batteries has also highlighted technical challenges related to aging, safety, and thermal stability. To prevent overheating and cell imbalance, larger battery packs require continuous monitoring. As a result, modern battery systems are no longer passive energy storage devices but instead actively managed systems within a network of complex technical environments.

Battery Management Systems (BMS) play a significant role in securing safe and efficient operations. BMS are used to monitor electrical and thermal parameters while approximating different internal states, such as state of charge (SOC) and state of health (SOH). Because these internal states cannot be measured directly, they must be calculated using estimation algorithms and mathematical models. Widely adopted techniques in lithium-ion battery management include Kalman filtering and equivalent circuit modeling (ECM) [4].

Despite the success and maturity of lithium-ion technology, research advances towards next-generation battery concepts. One of the most promising of these alternatives are solid-state batteries. Replacing the liquid electrolyte with a solid polymer or ceramic based material, these solid-state systems seek to improve safety and energy density [5]. However, the introduction of solid electrolytes modifies mechanical behaviour and electrochemical interfaces, which could lead to a need  for new monitoring strategies and control system redesigns. The differences in thermal characteristics and degradation behaviour between these two technologies suggests that already established BMS architectures could need adaptation for solid-state implementation.

In comparison to electrochemical devices, betavoltaic batteries utilize a fundamentally different principle. Using semiconductor junctions, they convert the energy released from radioactive decay into electrical power. Even though they have a typically low power output, they can function for prolonged periods of time without the need for replacement or refueling [6]. These features make them appropriate for niche but important applications such as medical devices or remote self-operating sensors. Looking at them from a system integration viewpoint, their monitoring requirements are vastly different from conventional batteries, making active charging control generally not needed.

While many studies usually focus on electrochemical performance and material properties, not many works examine the different battery technologies from an automation and control perspective. The operating principles of these different technologies directly impact state estimation methods, complexity of system integration, and thermal management requirements. Therefore, a structured comparison of these battery types that considers both automation challenges and performance characteristics is necessary.

The aim of this thesis is the comparison of conventional electrochemical batteries, solid-state batteries, and betavoltaic batteries in respect of both automation related requirements and technical performance. The thesis will analyze lifecycle characteristics, energy density, and safety, while also assessing variation in system level integration, control architecture, and estimation complexity. This thesis intends to give a broader understanding of how different battery technologies can be incorporated into modern energy systems by combining automation engineering principles with technological evaluation.

# 2 Fundamentals of Battery Storage Technologies

## 2.1 Electrochemical Principles

Electrochemical batteries work by converting chemical energy into electrical energy by way of redox reactions (reduction-oxidation) happening at the two internal electrodes which are separated by an electrolyte. While the material compositions of different battery chemistries are different, the overall operating principle is similar. A battery cell consists of a cathode (positive electrode), an anode (negative electrode) and a separating electrolyte that allows ionic transfer while blocking direct electrical contact between the two electrodes.

During discharge of electricity, the anode undergoes oxidation, which releases electrons to the internal circuit. These electrons move through the connected load to the cathode, where a reduction reaction happens. Simultaneously, ions move through the electrolyte to preserve charge neutrality. The open circuit voltage of the cell is determined by the potential difference between the two electrodes. The resulting voltage can be derived from thermodynamic relationships and depends on the electrochemical potential of the active materials.

In lithium-ion batteries, lithium ions move between intercalation materials in the cathode and anode compositions. Commonly used materials for the anode and the cathode are graphite and layered metal oxides, respectively [3]. While charging, lithium ions are pushed from the cathode to the anode by an external voltage. During discharge, the process is reversed. One of the key reasons for the long cycle life and high efficiency of lithium-ion batteries is the reversible intercalation mechanism.

While solid state batteries employ the same principle of the redox reaction, the liquid electrolyte is replaced by a solid ionic conductor. This change in the battery cell’s structure affects the interface resistance, mechanical stability, and ionic conductivity [5]. Although the electrochemical reactions are similar to those in conventional lithium-ion architectures, solid state systems are introducing additional restrictions connected to the contact quality between solid phases.

Aging, temperature, and current rate are all influenced by the electrochemical processes inside a battery. The increase in internal resistance is caused by side reactions and material degradation. These effects are directly affecting the voltage behaviour under load conditions. Looking at it from an engineering standpoint, this means that the perceived battery voltage cannot be used as a simple indicator of energy stored. Batteries must be understood as dynamic systems, whose behaviour is dependent on multiple variables interacting with each other.

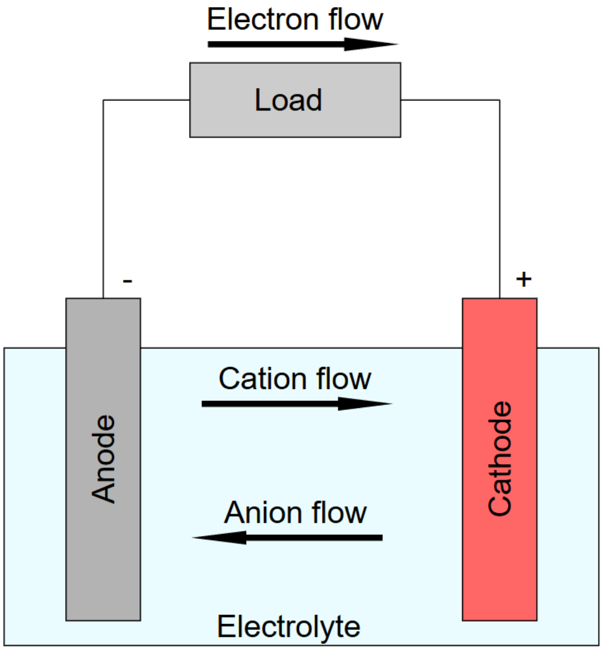

***Figure 1*** *Illustration of a basic electrochemical battery, showing the anode, cathode, and electrolyte, along with electron flow through the external circuit and ion transport within the cell.*

## 2.2 Performance Metrics

Several key performance metrics are commonly used to compare differing battery technologies. Among the most used are energy density, power density, efficiency, lifecycle, and cost.

Energy density of a battery is used to describe how much energy can be stored per unit mass (Wh/kg) or per volume (Wh/L). Higher energy density is important in portable electronics and electric vehicles, where size and weight constraints are critical. Current lithium-ion batteries are offering higher energy density than traditional and outdated lead-acid systems, explaining their widespread use in high-performance applications [3].

In contrast, power density tells us how quickly stored energy can be released. It is expressed in (W/kg) and depends on electrode kinetics and internal resistance of the system. Higher energy density batteries do not necessarily have high power density. Some chemistries designed for long term storage might not keep up with rapid discharge without significant voltage drop. In grid applications, higher power capacity is usually more important than maximum energy capacity [1].

Efficiency is usually defined as the ratio of energy delivered during discharging vs energy supplied during charging. Lithium-ion systems normally achieve high efficiencies, usually above 90% under average operating conditions [3]. However, extreme temperatures or high current rates often cause efficiency to decrease due to resistive losses.

In large scale operations, cost remains a decisive factor. The cost of a battery system is often expressed in (€/kWH). While lithium-ion costs have notably decreased over the past decade or two, manufacturing complexity and material availability influence economic viability. Although solid state batteries are looking promising in terms of energy density and safety, they currently suffer from higher production costs due to challenges in material processing [5].

It is important to understand that these performance metrics are not independent from each other. Increasing energy density can reduce thermal stability, which in turn may lead to the increased need for more advanced cooling systems. Performance assessment must be linked to system level considerations, instead of examined in isolation.

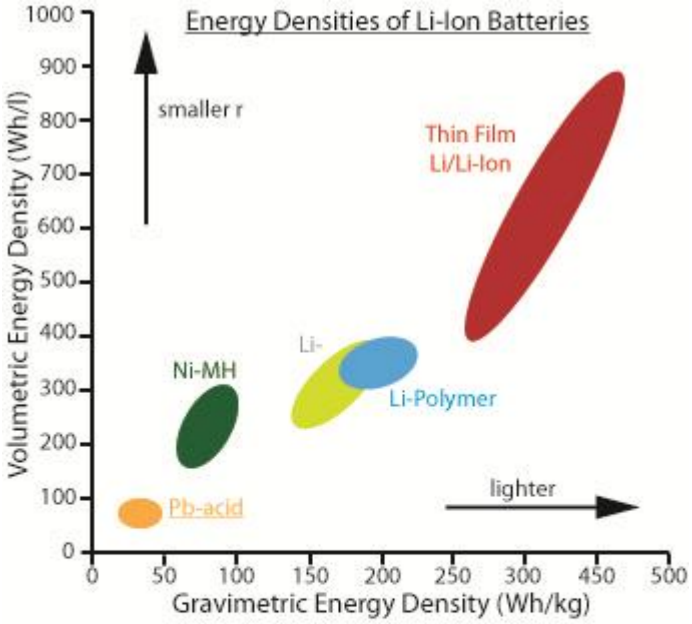

***Figure 2.*** *Ragone plot comparing volumetric and gravimetric energy densities of various energy storage technologies. Image reprinted from "Ragone plot for diff Li batteries" (public domain), Wikimedia Commons [21]*

## 2.3 Automation and Control Perspectives

While electrochemical principles explain the physical behaviour of batteries, control systems and automation dictate how efficiently and safely they are able to operate in real world applications. Modern battery systems count on Battery Management Systems (BMS) to oversee thermal, electrical, and operational variables.

A BMS is generally used to measure pack current, cell voltages, and temperatures at multiple different points within the battery pack. The measurements are utilized to keep the system protected from undervoltage, overvoltage, overcurrent, and overheating. In multi-cell arrangements, the BMS also executes cell balancing to bring down the differences in charge levels between individual cells.

Estimating the state of charge (SOC) is one of the most important duties of the BMS. Because SOC can not be measured directly, estimations of mathematical models and filtering techniques must be used. Initial strategies counted on simple coulomb counting, which integrated current over time. This method, however, accumulates errors and requires regular recalibration. More developed methods utilize equivalent circuit models combined with observers, like the Extended Kalman Filter [4]. This allows improved estimation accuracy and correction based on voltage in real time. The order and choice of the ECM can notably affect SOC estimation performance under load conditions [7]. This highlights the importance of model selection in BMS design.

Using resistors and capacitors that approximate dynamic voltage behaviour, we can use equivalent circuit modeling to represent the battery [8]. While these models are simplifications, they are used because they can offer a compromise between accuracy and computational complexity. In grid scale and automotive systems, real time constraints need estimation algorithms that can dependably operate under limited processing resources.

Besides SOC, the estimation of state of health (SOH) has become more important. SOH indicates internal resistance growth over time and capacity fade. Good SOH estimations improve overall safety and support predictive maintenance. Different model- and data-driven techniques have been suggested for this purpose [9]. Model based proposals that improve upon equivalent circuit representations, such as those assessed in [7], have been proven successful in tracking degradation by linking battery aging to changes in circuit parameters. Reliable battery health monitoring is becoming a key economic factor as battery packs are growing larger and more expensive.

Another important aspect of battery automation is thermal management. Internal resistance, aging, and reaction rates are all affected by temperature. In lithium-ion systems, extreme heat can trigger a thermal runaway reaction [3,5], which can lead to an uncontrollable rise in temperature. Because of this, BMS units are usually outfitted with cooling systems that are used to regulate temperature through forced liquid or air cooling. Spatial temperature gradients within large battery packs must be taken into account by control strategies [1,3].

Looking at it from a systems perspective, batteries exhibit time varying and nonlinear behaviour. Variables can change as the battery degrades, and performance can be influenced by external conditions. Therefore, battery control can be more complex than most traditional electrical subsystems. Sensor reliability, estimation algorithms, and accurate modeling are vital components of modern-day battery integration [4,7,8].

Summarizing, understanding of battery fundamentals requires not just knowledge of performance metrics and electrochemical reactions, but also estimation techniques and control architecture. In many safety critical and high energy implementations, automation engineering plays a vital role in making sure that theoretical battery performance can be translated to practical systems.

# 3 Conventional Battery Technologies

## 3.1 Lead-acid and Nickel Based Batteries

One of the oldest commercially successful battery technologies are lead-acid batteries. While developed in the 19th-century, they still continue to be widely used in backup power systems, starter automotive systems, and uninterruptible power systems (UPS). Operation of lead-acid batteries is based on the reversible reaction between a sponge lead at the negative electrode, a lead dioxide at the positive electrode, and a sulfuric acid electrolyte. During discharge, electrodes are converted into lead sulfate as they release electrical energy [2,10]. Regardless of their long history, lead-acid systems are still used in stationary energy storage because of their mature manufacturing infrastructure and low cost [1].

Even though the specific energy of lead-acid systems is notably lower than that of lithium-ion systems, they offer tolerance to overcharging, high recyclability, and robustness. However, lead-acid batteries suffer from weight, and limited cycle life, which limits their usage in high performance mobile systems [2,3]. The electrochemical behaviour of lead-acid batteries can lead to sulfation and stratification of the electrolyte over prolonged periods of partial SOC operations, leading to reduced performance over time [10].

From an automation standpoint, lead-acid batteries are simpler to manage. SOC estimation is often carried out using temperature compensation combined with voltage-based methods, since the open circuit voltage curve of lead-acid batteries is far more predictable than lithium-ion cells. Aging effects can introduce nonlinearities that may complicate accurate SOH estimations over long term use [4,9]. Reliable monitoring in stationary systems remains important to prevent capacity loss and making sure the system remains available.

Nickel based batteries, like nickel-metal hydride (NiMH) and nickel-cadmium (NiCd), were developed as substitutes for lead-acid systems. NiMH had lower environmental impact and increased energy density, which made them fit for early hybrid electric vehicles before the adoption of lithium-ion technology [3]. NiCd batteries provided strong tolerance to deep discharge and improved cycle life, but cadmium toxicity raised environmental concerns and restricted their widespread application [2]. Higher self-discharge rates and lower specific energy of these batteries have led to lithium-ion systems gradually replacing them in most modern applications.

## 3.2 Lithium-ion Technologies

Lithium-ion batteries are the dominant battery technology for portable electronics, electric vehicles, and are becoming increasingly used in grid-scale storage systems. The popularity of these systems is mostly due to their high round trip efficiency, high energy density, and comparatively long cycle life [3]. Additionally, material improvements in electrolyte and cathode designs have increased performance characteristics and safety [5].

Lithium-ion batteries operate by utilizing the reversible lithium-ion intercalation between the cathode and anode materials. Dissimilar to lead-acid systems, lithium-ion technology relies on ion insertion into host lattice structures instead of bulk phase transformations, allowing notably higher volumetric and gravimetric energy densities [3, 5]. While having many upsides, this intercalation mechanism also makes lithium-ion systems sensitive to temperature extremes and overvoltage, which can lead to internal short circuits, lithium plating, or thermal runaway [3].

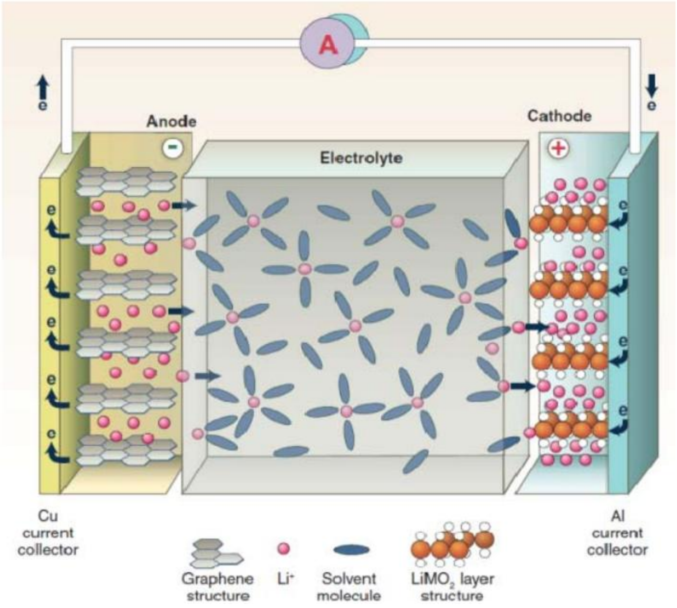

***Figure 3.*** *Cross-sectional structure of a lithium-ion battery. Reprinted from Yang et al. [19] Copyright 2012 Yang*

From an automation engineering standpoint, lithium-ion systems introduce considerable control challenges. Voltage SOC relationships of lithium-ion systems are nonlinear and temperature dependent, leading to unreliability in simple voltage-based estimation. Because of this, practical BMS implementations use model-based estimation techniques [4,8]. ECM combined with Kalman filtering approaches are often used because of their balance between estimation accuracy and computational efficiency [4,7]. Higher order resistor comparator models notably improving SOC estimation performance under dynamic load conditions have been demonstrated in comparative analyses [7,8].

Besides SOC estimation, lithium-ion systems need constant SOH monitoring since internal resistance growth and capacity fade influence safety margins and driving range. Data driven estimation methods and model-based parameter tracking have been suggested to predict remaining useful life and monitor degradation [9]. The integration of aging models into BMS algorithms is important especially in electric vehicle applications, where major economic factors are represented by battery replacement.

Because of the lithium-ion system's potential safety risks, and high energy density, thermal management has become critical. Active cooling techniques, like liquid cooling circuits and forced air cooling systems, are consistently integrated with the BMS to control temperature and block thermal runaway [3,5]. The coupling between thermal dynamics and electrochemical behaviour presents complexity into control design, which requires coordinated modeling approaches.

### 3.3 Flow Batteries, Sodium-Sulfur, and Other Stationary Systems

Although lithium-ion systems dominate most mobile applications, alternative technologies continue to be vital in stationary energy storage systems where lifetime, energy capacity, and safety are not limited by volume and weight.

Flow batteries, like vanadium redox flow batteries, use circulating liquid electrolyte to store energy. This design permits independent scaling of power output (stack size) and energy capacity (tank size), making the technology fit for grid-level storage systems [1,2]. Due to the absence of traditional solid phase structural degradation mechanisms, flow batteries offer high operational safety and long cycle life [1]. Flow batteries also exhibit lower energy density, and require pumps and controllers, which increases system complexity.

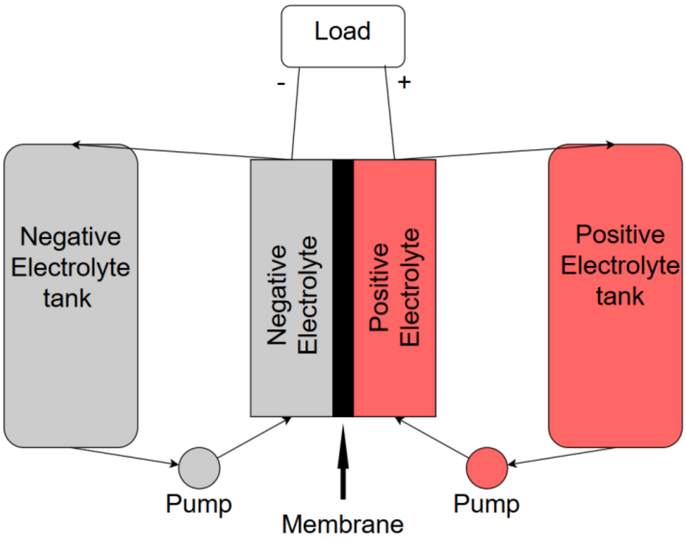

***Figure 4.*** *Simplified diagram of a flow battery system, showing external electrolyte storage tanks, pumps, and the electrochemical cell stack.*

From an automation perspective, flow battery systems are closer to chemical process plants than conventional battery packs. Electrolyte flow rate, pressure, temperature, and SOC of separate reservoirs must be regulated by control strategies, leading to multi-variable control challenges. Therefore, supervisory control and accurately integrated sensors are vital in preventing imbalance between half cells and maintaining efficiency [1].

Sodium-sulfur (NaS) systems constitute another stationary storage option. Operating at higher temperatures (often 300-350 ˚C), NaS batteries count on molten sodium and sulfur separated by a solid electrolyte. Compared to other stationary storage technologies, they yield a longer cycle life, and relatively higher energy density [2]. Because of the need to maintain a higher operating temperature, continuous thermal management and robust containment and monitoring systems are necessary. Therefore, automation systems for NaS solutions must ensure fault detection and stable thermal regulation throughout operation.

In comparison to conventional lithium-ion systems, stationary battery technologies usually prioritize cost per kWh, durability, and operational stability as opposed to fast transient response. The control designs of these stationary battery systems therefore focus on thermal stability, system level optimization, and degradation monitoring rather than rapid dynamic performance [1,2].

# 4 Solid-State Battery Technologies

## 4.1 Solid Electrolyte Materials

A promising next generation battery storage technology is represented by solid-state batteries (SSBs). In contrast to conventional lithium-ion batteries that use liquid electrolytes, SSBs employ solid ionic conductors in order to move lithium ions between the anode and the cathode. Multiple potential advantages are offered by this structural change, including increased thermal stability, improved safety, and higher energy density [5,13].

Many different kinds of solid electrolyte materials have been assessed, including polymer electrolytes, ceramic oxides, and sulfide-based electrolytes. Ceramic electrolytes like lithium lanthanum zirconium oxide (LLZO) have been observed to show relatively good ionic conductivity, and high chemical stability, while their natural brittleness can make manufacturing processes more complicated. On the other hand, sulfide-based electrolytes provide good interface contact with electrodes, and even higher ionic conductivity, while their sensitivity to moisture may require controlled environments during manufacturing [5,14].

In comparison to ceramic materials, polymer-based electrolytes offer easier production and even better mechanical flexibility. However, their ionic conductivity is generally lower at room temperatures, leading to higher required operating temperatures for the performance to be acceptable. Therefore, combining polymer matrices with ceramic particles into hybrid solid state structures are also being researched in order to balance mechanical stability and conductivity [3,14].

SSBs safety characteristics, thermal resistance, battery performance, and cycle life are significantly influenced by the selection of electrolyte materials. Consequently, ongoing research of SSBs is heavily focused on improving ionic conductivity and reducing interfacial resistance between the electrode materials and the electrolyte [5,13].

## 4.2 Advantages and Challenges of Solid-State Batteries

The potential improvement in safety compared to conventional lithium-ion systems has been one of the main motivators for the development of SSBs. Liquid electrolytes are generally flammable organic solvents that, when exposed to abusive conditions, can contribute to thermal runaway events. On the other hand, solid electrolytes are typically non-flammable and less prone to leakage, which greatly reduces the risk of catastrophic failure [5,13].

The potential usage of lithium metal anodes poses another great advantage. Lithium metal can offer a greater theoretical capacity, than that of the graphite anodes used in conventional lithium-ion batteries. If implemented successfully, this could greatly increase the energy density of battery systems. Higher energy density is especially valuable for portable electronics and electric vehicles [3,13].

Even with all these advantages, many different technical challenges still remain until SSBs can become practical in large scale commercial implementations. One crucial issue is the formation of high resistance interfaces between the electrode materials and solid electrolytes. This leads to bad interfacial contact which can reduce power performance, and limit ion transport. These problems are amplified at higher current densities [5,14].

A second concern includes lithium dendrite formation. While solid electrolytes were at first expected to suppress the formation of lithium dendrites, experimentation has shown that under specific conditions dendrites can still grow through some solid materials. The prevention of dendrite formation continues to be an active area of research [3,13].

## 4.3 Control and Integration Considerations

From an automation engineering standpoint, SSBs present new monitoring and control challenges. Though the removal of liquid electrolytes does improve safety, it also changes the electrochemical and thermal relationships of the battery. During operation, these differences can affect dynamic response characteristics and charging behaviour [4,5].

Depending on the electrolyte composition, SSBs frequently display slower ion transport dynamics and different internal resistance characteristics. Under varying load conditions, these aspects can impact transient response and charging behaviour. Therefore, BMS have to adapt control strategies and estimation algorithms in order to account for these differences [4,7].

Even though model parameters can greatly differ from those used in conventional lithium-ion systems, state estimation methods like Kalman filtering and ECM can still be used for SSBs. Since interfacial resistance effects can change as the battery ages, accurate parameter identification becomes especially important [4,7].

Thermal management systems may also be different for SSBs. While solid electrolytes usually provide more thermal stability, local heating can still happen in high current operation. In order to prevent mechanical stress or degradation of solid electrolyte layers, sufficient monitoring systems must be implemented to ensure that temperature gradients remain within acceptable limits [3,5].

# 5 Betavoltaic Batteries

## 5.1 Fundamental Concepts

Betavoltaic batteries are considered to be a type of nuclear energy conversion devices that can generate electrical power from radioactive decay. Different from conventional electrochemical devices that store and release energy through chemical reactions, betavoltaic systems use semiconductor materials to convert the kinetic energy of beta particles into electricity [6,15].

In a common betavoltaic device, a radioactive isotope like tritium or nickel-63 undergoes a decay process and emits beta particles. These high energy electrons interact with the internal semiconductor junctions and create electron-hole pairs, similarly to the photovoltaic effect seen in solar cells. The following charge carriers are then collected by the internal electrodes of the device, which produces a tiny but continuous electric current [15,16].

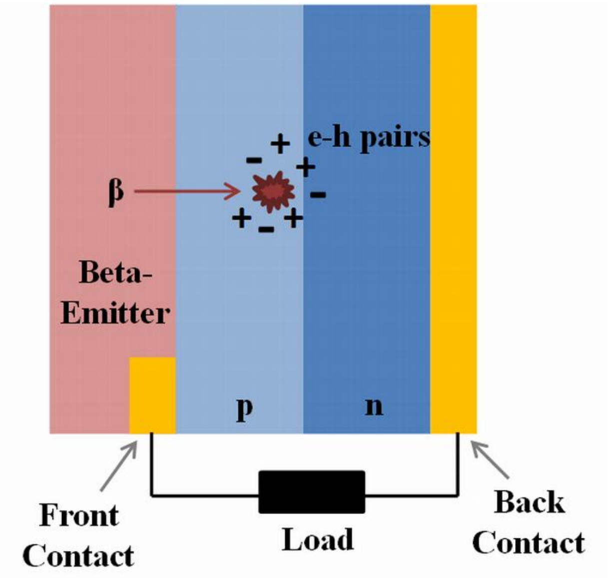

***Figure 5.*** *Conceptual diagram of a betavoltaic battery, where beta radiation from a radioactive source interacts with a semiconductor junction to generate electrical energy. Reprinted from Harrison et al. [20] Copyright 2013 Harrison*

Since the process of radioactive decay occurs over a long time, betavoltaic devices are able to supply power for extremely long durations, usually lasting multiple years or even decades. While the output power of these devices is typically low, usually ranging from microwatts to milliwatts, betavoltaic devices have a long operational lifetime which makes them an attractive option for specialized applications where the battery replacement can be impractical [6,15].

## 5.2 Material and Semiconductor Considerations

The energy conversion performance of different betavoltaic devices is strongly dependent on both the radioactive source, as well as the semiconductor materials used for said energy conversion. Usual isotopes that emit beta particles include tritium, nickel-63, and promethium-147. The selection of the isotope for the battery is based on the isotope's half-life, radiation energy spectrum, and safety [15,16].

The semiconductor materials used in betavoltaic converters are similar to those in photovoltaic devices. The common materials include silicon, silicon carbide, and gallium arsenide. In order to minimize over time device degradation from radiation damage, these materials must be efficient in absorbing beta particles. Thus, radiation tolerance is an important design consideration when selecting materials for the semiconductor [6,15].

The energy conversion efficiency from radioactive decay to electrical power is another key factor. In reality, typical conversion efficiencies for betavoltaic devices are only a few percent, mostly because of energy losses that come with particle scattering and incomplete charge carrier collection. Despite these limiting factors, their long operational lifetime usually makes up for the relatively low efficiency [6,15].

## 5.3 Applications and Limitations

Because of their unique attributes, betavoltaic devices are most commonly used in niche applications where the importance of reliability and long lifetimes outweigh the need for higher power output. One good example is implantable medical devices, where battery replacement becomes impractical and difficult. Such devices could be potentially powered for multiple years without maintenance with the use of betavoltaic batteries [15,16].

Space systems and remote sensing poses another potentially suitable application type. Long-lasting power sources are highly valuable in environments where maintenance is difficult or impossible. Because of that, betavoltaic devices could be used as low-power generators for many different devices operating in isolated locations [6,15].

Regardless, multiple limitations stand in the way of widespread usage of betavoltaic devices. The typically lower power density of this technology makes them unsuitable for high energy applications like grid storage or electric vehicles. On top of that, there are regulatory concerns linked to the disposal and handling of radioactive materials that can make their use in commercial products difficult [6,16].

## 5.4 Control and Integration in Automated Systems

The integration of betavoltaic power sources is wildly different from that of conventional batteries. In order to ensure safe operation, electrochemical batteries usually need continuous monitoring of parameters like temperature, SOC, and internal resistance. By contrast, betavoltaic devices deliver a relatively predictable and stable power output based mainly on the rate of radioactive decay [6,15].

Since the decay process obeys a known exponential law, the long-term power output of betavoltaic devices can be estimated with high accuracy. Certain aspects of system design are simplified by this predictability, as complex state estimation algorithms become overall unnecessary. Alternatively, power management circuits are usually focused on energy buffering and voltage regulation in order to allow for changes in load demand [15,16].

Therefore, betavoltaic devices are commonly paired with energy storage components like rechargeable micro batteries or capacitors. These auxiliary devices store energy and supply power when immediate load demand exceeds the output of the betavoltaic power source. Corresponding hybrid designs allow long-lived power systems to support sporadic communication tasks and sensor operation in autonomous applications [6,15].

# 6 Comparative Analysis Across Battery Technologies

## 6.1 Performance Metrics Comparison

The performance characteristics like cost, energy density, power capacity, and operational lifetime are vastly different between battery technologies. Which battery types are suitable for specific applications like grid scale storage, low power autonomous devices, or electric vehicles, are strongly affected by these aforementioned parameters.

Currently, lithium-ion batteries provide one of the best balances between efficiency, cycle life, cost, and energy density. Classic lithium-ion cells can reach gravimetric energy densities up to 250 Wh/kg, which makes them very suitable in applications where weight and volume are considered important [3,13]. The widespread adoption of lithium-ion devices in consumer electronics and electric vehicles is due to their relatively high round trip efficiency and mature manufacturing infrastructure.

Conversely, lead-acid batteries show notably lower energy density of around 30 to 50 Wh/kg. In spite of this limitation, they remain commonly used in backup power applications due to their lower cost and high recyclability [2,10]. Compared to lead-acid systems, Nickel based devices like NiCd and NiMH offer improvements in energy density at the cost of lower specific energy and higher self-discharge rates. This has limited their modern use compared to lithium-ion cells [2,3].

Sodium sulfur and flow batteries occupy an important niche within stationary energy storage systems. Prioritizing scalability and long cycle life over energy density, technologies like vanadium redox flow batteries allow the adjusting of tank size and stack configuration in order to independently scale energy capacity and power output. This makes them especially attractive for renewable energy integration and grid storage [1,11].

Through the use of solid electrolytes and lithium metal anodes, SSBs have the potential to improve energy density even beyond conventional lithium-ion systems. Even so, many of these technologies are still in development or early commercialization stages. Improving large scale manufacturing methods and overcoming material interface challenges are dependencies that the future performance advantages of SSBs depend on [5,14].

Fundamentally different from electrochemical batteries in terms of performance metrics, betavoltaic devices provide extremely long operational lifetimes at the cost of low continuous power generation and low power output. Common power output levels can range from microwatts to milliwatts, which makes them fit for medical implants and long-term sensor systems rather than energy intensive applications [6,15].

| | *Conventional lithium-ion* | *Lead-acid* | *Flow batteries* | *Solid-state batteries* | *Betavoltaic devices* |
|---|---|---|---|---|---|
| *Energy Density (Wh/kg)* | 150-250 | 30-50 | 20-50 | 250-500 | 0.1-1 |
| *Power density (W/kg)* | 200-3000 | 180-600 | 50-200 | 200-2000 | 0.01-1 |
| *Lifetime* | 500-2000 cycles/5-15 yrs | 200-1000 cycles/3-5 yrs | 10k-20k cycles/10-20 yrs | 1k-5k cycles/10-20 yrs | 10-50+ yrs |
| *Cost(€/kWh)* | 90-280 | 45-140 | 280-740 | 370-740+ | Extremely high |
| *Control complexity* | Medium | Low | High | Medium-high | Low-medium |

***Table 1.*** *Comparative overview of selected battery technologies.*

## 6.2 Control and Battery Management Requirements

Besides the electrochemical performance differences, battery technologies also differ in their control and automation requirements. BMS are especially vital for high energy technologies, where incorrect operation could lead to accelerated degradation and safety concerns.

Lithium-ion systems require advanced BMS architectures in order to keep an eye on current, voltage, and temperature over multiple cells. Since the connection between SOC and voltage is temperature dependent and nonlinear, it is common to use model-based estimation methods. ECM combined with observers like Kalman filtering allows accurate real time SOC estimation while preserving computational efficiency for embedded control systems [4,7,8].

Another critical component of lithium-ion battery control systems is thermal management. Higher energy densities increase heat generation during rapid charging and discharging. When improperly managed, this can lead to thermal runaway events. As a result, modernized battery packs use temperature monitoring networks and cooling systems to allow the BMS to control operating conditions and maintain safe performance limits [3,5].

In contrast, conventional lead-acid batteries need less complex control strategies. SOC estimation is usually carried out using temperature compensation combined with voltage-based measurements. However, periodic monitoring is still required for long-term degradation processes like sulfation in order to ensure system reliability in backup power applications [10].

Flow battery systems present a different type of control challenge. Since external tanks are used to store the electrolyte which is then circulated through the electrochemical cell stack, system operation must consider both fluid dynamic and electrochemical processes. Because of this, automation systems need to control electrolyte flow rates, pump speeds, and tank levels while maintaining stable electrochemical conditions [1,11].

Because solid electrolytes are generally non-flammable, SSBs might eventually simplify certain safety concerns. However, control systems still need to tackle challenges related to temperature gradients, dendrite formation, and interfacial resistance. Reliable modeling and parameter estimation remain vital for maintaining performance as these systems grow toward commercial usage [5,13].

Betavoltaic batteries need comparatively simple control systems due to their predictable output power which can be derived from radioactive decay processes. Integration circuits do not need complex SOC estimation algorithms, instead focusing primarily on energy buffering and voltage regulation to accommodate load demand variance [5, 15].

### 6.3 Application Suitability Across Technologies

Target application requirements have a heavy impact on the suitability of different battery technologies. Technology selection is influenced by different factors such as lifetime, energy density, cost, safety, and control complexity.

Currently, lithium-ion batteries offer the most practical solution for electric vehicles due to their high efficiency, high energy density, and mature supply chains. Advanced BMS are the reason why these batteries can operate safely under demanding conditions while maximizing lifetime and performance. [3,4].

Renewable energy integration uses stationary energy storage systems, which often prioritize cost efficiency and long cycle life instead of volume or weight constraints. Therefore, technologies like flow batteries and sodium-sulfur batteries are well suited for grid level storage applications where durability and scalability are vital [1,11].

Backup power systems in industrial facilities and telecommunication infrastructure frequently count on lead-acid batteries because of their low cost, reliability, and well-established maintenance procedures. While newer lithium-ion systems are increasingly being implemented, lead-acid systems remain commonly used in many different stationary applications because of their mature infrastructure [2,20].

SSBs might eventually replace conventional lithium-ion systems in applications where energy density and safety are especially important. However, notable challenges related to material stability and manufacturing scalability needs to be tackled before general adoption can occur [5,13].

Betavoltaic devices are most suitable for specialized applications that need extremely long operational lifetime with minimal maintenance. These applications include remote sensors, medical implants, and autonomous monitoring systems that operate in environments where maintenance and battery replacement is impractical or impossible.

# 7 Conclusions and Future Directions

This thesis studied and compared several battery technologies from automation engineering and electrochemical perspectives. The examination covered conventional battery systems like lithium-ion and lead-acid batteries, solid-state technologies, and betavoltaic power sources. The comparison heavily focused on control requirements, performance characteristics, and applicability for different applications.

Among the different technologies examined, lithium-ion systems remain the most used because of their balanced performance in terms of efficiency, cost, and energy density. Their mature manufacturing processes and well developed BMS supports their dominance in portable electronics and electric vehicles. However, under dynamic load conditions the operation of these battery systems require sophisticated control strategies to ensure safety and extend lifetime [3,4].

Conventional technologies like lead-acid and nickel-based systems continue to have an important role in applications where reliability, cost, and simplicity are more vital than performance. In comparison, sodium-sulfur batteries and flow batteries are more suitable for stationary energy storage, where compactness is overshadowed by the need for long cycle life and scalability [1,11].

SSBs offer a promising direction, presenting potential improvements in energy density and safety. In spite of these advantages, notable challenges remain, especially in terms of long-term reliability, manufacturing scalability, and material interfaces. From an automation point of view, these systems will continue to need advanced control strategies and monitoring, although some concerns about safety can be reduced compared to liquid based systems [5,13].

Betavoltaic batteries are fundamentally different from electrochemical systems and hold a niche role in energy storage. Due to their extremely long operational lifetime and stable power output, they are suitable for low power applications like medical devices and remote sensors. However, their regulatory constraints and low power output limit their wider usage [6,15].

From an automation engineering perspective, one of the main conclusions of this thesis is that different battery technologies require different levels of control complexity. High performance systems like lithium-ion batteries need advanced thermal management, real time monitoring, and advanced estimation algorithms. In comparison, more stable or simpler systems, like betavoltaic power sources, need less complex control but might need more components due to system integration and energy buffering.

The future research of battery technologies is expected to focus on reducing costs, enhancing safety, and improving energy density, as well as developing more sustainable production methods and materials [17,18]. Additionally, advancements in BMS may further improve reliability and performance. Increasingly sophisticated automation and control strategies will be required for the integration of batteries into larger energy systems, like renewable energy networks and smart grids.

In short, battery technologies continue to have an important role in the adaptation toward sustainable energy systems. Although no single technology is without challenges, understanding the differences and control requirements is vital for designing efficient energy storage solutions. Continued progress in both system level integration and materials science is expected to expand the role of batteries in future energy infrastructures [17,18].

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