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Review On: Energy Storage: From Innovation to Implementation

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Abstract
Energy storage systems are becoming a key part of today's power networks. They help improve how efficiently electricity is used and ensure the power supply stays stable and reliable in systems using both direct current (DC) and alternating current (AC). These systems are especially important for helping balance the power grid and making it easier to use renewable energy sources like solar and wind. They are also essential in high-demand areas like airplanes, ships, and electric vehicles, where they help handle peak power needs in a cost-effective way and make the systems more dependable and efficient. Recent research and development have focused on high-power energy storage devices such as supercapacitors, superconducting magnetic energy storage (SMES), and flywheels. These technologies are known for being able to deliver high power quickly and recharge rapidly, which makes them perfect for situations that require fast energy delivery and recovery. Another major trend is the use of hybrid energy storage systems (HESS), which combine different types of energy storage devices. These hybrid systems offer more flexibility and better performance, making them suitable for a wide range of uses, especially for supporting critical systems and sudden, high-energy demands (pulse loads). This paper gives an overview of the latest developments in high-power energy storage technologies, including lithium-ion batteries, which are widely used due to their high energy storage capacity. It also looks at how hybrid systems are being used in microgrids and in situations that involve critical or pulsed energy demands. Finally, the study compares these technologies in terms of power, energy capacity, cost, lifespan, and overall performance.

Keywords: *Battery Energy Storage System (BESS); Battery Management System (BMS); Lithium-Ion Batteries (Libs); Battery Health Monitoring; Health Indicators (His); Renewable Energy Resources.*

1. Introduction
As the demand for electricity grows and the types of energy sources change, we need more energy resources. Fossil fuels cause pollution and harm the environment. To protect the environment and provide sustainable energy, we are adding renewable energy sources like solar and wind to our power systems. However, these renewable sources don't provide energy all the time because they depend on weather. One way to solve this problem is by using energy storage systems together with renewable energy. With more electric vehicles (EVs) on the road, their batteries can store energy not just to drive the cars but also to connect to the power grid. This allows energy to flow both ways: charging the car from the grid or sending energy back to the grid. Battery management systems (BMS) are important to keep the batteries safe and reliable for both the user and the grid. EV batteries go through many charging

and discharging cycles, and over time, their performance gets worse. We can measure battery health by checking certain indicators and estimating the battery's state of health (SOH). SOH estimation helps us understand how much the battery is aging and how reliable it is. This paper looks at the latest methods to estimate battery health and other important battery states. Battery technology is improving fast because of new materials and better battery management methods. Researchers have suggested many ways to estimate battery health and states. In 2023, there were about 1850 research papers focused on estimating battery SOH and how much longer batteries will last.

2. Objectives And Key Contributions

This paper offers an in-depth examination of the structure of Battery Management Systems (BMS) and explores health indicators (HIs) as part of their functionality. The main aims of this research include:

- Thoroughly analyzing the properties of various types of batteries, with special emphasis on lithium-based batteries.
- Reviewing the functions of battery management systems and highlighting recent developments in this field.
- Presenting a straightforward classification of health indicators based on electrical and temperature measurements, along with visual representations of these indicators according to the proposed grouping.

The study delivers a detailed overview of BMS operations and highlights essential health indicators. It also investigates comprehensive methods for estimating battery states such as State of Health (SOH), State of Charge (SOC), State of Safety (SOS), State of Function (SOF), State of Power (SOP), State of Energy (SOE), State of Temperature (SOT), and the Remaining Useful Life (RUL) assessment. This paper covers a variety of health indicator metrics related to voltage, current, and temperature, categorizing each technique as utilized by the BMS. The major health indicators are grouped because BMSs devote considerable computational resources to calculating these metrics.

3. Battery Energy Storage System [BESS]

Rechargeable energy storage systems are widely utilized across a broad range of applications—from large-scale electric grids to compact, low-power devices—due to their ability to address the intermittency issues of renewable energy and offer long-term reusability. The variability in weather conditions, seasonal changes, and the time of day significantly affects the energy output from wind and solar power sources. As renewable energy sources become increasingly cost-competitive in delivering carbon-free electricity, the use of rechargeable batteries has become more prevalent. These batteries are charged during periods of excess power production and later supply power when generation is insufficient, assuming they are connected to a charging infrastructure. For mobile and portable systems such as electric vehicles (EVs), smartphones, and drones, recharging typically requires temporarily taking the device out of service to connect it to a power source. Over time, repeated charging and discharging cycles cause battery performance to deteriorate. This degradation accelerates under conditions like temperature extremes, irregular charging times, deep discharges, and partial cycling without reaching a full charge. A detailed review of established battery technologies—including lead-acid, nickel-based, and lithium-based systems—is presented in. In contrast, emerging battery chemistries such as sodium-ion, flow batteries, high-temperature batteries, and fuel cells are discussed in. Comparative analyses of cost, lifecycle, energy and power densities, and efficiency for lead-acid, nickel-cadmium, and lithium-ion batteries are detailed in, with lithium-ion identified as offering superior performance—albeit at a higher cost. Research into lithium batteries began as early as 1912, though lithium-ion batteries did not gain prominence until 1976. Early lithium-metal batteries (LMBs) used metallic lithium anodes and nonaqueous electrolytes, which significantly improved both specific energy and energy density. The development of intercalation materials by Whittingham in 1976 marked a turning point, leading to increased research and development in rechargeable LMBs. These batteries offer low operating voltage and high specific capacity, making them suitable candidates for electric vehicle (EV)

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applications, although safety concerns have limited their commercial adoption. Lithium nickel cobalt aluminium oxide (NCA) batteries are noted for their advantages in lifespan, power density, energy storage capacity, cost-effectiveness, and safety, as discussed in. A detailed comparison of major lithium battery chemistries—based on factors like cost, durability, performance, safety, power density, and energy density—is presented in. Among them, lithium titanate oxide (LTO) stands out as the most cost-efficient, while lithium iron phosphate (LFP), lithium manganese oxide, and nickel manganese cobalt (NMC) chemistries are similarly priced. In terms of longevity, both NMC and LTO excel, with LTO also delivering the highest overall performance.

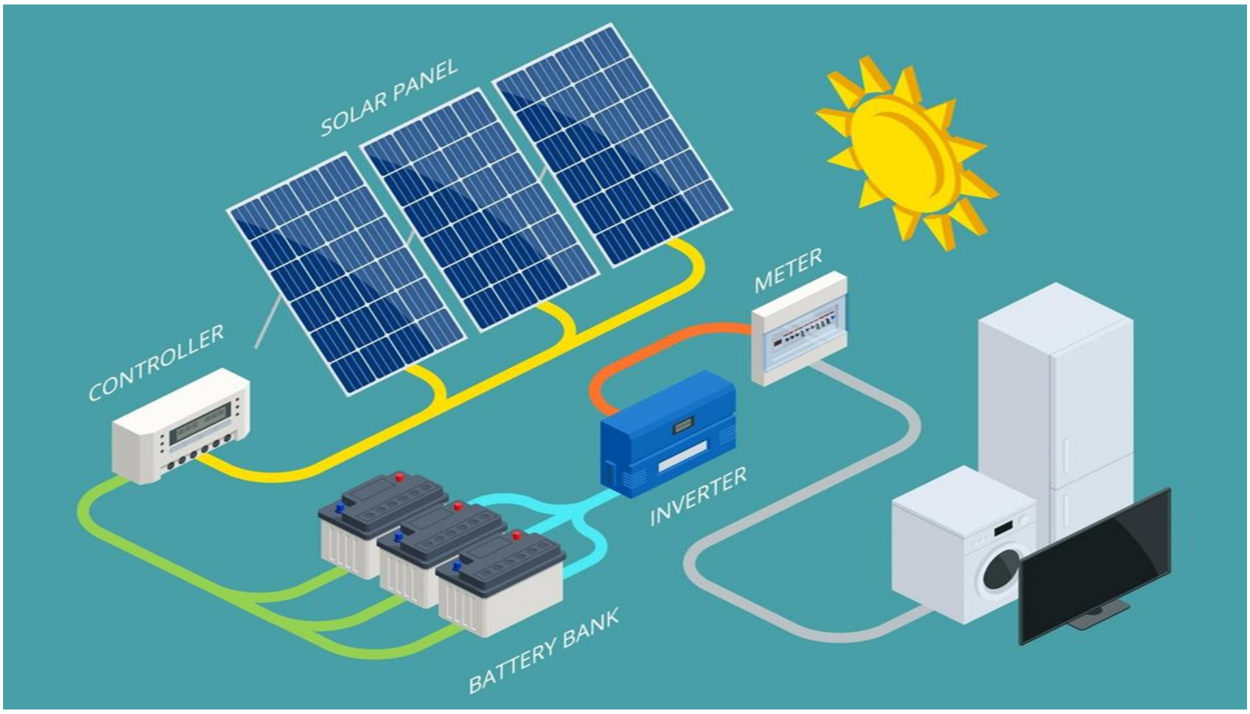

Figure 1 Solar Panel Diagram

4. Battery Management System (BMS)

A Battery Management System (BMS) is an electronic unit that serves as the communication bridge between a battery pack and external devices such as a load or charger. A well-designed BMS plays a critical role in optimizing battery performance, ensuring operational safety, and prolonging the overall lifespan of the battery. It is a combination of hardware and software components. The BMS continuously monitors key parameters such as individual cell voltages, current flow, and temperature to assess battery health, detect faults, and track charge-discharge cycles. Its core functions are divided into several categories, including thermal management, charge equalization across cells, protection against overvoltage, overcurrent, and overcharging, as well as evaluating battery aging and estimating remaining usage time.

4.1. Measurement Functionality:

The BMS uses sensors to capture signals such as individual cell voltages, chassis temperature, and current flowing through the battery. These signals are then converted from analog to digital form using an analog-to-digital converter (ADC). The voltage, current, and temperature readings are sampled at regular intervals, digitized, scaled appropriately, and stored in memory. This data is used to generate time-series records, which are further analyzed to identify performance metrics and trends.

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4.2. Protection Functionality

The Battery Management System serves as the primary safeguard against hazardous operating conditions. Batteries can suffer from overcharging, which results in excessive voltage and current, causing long-term degradation. Similarly, over-discharging at high currents can render the battery unusable. Such electrical extremes can also cause dangerous temperature rises, potentially leading to thermal runaway or fire. The BMS works to prevent these conditions by maintaining electrical and thermal stability. It also monitors system faults and detects defective or non-functional cells, isolating them if the hardware supports it. In the event of a fault or abnormal condition, the BMS alerts the user via visual indicators or display units (when available).

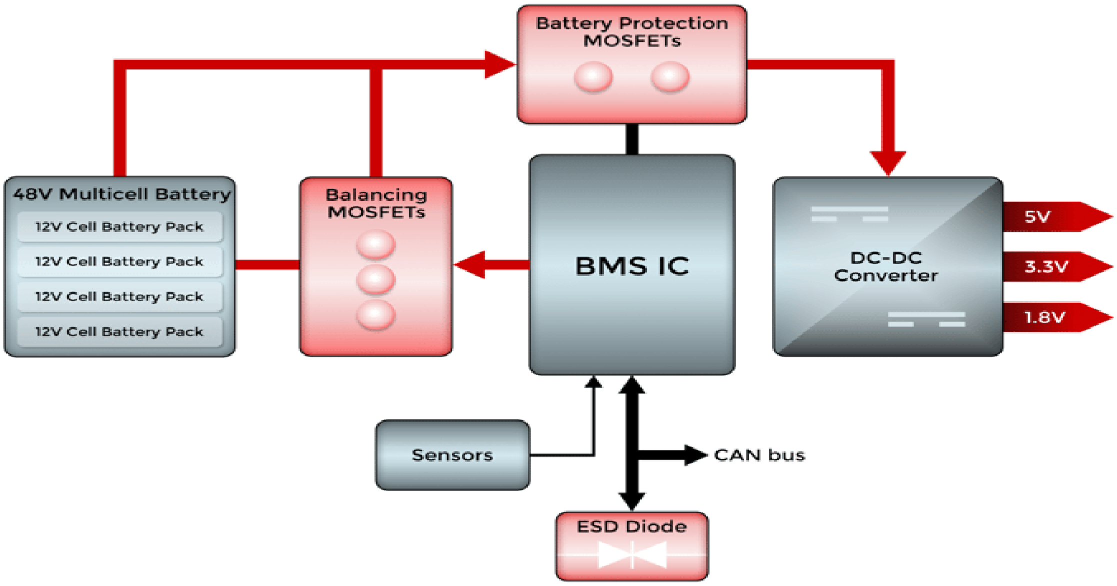

Figure 2 **Battery Protection MOSFETs**

5. Role of Batteries in Energy Storage

Batteries play a crucial role in energy storage systems, especially as the world shifts toward renewable energy sources like solar and wind. Since these sources are intermittent (i.e., they don't produce energy all the time), batteries help store excess energy and release it when needed.

Key Roles:

5.1. Grid Energy Storage

- Balances supply and demand by storing energy during low demand and releasing it during peak demand.
- Supports grid stability and prevents blackouts.

5.2. Renewable Energy Integration

- Stores excess solar or wind energy when production is high and supplies it during low production times.
- Enhances reliability and consistency of renewable energy.

5.3. Electric Vehicles (EVs)

- Serve as the primary energy source for propulsion.
- It can also support grid storage via "vehicle-to-grid" (V2G) systems.

5.4. Uninterruptible Power Supply (UPS)

- Provides backup power during outages to critical systems (hospitals, data centers, etc.).

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5.5. Portable Power:

- Powers mobile devices (phones, laptops), tools, and off-grid applications.

6. Types of Batteries

Batteries are categorized based on their chemistry, application, and rechargeability.

6.1. Primary Batteries (Non-rechargeable)

Used once and discarded.

- Alkaline Batteries (Zinc-Manganese Dioxide)
- Common in household electronics.
- Lithium Batteries
- High energy density, used in cameras, watches, etc.

6.2. Secondary Batteries (Rechargeable)

It can be recharged and reused multiple times.

6.2.1. Lithium-ion (Li-ion)

- **Applications:** Smartphones, laptops, EVs, grid storage.
- **Advantages:** High energy density, lightweight, long cycle life.
- **Disadvantages:** Expensive, sensitive to high temperatures.

6.2.2. Lithium Iron Phosphate ($LiFePO_4$)

- **Applications:** EVs, solar storage systems.
- **Advantages:** Long life, thermal stability, safer than regular Li-ion.
- **Disadvantages:** Lower energy density.

6.2.3. Lead-Acid

- **Applications:** Automobiles, backup power, UPS.
- **Advantages:** Low cost, reliability.
- **Disadvantages:** Heavy, shorter cycle life, environmental concerns.

6.2.4. Nickel-Cadmium (NiCd)

- **Applications:** Power tools, aviation.
- **Advantages:** Long life, good performance in extreme conditions.
- **Disadvantages:** Toxic (cadmium), memory effect.

6.2.5. Nickel-Metal Hydride (NiMH)

- **Applications:** Hybrid cars, AA/AAA batteries.
- **Advantages:** Higher capacity than NiCd, less toxic.
- **Disadvantages:** Self-discharge, lower lifespan than Li-ion.

6.2.6. Flow Batteries (e.g., Vanadium Redox)

- **Applications:** Large-scale grid storage.
- **Advantages:** Scalable, long cycle life.
- **Disadvantages:** Low energy density, complex system.

7. Future Trends in Battery Management System (BMS) Development

As BMSs become more interconnected and accessible through various devices, cybersecurity is becoming a critical area for future research. It's essential for future BMSs to have strong capabilities to detect and isolate cyber threats. This interconnectivity also enables collaborative optimization, where systems can work together to solve complex problems with multiple goals, increasing both computational efficiency and battery storage reliability. Another major trend is the use of physics-informed neural networks (PINNs)—advanced AI models that incorporate battery physics—to improve the accuracy of battery condition estimates and to detect potential faults in battery packs early. To handle the unpredictability of renewable energy sources and maintain secure grid operations, future BMSs will need to adopt remedial action schemes using various communication technologies.

7.1. Key trends in BMS development include

- Smart sensing of a wide range of battery behaviors (electrochemical, mechanical, acoustic, and optical).
- Using big data technologies to manage and analyze large volumes of high-quality measurement data.
- Employing blockchain for secure and transparent data management within energy networks.
- Incorporating advanced AI models, such as attention-based transformers, to enhance decision-making and control.

Conclusion

This paper provided a review of battery technologies with a focus on lithium-ion BESSs, a comprehensive review of battery management systems (BMSs) and

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functionality, and a review and classification of health indicators (HIs) as one of the functionalities provided by BESS BMSs. An extensive review of the wide range of battery characteristics in terms of performance and capacity was provided. The typical cell-level operating parameters of the batteries were also compared. When selecting a battery for a load-specific application, specific characteristics must be considered to appropriately match the requirements. The advantages and limitations of the recently developed Li-metal batteries were also covered as they are the blocks that are supporting EVs and grid-connected renewable sources.