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Next-generation batteries and U.S. energy storage: A comprehensive review: Scrutinizing advancements in battery technology, their role in renewable energy, and grid stability

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Abstract

This study provides a comprehensive review of next-generation battery technologies and their critical role in U.S. energy storage, particularly focusing on renewable energy integration and grid stability. The main objectives were to assess the current advancements in battery technology, evaluate their economic viability and environmental impacts, and understand the implications for stakeholders in renewable energy and grid management. Employing a systematic literature review and content analysis, the study analyzed data from peer-reviewed articles, industry reports, and government publications published between 2014 and 2024. Key findings indicate significant progress in battery efficiency, lifespan, and safety, primarily driven by innovations in lithium-ion and sodium-ion batteries. These advancements are pivotal in enhancing energy storage capabilities and facilitating the integration of renewable energy sources into the grid. However, challenges such as material scarcity, environmental concerns, and the need for improved recycling methods were identified. The study also highlights the importance of regulatory frameworks and policies in shaping the development and deployment of these technologies. Strategic recommendations for industry leaders and policymakers include focusing on sustainable material sourcing, investing in alternative battery chemistries, and implementing supportive regulatory frameworks. In conclusion, the study underscores the transformative potential of advanced battery technologies in achieving a sustainable energy future, suggesting future research directions in material development, battery chemistries, and integration with smart grid technologies.

Keywords: Grid Stability; Next-Generation Batteries; Battery Efficiency; United States.

1. Introduction

1.1. Overview of the Current Energy Landscape and the Role of Batteries

The contemporary energy landscape is undergoing a significant transformation, primarily driven by the global shift towards renewable energy sources and the imperative to reduce carbon emissions. This transition is characterized by the replacement of conventional fossil-fuel-based power systems with renewable energy sources, such as wind and solar farms (Bayborodina et al., 2021). However, the integration of these renewable sources presents unique challenges due to their intermittent and stochastic nature. This variability poses a significant risk to the reliability and stability of the electric grid, necessitating the development of technologies that can provide a steady and stable supply of electricity.

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Battery energy storage systems (BESS) have emerged as a pivotal solution to these challenges. They play a crucial role in enabling the high uptake of renewable energy by providing a means to store excess energy generated during periods of high production and dispatch it during periods of low production or high demand (Sawant et al., 2023). This capability not only enhances the reliability of renewable energy sources but also contributes to the overall stability of the power grid.

The operation of grid-scale battery energy storage, particularly in electricity spot and contingency reserve markets, has been a subject of extensive research. Studies, such as those conducted by Bayborodina et al. (2021), have shown that the strategic operation of BESS can generate significant revenue while minimizing the impact on battery life. This is particularly important in markets with high volatility, where aggressive cycling of batteries can lead to accelerated aging. However, with the declining costs of battery replacement, strategies are being adjusted to optimize immediate revenues, even at the expense of shorter battery lifespans.

The role of batteries extends beyond grid stability and renewable energy integration. With the rise of electric vehicles (EVs), the development of charging infrastructure has become a critical component of the energy transition. The integration of EV charging infrastructure with the grid presents both challenges and opportunities. Rivera et al. (2023) highlight the importance of power electronics converters in this context, as they facilitate the efficient use of clean energy sources and enable more flexible and intelligent grid integration. This integration is essential for increasing the share of renewable energy in the power grid and ensuring the reliability of power systems in the face of growing EV adoption.

Furthermore, the impact of battery energy storage on system reliability, particularly in wind-integrated power systems, has been a focus of recent studies. Sawant et al. (2023) propose operational strategies for battery and wind cooperation, which have been shown to significantly improve system reliability. This cooperation is crucial in reducing dependence on fossil fuels and ensuring a stable supply of renewable energy.

Therefore, current energy landscape is characterized by a rapid transition towards renewable energy sources, with batteries playing a central role in addressing the challenges posed by this transition. The strategic operation of battery energy storage systems is crucial for enhancing the reliability and stability of the electric grid, facilitating the integration of renewable energy, and supporting the growing infrastructure for electric vehicles. As the energy landscape continues to evolve, the role of batteries is expected to become increasingly significant, driving further innovations and developments in this field.

1.2. Next-Generation Batteries in Renewable Energy and Grid Stability

The integration of next-generation batteries into renewable energy systems and grid stability is a critical area of focus in the current energy transition. The development and deployment of advanced battery technologies are essential for enhancing the efficiency, reliability, and sustainability of renewable energy sources, particularly in the context of an increasingly electrified world.

Lithium-based batteries, known for their high energy density and long lifespan, are at the forefront of this transition. They are pivotal in addressing the qualitative and quantitative demands of large-scale devices such as electric vehicles (EVs) and handheld equipment. The evolution of lithium batteries, from fundamental materials like cathodes, anodes, electrolytes, and separators to complex design systems including all solid-state and anode-free batteries, is shaping the future of energy storage (Song et al., 2021). These advancements are not only increasing energy density but also enhancing systematic stability, making them more feasible for widespread electrification in society.

The role of batteries extends beyond just energy storage; they are increasingly being recognized for their potential in grid stability. For instance, repurposed EV batteries, after completing their life in vehicles, still possess significant potential to serve as energy storage equipment. This is particularly relevant in countries like India, which is aggressively pursuing e-mobility to reduce its carbon footprint. The use of repurposed EV batteries as grid-level energy storage systems can increase the reliability of renewable energy plants, offering an economical and sustainable solution compared to new batteries or conventional coal-fired thermal power plants (Vishwakarma et al., 2022). This approach not only provides a cost-effective energy storage solution but also contributes to a circular economy by reusing EV batteries.

The incorporation of renewable energy sources into the power grid is causing a significant overhaul in grid topology, composition, and dynamics. The distributed nature of renewable energy sources, including household-level photovoltaic systems, poses challenges to grid stability and resilience. Research has shown that the resilience of power

grids exhibits daily oscillations due to the fluctuating structure of the grid and power demand. This can lead to a substantial decrease in grid resilience, particularly during periods of highly clustered generator output. Interestingly, the addition of batteries, while enabling consumer self-sufficiency, does not necessarily resolve these issues. It is crucial to understand how the distributed layout of renewable energy sources affects network stability and to develop strategies to mitigate potential disruptions (Smith et al., 2022).

In summary, next-generation batteries play a vital role in the renewable energy landscape and grid stability. The advancements in lithium-based battery technologies are crucial for meeting the increasing demands of electrification and renewable energy integration. The strategic use of repurposed EV batteries as grid-level energy storage systems offers an economical and sustainable approach to enhancing grid reliability. However, the challenges associated with the distributed nature of renewable energy sources and their impact on grid stability must be addressed to ensure a resilient and sustainable energy future.

1.3. Historical Evolution of Battery Technology and Energy Storage Solutions

The historical evolution of battery technology and energy storage solutions is a tale of continuous innovation and adaptation to meet the growing demands of an electrified world. From the early days of simple electrochemical cells to the sophisticated lithium-ion batteries of today, the journey of battery technology has been marked by significant milestones that have revolutionized energy storage and usage.

The lithium-ion (Li-ion) battery, a cornerstone of modern energy storage technology, has undergone substantial development since its inception. These batteries have become the leading choice for a wide range of applications, including electric vehicles (EVs), portable electronics, and renewable energy storage systems. The evolution of Li-ion batteries has been driven by the need to overcome challenges such as limited energy density, safety concerns, and sustainability issues. Innovations in electrode materials and designs have been central to increasing the energy density and capacity of these batteries. Moreover, advancements in thermal management systems and materials have addressed safety concerns, making Li-ion batteries more reliable and efficient (Ahmed & Maraz, 2023).

Another significant development in the realm of energy storage is the emergence of flow batteries. These batteries are particularly promising for industrial energy storage applications due to their long cycling life, reliable design, high safety, and relative maturity. Flow batteries offer unique advantages, such as the ability to independently scale power and energy, making them suitable for large-scale energy storage applications. However, challenges such as high cost and low energy density have hindered their widespread adoption. Recent research has focused on new flow battery systems, exploring innovative chemistries and designs to enhance their performance and reduce costs. The advancement of flow batteries is crucial for promoting the evolution of the energy structure and popularizing the use of renewable energy sources like wind and solar energy (Yang, 2022).

The integration of renewable energy sources with battery technology has also seen significant progress. Electric vehicle battery charging systems, for instance, have evolved to incorporate sustainable energy sources like photovoltaics. These systems use compact and straightforward bidirectional converters that can draw power from traditional electrical sources or renewable energy sources. The development of such systems is pivotal in addressing the challenges posed by the increasing popularity of EVs and Plugin hybrid electric vehicles (PHEVs). By enabling the use of renewable energy for EV charging, these systems contribute to environmental protection and energy conservation. Simulations and experimental studies have demonstrated the effectiveness of these systems in various scenarios, highlighting their potential in the field of EV charging and energy storage (Duro, Serôdio, & Baptista, 2023).

The historical evolution of battery technology and energy storage solutions reflects a journey of innovation and adaptation. The development of lithium-ion batteries and flow batteries has been instrumental in meeting the increasing demands of an electrified world. The integration of renewable energy sources with advanced battery technologies further underscores the transformative potential of these solutions in achieving a sustainable energy future.

1.4. Aim and Objectives of the Study

The aim of this comprehensive study is to critically analyze and evaluate the advancements in next-generation battery technologies and their impact on the integration and management of renewable energy sources within the grid. The study seeks to understand how these technological innovations in battery systems can contribute to enhancing grid stability, energy efficiency, and sustainability in the context of an evolving global energy landscape.

The research objectives are;

- To assess the current state of battery technology and energy storage.
- To investigate technological advancements in battery composition and design.
- To analyze the economic and environmental implications of advanced battery technologies.

2. Methodology

The methodology for this study is structured around a systematic literature review and content analysis, focusing on next-generation batteries and their role in U.S. energy storage, particularly in renewable energy integration and grid stability.

2.1. Data Sources

The primary data sources for this study include academic journals, conference proceedings, industry reports, and government publications. Key databases such as IEEE Xplore, ScienceDirect, JSTOR, and Google Scholar are utilized to access peer-reviewed articles. Additionally, reports from energy industry stakeholders, policy documents, and technical standards are sourced to provide a comprehensive view of the subject.

2.2. Search Strategy

The search strategy involves using specific keywords and phrases related to next-generation batteries, renewable energy, grid stability, and energy storage. These keywords include "battery technology," "energy storage," "renewable energy integration," "grid stability," "lithium-ion batteries," and "battery efficiency." Boolean operators (AND, OR) are used to combine these terms effectively and refine the search results.

2.3. Inclusion and Exclusion Criteria for Relevant Literature

The inclusion criteria for relevant literature in this study encompass peer-reviewed articles published between 2014 and 2024, focusing on next-generation battery technologies and their applications in energy storage and grid stability. This includes studies that provide insights into the technological advancements, economic viability, and environmental impacts of these battery systems, as well as their integration in renewable energy and grid stability contexts. Reports and publications from credible industry and government sources that offer substantial information on the subject are also included. On the other hand, the exclusion criteria rule out articles not published in English, studies that concentrate solely on traditional battery technologies without relevance to next-generation advancements, and publications that do not directly address the integration of battery technology in renewable energy or grid stability. This approach ensures that the literature reviewed is both relevant and current, providing a comprehensive understanding of the latest developments and trends in the field of battery technology and energy storage.

2.4. Selection Criteria

The selection of literature for review is based on the relevance to the study's aim and objectives. Abstracts and summaries of the identified articles are initially reviewed to assess their applicability. Full texts are then examined for those that meet the inclusion criteria. Priority is given to recent studies that provide novel insights or significant contributions to the field of battery technology and energy storage.

2.5. Data Analysis

Data analysis involves content analysis of the selected literature. Key themes, trends, and patterns related to battery technology advancements, economic viability, environmental impacts, and policy implications are identified and categorized. The analysis also includes a critical review of the methodologies, findings, and conclusions of the selected studies. This approach enables the synthesis of a comprehensive understanding of the current state and future directions of next-generation batteries in the context of U.S. energy storage and renewable energy integration.

3. Literature Review

3.1. Fundamental Principles of Battery Technology and Energy Storage

The fundamental principles of battery technology and energy storage are rooted in the intricate interplay of chemistry, physics, and engineering. These principles have been refined over the years, leading to the development of various

battery technologies that are crucial in the transition to clean energy resources. This transition is imperative for addressing climate change, driven largely by the emission of greenhouse gases from the massive use of fossil fuels.

At the core of battery technology is the concept of electrochemical energy storage, where chemical energy is converted into electrical energy. This process involves the movement of ions between the anode and cathode through an electrolyte, accompanied by electron flow in the external circuit. Lithium-ion batteries, a dominant technology in this field, exemplify this principle. They have become the leading energy storage technology due to their high energy density, efficiency, and sustainability. The gradual replacement of internal combustion engine vehicles with electric vehicles, powered by lithium-ion batteries, is a testament to the pivotal role of these batteries in reducing reliance on fossil fuels (Kang et al., 2022).

Electrochemistry plays a vital role in battery research and development. Fundamental electrochemical relations like Sand's law, the Nernst equation, Ohm's law, and Faraday's laws are crucial for understanding and predicting the behavior of battery cells. These principles are not only essential for the basic operation of battery cells but also serve as powerful tools for in situ monitoring and diagnostics. By applying these electrochemical fundamentals, researchers can develop more effective and impactful strategies for advancing battery technology. This approach is essential for addressing limitations in performance criteria such as energy/power density, fast charge capability, and cycle life, which are critical for the continued evolution of battery technology (Winter et al., 2022).

Sodium-ion batteries represent another important development in energy storage solutions. These batteries offer a sustainable and low-cost alternative to lithium-ion batteries, making them an attractive option for large-scale energy storage. The fundamental principles behind sodium-ion batteries involve similar electrochemical processes as lithium-ion batteries but utilize sodium ions instead. This technology has overcome significant challenges to achieve commercialization and is poised to play a crucial role in meeting the increasing global energy demand. The future of sodium-ion batteries looks promising, with opportunities for deployment in various applications and the potential for further technological advancements.

The fundamental principles of battery technology and energy storage are central to the development of efficient, sustainable, and high-performance energy storage systems. The advancements in lithium-ion and sodium-ion batteries, driven by a deep understanding of electrochemistry, are paving the way for a future where renewable energy sources can be effectively harnessed and utilized. As the world continues to grapple with climate change and the depletion of fossil fuels, the role of advanced battery technologies in the energy transition becomes increasingly significant.

3.2. Technological Advancements in Battery Composition and Design

The field of battery technology has witnessed remarkable advancements in recent years, particularly in the composition and design of batteries. These developments are crucial in addressing the growing demand for efficient, reliable, and sustainable energy storage solutions, especially in the context of electric vehicles (EVs) and renewable energy systems.

One of the key areas of advancement is in the battery technologies of electric vehicles. The automotive industry has seen a significant shift towards electric vehicles, driven by advancements in battery technology that offer improved choice, reduced prices, and enhanced performance. The evolution of electric vehicle batteries has focused on maximizing energy storage within a compact design, making EVs increasingly competitive with combustion engine vehicles. This progress has been facilitated by exploring alternative materials for electrodes and batteries, leading to faster and more reliable charging capabilities. The continuous innovation in this domain is expected to further revolutionize the automobile industry in the future (Raja, Raja, & Kavvampally, 2022).

The state of the art in battery technology encompasses a wide range of innovations and advancements. From the fundamental understanding of batteries and their operation to the exploration of various types, including primary and secondary batteries, the field has evolved significantly. Lithium-ion batteries, in particular, have been the focus of extensive research due to their specific properties and innovative mode of operation. These batteries are characterized by high energy density, long cycle life, and stability, making them ideal for a variety of applications. The advancements in charging and discharging methods, including technologies like LiFePO₄, have further enhanced the performance and reliability of lithium-ion batteries (Popa, Popa, & Mocanu, 2023).

Another significant advancement in battery technology is the development of two-dimensional materials as anodes for lithium-ion batteries. Materials such as graphene, MXenes, and transition metal dichalcogenides have garnered attention due to their unique physicochemical properties. These materials offer efficient ion transport, large surface areas for enhanced ion adsorption, and accelerated surface redox reactions. The focus on the design and manipulation

of advanced interface architectures for anodes has led to significant improvements in battery performance. The exploration of composition-structure-property relationships in these materials has opened new avenues for optimizing anode performance in lithium-ion batteries. Furthermore, the application of two-dimensional materials extends beyond conventional lithium-ion batteries, promising advancements in various energy storage systems (Ali et al., 2023).

The technological advancements in battery composition and design have been instrumental in meeting the increasing demands for energy storage in various sectors. The evolution of electric vehicle batteries, the exploration of innovative materials and charging technologies, and the development of advanced anode materials have collectively contributed to the enhancement of battery performance. As the world continues to move towards sustainable energy solutions, these advancements in battery technology play a pivotal role in enabling the transition and shaping the future of energy storage.

3.3. Analysis of High-Performance Battery Systems for Renewable Energy Integration

The integration of high-performance battery systems into renewable energy grids is a critical aspect of the ongoing energy transition. These systems play a pivotal role in balancing power generation and utilization, particularly in grids with a high proportion of renewable energy sources. The effectiveness of battery storage systems is largely dependent on their performance, which includes factors such as energy density, temperature independence, and cost-effectiveness.

Battery storage systems, especially lithium-ion batteries (LIBs), have become increasingly important in both stationary applications and the mobility sector. LIBs are known for their high energy efficiency, long cycle life, and relatively high energy density, making them suitable for grid-level energy storage applications. The operation mechanism, battery design and construction, and the advantages and disadvantages of LIBs have been extensively analyzed. Their application in grid-level energy storage systems is evaluated in terms of frequency regulation, peak shifting, integration with renewable energy sources, and power management. Despite their potential, challenges such as degradation, safety concerns, and cost remain significant hurdles in the widespread adoption of LIBs in grid-scale applications (Chen et al., 2020).

The evaluation of battery storage systems requires reliable methods and technical conditions to test and assess their performance under various scenarios. This is particularly important for lithium-based batteries, which are central to the operation of modern energy storage systems. The ability to examine the condition of the battery storage without disrupting or damaging the system is crucial. Various evaluation methods have been developed to assess the performance, safety, and longevity of these systems, ensuring their optimal operation in conjunction with renewable energy sources (Hallmann, Wenge, & Komarnicki, 2020).

In the context of wind energy, battery energy storage systems (BESS) have been used for ramp rate control and power system frequency performance enhancement. A hybrid model combining dynamic smoothing techniques and particle swarm optimization has been proposed to optimally size and control BESS for these purposes. This approach is particularly relevant in power systems with a large integration of wind energy, where the intermittency and fluctuation of wind power can pose challenges to grid stability. The implementation of BESS in such systems has shown improvements in ramp rate characteristics and enhanced transient and steady-state frequency response, indicating the effectiveness of these systems in high-proportion renewable energy grids (Tadie, Guo, & Xu, 2022).

High-performance battery systems, particularly lithium-ion batteries, are integral to the successful integration of renewable energy sources into the power grid. The evaluation and optimization of these systems are crucial for ensuring their effective operation in terms of energy storage, frequency regulation, and overall grid stability. Despite the challenges, the advancements in battery technology and the development of sophisticated control and evaluation methods are paving the way for more reliable and efficient renewable energy integration.

3.4. Breakthroughs in Battery Efficiency, Lifespan, and Safety

The advancements in battery technology, particularly in terms of efficiency, lifespan, and safety, are pivotal in the evolution of energy storage solutions. Recent research has focused on enhancing these aspects to meet the increasing demands of various applications, from electric vehicles (EVs) to grid-scale energy storage.

One significant breakthrough in lithium-ion battery technology is the improvement in efficiency and lifespan. Studies have shown that lithium batteries can achieve an efficiency of 98.54% for more than 600 cycles and a lifespan beyond 900 hours in specific configurations. This improvement is attributed to advancements in the chemical composition of anode and cathode materials, as well as the design of the battery cell itself. The development of models to predict the longevity of lithium-ion batteries based on experimental data has also been a key focus. These models, which include

polynomial regression and support vector machine (SVM) models, aim to predict the end-of-life of battery cells with high accuracy, thus enabling better management and optimization of battery usage (Guo, Gong, & Gao, 2023).

The all-vanadium flow battery represents another area of advancement, particularly in terms of safety and long-term performance. These batteries are known for their long lifespan, high efficiency, and safety features, making them suitable for large-scale energy storage applications. Research has been conducted to optimize the performance of all-vanadium flow batteries through numerical simulations, focusing on the internal energy and mass transfer mechanisms. The optimization of cell thickness and operating parameters has been shown to significantly impact the performance of these batteries, leading to improvements in energy efficiency and overall battery operation (Sun et al., 2023).

In the context of electric vehicles, the design of battery packs or accumulators, including their Battery Management Systems (BMS), is crucial for ensuring efficiency, safety, and reliability. The use of LiFePO₄ batteries in EVs has been explored, with a focus on optimizing the power density of the accumulator while minimizing degradation. The design considerations for these battery packs include cost, lifespan, safety, reliability, sustainability, and usability. The development of such battery systems is essential for enhancing the popularity and implementation of EVs in society, as they form the core element of electric vehicles (Pérez et al., 2021).

The breakthroughs in battery efficiency, lifespan, and safety are driving the evolution of energy storage solutions. The advancements in lithium-ion batteries, all-vanadium flow batteries, and battery systems for electric vehicles are testament to the ongoing efforts to enhance the performance and safety of these technologies. As the demand for efficient and reliable energy storage continues to grow, these advancements will play a crucial role in shaping the future of energy storage and utilization.

3.5. Review of Emerging Trends in Battery Technology and Energy Storage

The landscape of battery technology and energy storage is rapidly evolving, driven by the urgent need to address climate change and the increasing demand for renewable energy sources. Emerging trends in this field are shaping the future of energy storage, offering innovative solutions for sustainable energy conversion and storage.

One of the key trends in battery technology is the development of new materials and processes to enhance the performance of energy storage and conversion devices. This includes efforts to increase energy and power density, efficiency, durability, and safety of batteries. The transition to clean energy resources, such as solar, wind, and tidal power, is heavily reliant on the effectiveness of rechargeable batteries. These batteries are expected to remain the dominant technology for storing renewable energy and using it in an economic and efficient manner. The gradual replacement of internal combustion engine vehicles with electric vehicles, powered by advanced batteries, is a prime example of this trend. The focus on tuning the properties of component materials by modulating their crystal structure and microstructure, as well as optimizing materials processing and device assembly protocols, is central to these advancements (Kang et al., 2022).

In the context of electric vehicles (EVs), the integration of power electronics converter technology with energy storage management is emerging as a crucial trend. This technology is essential for achieving stable and reliable power transmission in EVs. Despite the significant contributions of various EV converters, challenges such as high component count, switching loss, current stress, computational complexity, and slow dynamic response persist. Research in this area is focused on addressing these limitations and exploring new opportunities for power converter technology in EVs. This includes modeling, experimental work, performance evaluation, and the development of innovative energy storage, controller, optimization, and energy transfer schemes (Lipu et al., 2022).

Another emerging trend is the comprehensive assessment of the trends and developments in battery innovation. This involves analyzing patent data to identify leading patent applicants, countries of origin, and the main battery components. The lithium-ion battery remains the most vibrant technology, with lithium-sulfur and flow batteries being notable emerging technologies. The interactions of batteries with clean energy technologies, such as battery charging and photovoltaic energy, as well as battery charging and electric vehicles, are also significant. The majority of patents in this field represent incremental and product innovations, indicating a robust rise in patenting in batteries. This trend highlights the importance of continuous innovation in battery technology for the development of low-carbon energy technologies (Silva, Távora, & Mendonça, 2023).

The emerging trends in battery technology and energy storage are redefining the way we store and use energy. The advancements in materials, processes, and integrated technologies are paving the way for more efficient, durable, and

safe energy storage solutions. As the world continues to move towards a sustainable energy future, these innovations in battery technology will play a crucial role in enabling the transition and meeting the growing energy demands.

4. Discussion of Findings

4.1. Evaluating the Impact of Advanced Battery Technologies

The advancement of battery technologies, particularly lithium-ion batteries (LIBs), has significantly influenced various sectors, including electric vehicles (EVs) and renewable energy storage. Evaluating the impact of these technologies involves considering technological, economic, and environmental aspects.

One of the critical areas of impact is the recycling and reuse of spent LIBs. The growing LIB market, driven by consumer demand and the need to reduce greenhouse gas emissions, has brought attention to the socio-environmental impacts of LIB production. The extraction of lithium and other materials used in these batteries has consequences on human health, agriculture, and ecosystems. Recycling spent LIBs presents an opportunity to minimize environmental impacts and conserve natural resources. Current approaches to recycling and reuse are varied, with different technological options offering their own set of advantages and challenges. Small-scale recycling technology is emerging as a potential solution to overcome barriers associated with recycling spent LIBs. This approach aligns with the global supply chain's shift towards sustainable and reliable secondary sources of valuable materials (Hossain, Sarkar, & Sahajwalla, 2023).

The application of advanced battery technologies in electric vehicles also presents several challenges and opportunities. The effectiveness of EVs is contingent upon the functionality and management of battery energy storage. Issues such as limited driving range, access to charging stations, charging times, and safety considerations are central to the adoption of EVs. Technological advancements in battery technology have extended the driving range per charge, and innovations in charging infrastructure, such as extreme fast charging (XFC) technology and intelligent transport systems (ITS), are improving the practicality of EV adoption. Additionally, the development of EV charging standards and risk management strategies ensures a secure charging system. Addressing these challenges through innovative technologies is crucial for realizing a comprehensive and sustainable charging network, facilitating the transition towards cleaner transportation (Wang, 2023).

Environmental technological innovations, including advanced battery technologies, play a crucial role in achieving sustainable development. The balance between economic, environmental, and social considerations is essential in designing technology that promotes sustainability. Technological innovations in battery technology are aligned with the requirements of Smart Industry 4.0 and 5.0, incorporating green practices into production methods. The use of tools like Cleaner Production (CP), Environmental Accounting (EA), Pollution Prevention (PP), Recycling (R), Life Cycle Analysis (LCA), Eco-labelling (EL), and the Environmental Technologies Action Plan (ETAP) are significant in promoting sustainable development. The economic viability of each technology, considered over a period of 20+ years, is essential for sustainability (Chovancová et al., 2023).

The impact of advanced battery technologies is multifaceted, encompassing technological, economic, and environmental dimensions. The advancements in recycling and reuse of LIBs, the challenges and opportunities in the application of these technologies in EVs, and the role of environmental technological innovations in sustainable development highlight the significance of these technologies in shaping a sustainable future.

4.1.1. Technological, Economic, and Environmental Considerations

The advancement of battery technologies, particularly lithium-ion batteries (LIBs), has significant implications for the global transition to sustainable, low-carbon energy systems. Evaluating the impact of these technologies requires a comprehensive understanding of their technological, economic, and environmental aspects.

One of the primary environmental concerns associated with LIBs is their global supply chain's impact. A study analyzing the cradle-to-gate energy use and greenhouse gas emissions of current and future nickel-manganese-cobalt and lithium-iron-phosphate battery technologies highlights this issue. The research indicates that around two-thirds of the total global emissions related to battery production are concentrated in three countries: China, Indonesia, and Australia. The study also projects that electricity grid decarbonization could reduce future battery production emissions by up to 38% by 2050. Additionally, the use of secondary materials via recycling can significantly reduce the environmental burdens associated with the extraction and processing of materials from primary sources. Direct recycling offers the lowest impacts, followed by hydrometallurgical and pyrometallurgical methods, reducing greenhouse gas emissions by 61, 51, and 17%, respectively (Llamas-Orozco et al., 2023).

The economic and sustainable environmental impact of policies in the new energy vehicles and lithium battery industry is another critical area of consideration. Policies targeting the consumption and supply of new energy vehicles and the research and development of energy technologies like lithium batteries can have significant impacts. These policies play a positive role in increasing the output of new energy vehicles, reducing environmental pollution, and encouraging the progress of lithium battery research. However, the reduction of subsidies and the improvement of selection criteria need to align with market conditions and the progress of relevant energy research. Balancing economic effects and improving energy utilization is essential for achieving sustainable development (Tu, 2023).

A systematic investigation of the environmental impact between lithium-ion and sodium-ion batteries provides insights into the comparative environmental performance of these technologies. The study discusses the environmental impact of these batteries in terms of water pollution, solid pollution, raw material, recycling, and gas emissions. Using the Analytic Hierarchy Process (AHP) method, the study analyzes which battery technology is better in terms of environmental impact. The findings of this investigation are crucial for informing decisions on battery technology selection, especially in applications where environmental considerations are paramount (Lei et al., 2023).

In conclusion, the technological, economic, and environmental considerations of advanced battery technologies are multifaceted and complex. The environmental impacts of the global lithium-ion battery supply chain, the economic and policy implications in the new energy vehicle and lithium battery industry, and the comparative environmental performance of lithium-ion and sodium-ion batteries are key areas that need to be addressed. These considerations are vital for guiding the development and implementation of sustainable battery technologies and policies.

4.1.2. Addressing Challenges in Current Battery Technologies and Exploring Solutions

The rapid evolution of electric and hybrid vehicle battery technologies has brought significant advancements, but it also presents a range of challenges that need to be addressed. Lithium-ion batteries, which are at the forefront of this technological revolution, offer high energy density and extended life cycles, making them ideal for electric and hybrid vehicles. However, there are several hurdles that need to be overcome to fully realize the potential of these technologies.

One of the major challenges is the scarcity and price volatility of critical materials like cobalt and nickel, which are essential for the production of lithium-ion batteries. This issue poses a significant threat to the scalability and affordability of electric vehicles. Additionally, environmental concerns related to battery production and disposal necessitate the development of sustainable solutions. Innovations such as silicon anodes and solid-state electrolytes are being explored to improve battery efficiency and performance. However, energy density limitations continue to impact driving range and charging times, which are critical factors for the widespread adoption of electric vehicles (Madrid, 2023).

The automotive industry's shift towards electric vehicles has led to advancements in battery technology, but it also faces several challenges. The battery used in electric vehicles needs further exploration to harness maximum energy with a compact design. Alternative materials for electrodes and batteries are being reviewed to make charging faster and more reliable. The development of these technologies is crucial for electric vehicles to compete effectively with combustion engine vehicles. This paper reviews the current major challenges faced by the electric vehicle industry and explores possible solutions to overcome them (Raja, Raja, & Kavvampally, 2022).

The digitalization of battery manufacturing is another area that presents both challenges and opportunities. As the demand for state-of-the-art batteries drives gigascale production, there is a growing need for battery manufacturing processes that are cost-effective, scalable, and sustainable. The digital transformation of battery manufacturing plants can help meet these needs. This review discusses current and near-term developments in the digitalization of the battery cell manufacturing chain and presents future perspectives in this field. The integration of modeling approaches with data acquisition instruments and communication protocols in a framework for building a digital twin of the battery manufacturing chain is expected to guide more intelligent and interconnected battery manufacturing processes (Ayerbe et al., 2021).

In conclusion, addressing the challenges in current battery technologies is pivotal for the advancement of electric and hybrid vehicle battery technologies. The scarcity of critical materials, environmental concerns, energy density limitations, and the need for digitalization in battery manufacturing are key areas that require innovative solutions. Overcoming these challenges will pave the way for a cleaner and more ecologically mindful era of transportation.

4.1.3. Trends and Innovations in Battery Chemistry and Energy Density

The landscape of battery technology is rapidly evolving, with significant advancements in chemistry and energy density shaping the future of electric vehicles (EVs) and other applications. Understanding these trends and innovations is crucial for grasping the direction in which battery technology is heading.

Lithium-ion (Li-ion) batteries have become the preferred power source for EVs due to their high energy density, low self-discharge rate, and long cycle life. Recent advancements in Li-ion battery cell design have been driven by the growing market diffusion of EVs, resulting in customized and cost-effective cell designs tailored to automotive requirements. A statistical analysis of empirical data reveals several trends, such as increasing cell dimensions, differentiation between high-energy or low-cost cathode and anode materials, and increasing cell energy. These trends indicate a gain of about 100% in energy density and 70% in specific energy compared to the 2010 and 2021 averages. Despite these improvements, the widespread market diffusion of the latest cell technologies is slower than industry announcements suggest, and several well-known potentials are not yet fully exploited (Link, Neef, & Wicke, 2023).

The demand for high-power density and energy in the function of Li-ion batteries (LIBs) is rising, especially in Electric Drive Vehicles and Energy Storage devices. This review discusses alternate battery technologies that can potentially replace existing LIB technology. It covers the electrical performances of Li batteries, their challenges, and upcoming battery technologies like graphene batteries and redox flow batteries. These emerging technologies have the potential to compete in the current market and address the challenges faced by LIBs, such as energy density limitations and environmental concerns (Daya & Paul, 2022).

From the foregoing, the trends and innovations in battery chemistry and energy density are pivotal for the advancement of battery technologies. The developments in Li-ion batteries, the exploration of alternative battery technologies, and the progress in Li-S flow batteries are shaping the future of energy storage. These advancements are crucial for meeting the growing demands for efficient, high-energy-density storage solutions in various applications.

4.1.4. Future Directions in Battery Technology and Energy Storage

The future of energy storage technologies, particularly in the context of renewable energy systems, is a rapidly evolving field with significant advancements and potential directions. Understanding these developments is crucial for shaping the future landscape of energy storage and its integration with renewable energy sources.

A comprehensive review of the progress in energy storage technologies highlights the widespread adoption of renewable energy sources such as wind and solar power. The focus is on three main aspects: battery storage technology, electricity-to-gas technology for increasing renewable energy consumption, and optimal configuration technology. The future development of energy storage is expected to be more oriented toward studying power characteristics and frequency characteristics, with a focus on the stability effects brought by transient shocks. This review compiles and assesses various energy storage technologies, providing a reference for future research (Wei et al., 2023).

Rechargeable sodium-ion batteries (SIBs) are emerging as a viable alternative to lithium-ion battery technology. Their raw materials are economical, geographically abundant, and less toxic. With the increasing reliance on renewable energy sources and the anticipated integration of high-energy-density batteries into the grid, concerns regarding the sustainability of lithium have arisen. SIBs, benefiting from the abundance of sodium and sharing electrochemical characteristics similar to LIBs, have gained attention as a potential energy storage alternative. High-entropy chemistry has emerged as a new paradigm, promising to enhance energy density and accelerate advancements in battery technology to meet growing energy demands. This review uncovers the fundamentals, current progress, and views on the future of SIB technologies, focusing on the design of novel materials (Singh et al., 2023).

The future directions in battery technology and energy storage are marked by advancements in lithium-ion and sodium-ion batteries, with a focus on enhancing energy density, safety, and sustainability. The integration of these technologies with renewable energy systems and the exploration of new materials and chemistries are pivotal for the development of efficient and sustainable energy storage solutions.

4.2. The Role of Standards, Regulations, and Policy in Battery Technology and Energy Storage.

The role of standards, regulations, and policy is crucial in shaping the development and deployment of battery technology and energy storage systems. These regulatory frameworks significantly influence the business case for energy storage, particularly in the context of the European Union (EU) and the United Kingdom (UK).

A SWOT analysis of the impact of recent EU regulatory changes on the business case for energy storage, using the UK as a case study, reveals several key insights. Energy storage technologies, such as batteries, are essential for increasing the share of renewable energy generation and decarbonizing the electricity system. Recent regulatory changes aim to improve the business case for energy storage technologies on national networks. These changes include removing double network charging for energy storage, defining and classifying energy storage in relevant legislations, and clarifying ownership and grid access. However, most current regulations treat storage similarly to bulk generators, without considering the different sizes and types of energy storage. This results in storage with higher capacity receiving significantly higher payments in the capacity market and being exempt from paying renewable energy promotion taxes. Despite these changes, energy storage is still defined as a generation device, which limits its revenue streams from demand-side services. Regulators are encouraging changes that coexist with the current market and regulatory structure, rather than creating an independent asset class for energy storage (Gailani et al., 2020).

The development of electric vehicle (EV) energy storage technology is strategically important for achieving low-carbon growth and promoting the green transformation of the energy industry in China. This paper discusses the opportunities, challenges, and strategies related to developing EV energy storage under the carbon neutrality goal. It emphasizes the need to focus on developing battery technology, delivering longer cycle lives, improving the safety and availability of battery materials, and ramping up R&D efforts for vehicle-to-grid (V2G) management technologies. Creating a business ecosystem centered on V2G operating platforms and formulating top-level strategic plans across industries and organizations are essential. Additionally, developing an electricity-trading mechanism and promoting the implementation of technical standards related to EV energy storage are crucial (Liu et al., 2023).

The economic viability of battery energy storage in grid applications is linked to an accommodative and vibrant energy market and a responsive regulatory framework that ensures level playing fields for emerging technologies. Life cycle cost estimation using Monte Carlo Simulation addresses the stochastic nature of input data of battery storage technologies for different grid applications. Compensation for different grid applications varies, and fast regulation services tailored for battery storage applications demonstrate economic viability and a level playing field for battery storage technologies. This policy paradigm is worth emulating for other independent system operators (ISOs) (Nazar & Anwer, 2020).

In conclusion, standards, regulations, and policy play a pivotal role in the advancement of battery technology and energy storage. The regulatory landscape influences the business case for energy storage, the development of EV energy storage technology, and the economic viability of battery storage in grid applications. Navigating these regulatory frameworks is essential for fostering the growth and integration of energy storage technologies in the energy market.

4.3. Implications for Stakeholders in Renewable Energy and Grid Management.

The integration of renewable energy sources into the power grid and the involvement of customers in energy management have significant implications for stakeholders in the renewable energy and grid management sectors. These implications range from economic aspects to the technical challenges and opportunities in managing a more dynamic and complex energy system.

A study on the implications of smart grid and customer involvement in energy management and economics investigates the energy economics and forecasts for the Muzaffarabad area in Azad Jammu and Kashmir. The research examines the annualized energy estimation concerning varied customer photovoltaic (PV) system participation and the impact of consumer feedback on energy production. It highlights the relationship between the rising usage of renewable energy and falling greenhouse gas emissions and energy prices. The study found that PV systems could provide 61% of the total region's energy needs with maximum consumer involvement, reducing grid energy purchases to 52% and cutting energy cost from \$0.20 per kWh to \$0.09 per kWh. This demonstrates the potential economic benefits and environmental impact of increased customer participation in renewable energy systems (Rehman et al., 2023).

The design of a mini-grid consisting of four distributed microgrids, where the microgrids exchange energy, is another aspect of energy management in renewable energy systems. This design aims to increase the network efficiency and reduce transmission line losses of the distributed mini-grid. The study conducts power flow and short circuit analysis under various scenarios, such as grid-connected, non-grid, and renewable energy sources disabled. Sustainable use of electrical energy is achieved by increasing the network efficiency, demonstrating the technical feasibility and resilience of smart multi-microgrid systems with renewable generation (Dirmilli, Eyuboglu, & Gül, 2022).

A review of recent standalone and grid-integrated hybrid renewable energy systems focuses on system optimization and energy management strategies. It examines the architecture sizing and energy management strategies of these

systems, considering various locations and applications based on technical, reliability, environmental, and social factors. The study identifies various components that could help optimize the performance of hybrid renewable energy systems and highlights the potential of optimization-based energy management strategies to enhance the reliability and efficiency of these systems. Trends in the implementation of grid-integrated or off-grid hybrid renewable energy systems in remote, island, or urban locations are also highlighted, providing insights into the development of sustainable energy infrastructure (Basnet et al., 2023).

The implications for stakeholders in renewable energy and grid management are diverse and multifaceted. The economic benefits, technical feasibility, and environmental impact of increased customer participation in renewable energy systems, the resilience of smart multi-microgrid systems, and the optimization of hybrid renewable energy systems are key areas that stakeholders need to consider. These aspects are crucial for the successful integration and management of renewable energy sources in the power grid.

5. Conclusions

The study has highlighted significant advancements in battery technology, particularly in the context of energy storage and renewable energy integration. Key findings include improvements in battery efficiency, lifespan, and safety, driven by innovations in materials and design. Lithium-ion batteries have been identified as pivotal in the transition towards renewable energy, offering high energy density and efficiency. However, challenges such as material scarcity, environmental impacts, and the need for improved recycling methods have been noted. The study also underscores the growing importance of sodium-ion batteries as a sustainable alternative, offering economic and environmental advantages.

Looking ahead, the future of energy storage is poised at a crucial juncture with both challenges and opportunities. Technological advancements promise higher energy densities and safer battery chemistries, potentially revolutionizing energy storage in various sectors. However, the industry faces challenges in terms of material scarcity, cost, and environmental impacts. The integration of energy storage with renewable energy sources presents opportunities for grid stability and the reduction of carbon emissions, but requires advancements in grid infrastructure and energy management systems.

For industry leaders and policymakers, the study recommends a focus on sustainable material sourcing and the development of efficient recycling processes for batteries. Investment in research and development for alternative battery chemistries, such as sodium-ion batteries, is crucial. Policymakers should also consider implementing supportive regulatory frameworks and incentives to foster innovation and adoption of advanced battery technologies. Collaboration between industry, academia, and government is essential to address the technical, economic, and environmental challenges in battery technology and energy storage.

Finally, the study emphasizes the critical role of advanced battery technologies in the transition to a more sustainable energy future. Future research should focus on developing new materials and battery chemistries that are environmentally friendly and cost-effective. Exploring the integration of battery storage systems with renewable energy sources and smart grid technologies is also vital. Additionally, addressing the socio-economic aspects of battery technology adoption and its impact on energy markets and policies will be crucial. The continued evolution of battery technology will play a pivotal role in shaping the future of energy storage and renewable energy integration, offering a path towards a more sustainable and efficient energy landscape.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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