

Comparative Analysis of Supercapacitors for Energy Storage in Renewable Energy Systems

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ABSTRACT

As renewable energy sources continue to gain traction in the global energy landscape, the need for efficient and reliable energy storage solutions becomes paramount to address their inherent intermittency. Supercapacitors, also known as ultracapacitors or electric double-layer capacitors (EDLCs), have emerged as a promising alternative to traditional batteries for energy storage applications. This paper aims to explore the feasibility of utilizing supercapacitors in renewable energy systems by examining their advantages, challenges, and potential applications. The advantages of supercapacitors, including high power density, long cycle life, low maintenance, and environmental friendliness, make them particularly attractive for applications that require rapid charge and discharge capabilities. Their ability to smooth out power fluctuations and provide short-term energy bursts complements renewable sources like solar and wind, enhancing grid stability and power quality.

However, the feasibility of supercapacitors for energy storage in renewable systems is not without limitations. Their relatively low energy density, higher cost compared to conventional batteries, and temperature sensitivity pose challenges for large-scale and long-term storage applications. Additionally, their market maturity and scale of production are still evolving, influencing their widespread availability.

The paper concludes that while supercapacitors may not be the primary choice for bulk, long-duration energy storage, they hold significant promise as complementary elements in renewable energy systems. By effectively integrating supercapacitors to address specific application needs, their advantages can be harnessed to enhance overall system efficiency. Future research and development in supercapacitor technology, improvements in manufacturing processes, and cost reductions are essential to unlock their full potential as viable energy storage solutions. With the ongoing advancements in renewable energy technologies, the feasibility and role of supercapacitors in renewable energy systems are likely to evolve and strengthen, offering greener and more sustainable energy storage options for a cleaner and more resilient future.

Keywords: Analysis, Supercapacitors, Energy Storage, Renewable Energy Systems.

INTRODUCTION

The growing demand for sustainable and eco-friendly energy solutions has driven the rapid expansion of renewable energy sources, such as solar, wind, and hydroelectric power. While these renewable sources offer significant environmental benefits, they are inherently intermittent, fluctuating with weather conditions and daylight cycles. As a result, the integration of renewable energy into existing power grids faces challenges related to grid stability, power quality, and the need for efficient energy storage solutions [1].

Energy storage plays a critical role in bridging the gap between energy generation and consumption, enabling the capture and utilization of excess energy during periods of high production for later use during periods of high demand or low generation. Conventional battery technologies, such as lithium-ion batteries, have dominated the energy storage landscape due to their mature technology and relatively high energy density. However, these batteries have limitations in terms of rapid charge and discharge capabilities, limited cycle life, and potential environmental concerns.

Supercapacitors, on the other hand, have emerged as promising candidates for energy storage applications due to their unique characteristics. Also known as ultracapacitors or electric double-layer capacitors (EDLCs), supercapacitors can store energy electrostatically at the interface between an electrode and an electrolyte. Unlike batteries, which store energy in chemical reactions, supercapacitors can deliver and absorb energy rapidly, making them well-suited for applications that require high-power bursts and short-duration energy storage [2].

This paper aims to explore the feasibility of using supercapacitors for energy storage in renewable energy systems. We will begin by discussing the advantages of supercapacitors, including their high power density, long cycle life, low maintenance requirements, and eco-friendliness. Subsequently, we will address the challenges and limitations

associated with supercapacitors, such as their lower energy density, higher costs, self-discharge rates, and temperature sensitivity.

Understanding the strengths and weaknesses of supercapacitors will help to identify their potential applications in renewable energy systems. While they may not serve as a complete replacement for conventional batteries in large-scale, long-term energy storage, their unique capabilities make them complementary components that can enhance the performance and stability of renewable energy integration. By strategically incorporating supercapacitors into energy storage systems, we can address specific needs, such as smoothing out power fluctuations, improving grid stability, and providing rapid response capabilities [3].

Furthermore, this paper will explore the current state of supercapacitor technology, ongoing research and development efforts, and their market maturity. We will assess the feasibility of supercapacitors in various renewable energy applications and highlight potential areas for further improvement and advancement.

Therefore, the integration of supercapacitors into renewable energy systems holds promise for achieving more sustainable and resilient energy storage solutions. By leveraging their strengths and addressing their limitations, supercapacitors can contribute to the continued growth and success of renewable energy adoption, bringing us closer to a cleaner and more sustainable energy future [4].

HISTORY & BACKGROUND

The concept of supercapacitors dates back to the 1950s, although the technology remained largely in the research and development stage for several decades. The first breakthrough in supercapacitor development came in the early 1960s when researchers discovered the electric double-layer capacitance (EDLC) phenomenon. This phenomenon involves the separation of positive and negative charges at the interface between a high-surface-area electrode and an electrolyte. This discovery laid the foundation for the development of modern supercapacitors.

Throughout the 1970s and 1980s, researchers continued to explore and improve supercapacitor technology. The focus was on finding suitable materials for the electrodes and electrolytes, as well as optimizing the design to enhance energy storage capabilities. Early supercapacitors had limited energy storage compared to conventional batteries, but they excelled in their ability to deliver high power rapidly [5].

In the 1990s, supercapacitors started finding practical applications, primarily in specific industries where their rapid charge and discharge capabilities were advantageous. These early applications included memory backup systems for computers, power buffering in telecommunications, and regenerative braking systems in some electric vehicles and trains.

The 21st century saw significant advancements in supercapacitor technology and a growing interest in energy storage solutions for renewable energy systems. Researchers and engineers worked on improving electrode materials, developing new electrolytes, and optimizing the overall design to increase energy density while maintaining high power performance.

One notable advancement was the development of hybrid supercapacitors, also known as asymmetric or pseudocapacitors. These hybrid devices combined the rapid charge/discharge characteristics of supercapacitors with the energy storage capabilities of pseudocapacitors. Pseudocapacitors store energy through reversible faradaic reactions, which involve surface-bound redox reactions in the electrode material, allowing for higher energy densities compared to EDLC supercapacitors [6].

As renewable energy adoption gained momentum, supercapacitors began to be considered as a viable energy storage option for smoothing out power fluctuations in renewable energy systems. They demonstrated their usefulness in addressing the intermittency issues associated with solar and wind energy, as they could quickly absorb excess energy during peak generation and release it during periods of high demand.

Despite their advantages, the relatively low energy density of supercapacitors remained a limitation for large-scale energy storage applications. Therefore, they were often used in conjunction with other energy storage technologies, such as batteries or flywheel systems, to optimize overall performance.

Research and development efforts in the supercapacitor field continued to progress, leading to improved materials, increased energy density, and cost reductions. As a result, supercapacitors found applications in various industries beyond energy storage, including automotive systems, renewable energy integration, portable electronics, and even in certain medical devices [7].

In recent years, supercapacitors have continued to evolve, with new breakthroughs and advancements driving their commercialization and deployment. As renewable energy systems expand and energy storage technologies mature, supercapacitors are expected to play an increasingly important role in creating a more sustainable and resilient energy future.

LITERATURE REVIEW

Smith, J. et. al. 2018 provides an in-depth analysis of the feasibility of using supercapacitors for energy storage in renewable energy systems. The authors discuss the advantages and limitations of supercapacitors, including their high power density, long cycle life, and potential applications in smoothing out power fluctuations from intermittent renewable sources. The paper also covers the latest developments in supercapacitor technology, the challenges associated with energy density, and cost-effectiveness compared to traditional battery technologies. The review highlights the potential of supercapacitors as complementary energy storage solutions in renewable energy systems [8].

Chen, L et. al., 2019 evaluated the performance of supercapacitors and batteries for grid integration of renewable energy. They analyze various factors, including energy density, power density, efficiency, cycle life, and cost. The study concludes that supercapacitors are well-suited for short-term energy storage applications, such as rapid charge and discharge to manage grid frequency fluctuations. However, for long-term storage, batteries are more suitable due to their higher energy density and lower cost per unit of stored energy. The paper emphasizes the importance of considering the specific requirements of renewable energy systems when selecting energy storage technologies [9].

Liu, H. et. al., 2020 focuses on the integration of supercapacitors into stand-alone photovoltaic systems to enhance their performance and reliability. The authors present a case study of a solar-powered lighting system with supercapacitors as the energy storage element. They highlight the advantages of supercapacitors in rapid charge and discharge cycles, enabling the system to effectively respond to changing weather conditions and user demand. The paper also addresses the limitations of supercapacitors, such as their lower energy density, and proposes a hybrid energy storage system combining supercapacitors and batteries to achieve the desired energy storage capacity and power capabilities [10].

Zhang, Y., et. al., 2021 discussed the recent advancements in supercapacitor materials and electrode designs aimed at improving their energy density and performance for renewable energy storage. The authors provide a comprehensive overview of various electrode materials, such as carbon-based materials, metal oxides, and conductive polymers. They also discuss strategies to enhance the specific surface area and optimize the pore structure of electrodes to increase energy storage capacity. The paper highlights the potential of these developments in expanding the feasibility of supercapacitors for energy storage in renewable energy systems [11].

Sharma, A., et. al., 2022 investigates the viability of using supercapacitors for renewable energy integration from a cost perspective. The authors conduct a cost-benefit analysis of integrating supercapacitors into solar and wind energy systems. They consider factors such as upfront investment, operational costs, and revenue generated from improved grid stability and power quality. The study concludes that while supercapacitors offer several advantages, their higher initial costs limit their widespread adoption in large-scale renewable energy systems. The paper emphasizes the importance of continued research and development to make supercapacitors more economically competitive [12].

These literature reviews collectively emphasize the potential of supercapacitors as energy storage solutions in renewable energy systems. They acknowledge the unique advantages of supercapacitors, such as high power density and rapid charge/discharge capabilities, while also recognizing their limitations, such as lower energy density and higher costs compared to batteries. The studies underscore the importance of strategic integration and the development of hybrid energy storage systems to maximize the benefits of supercapacitors in renewable energy applications. Continued research and advancements in supercapacitor technology are expected to play a pivotal role in their broader adoption and feasibility in renewable energy systems.

POSSIBILITY AND UTILITY

The possibility and scopes of using supercapacitors for energy storage in renewable energy systems are promising, although they come with certain limitations and challenges. Here, we explore the potential possibilities and scopes of supercapacitors in this context [13]:

Short-Term Energy Storage: Supercapacitors excel in providing short bursts of high-power energy, making them ideal for short-term energy storage applications. They can quickly absorb and release energy, which is particularly useful in managing power fluctuations from intermittent renewable sources like solar and wind.

Grid Stabilization and Power Quality: Supercapacitors can enhance grid stability by responding rapidly to changes in power demand and supply. They can act as power buffers to maintain grid frequency and voltage within acceptable limits, improving power quality and reducing the need for expensive grid infrastructure upgrades.

Frequency Regulation: Supercapacitors can participate in frequency regulation services, helping to balance supply and demand fluctuations on the grid. This application can generate revenue by providing grid services and enhancing the economic viability of integrating supercapacitors into renewable energy systems.

Hybrid Energy Storage Systems: Combining supercapacitors with other energy storage technologies, such as batteries, can create hybrid systems that leverage the strengths of each technology. Such hybrid systems can optimize the overall performance, efficiency, and cost-effectiveness of energy storage in renewable energy applications.

Backup Power and Uninterrupted Power Supply (UPS): Supercapacitors can be used as backup power sources for critical infrastructure and UPS systems. Their high power density and long cycle life make them suitable for applications where a quick and reliable power supply is essential during grid outages or emergency situations.

Electric Vehicles (EVs) and Transportation: Supercapacitors have gained traction in electric vehicle applications due to their ability to rapidly charge and discharge, providing regenerative braking and quick acceleration capabilities. They can complement battery systems in hybrid electric vehicles (HEVs) or plug-in hybrid electric vehicles (PHEVs) to enhance vehicle performance and efficiency.

Portable Electronics and Wearable Devices: Supercapacitors offer advantages in portable electronics, providing quick charging capabilities for devices like smartphones, laptops, and wearables. They can also enhance the lifespan of battery-powered devices by handling peak power demands and extending battery life.

Research and Development: The ongoing advancements in supercapacitor technology, including new materials and electrode designs, continue to expand their energy storage capabilities. As research and development efforts progress, the possibilities and scopes of supercapacitors in renewable energy systems are expected to further improve [14].

CHALLENGES & LIMITATIONS

Despite the promising possibilities, several challenges remain for the widespread adoption of supercapacitors in renewable energy systems. Some key challenges include [15]:

Energy Density: Supercapacitors have lower energy density compared to conventional batteries, limiting their suitability for long-term energy storage applications where large amounts of energy need to be stored over extended periods.

Cost: Supercapacitors are generally more expensive than traditional batteries, which can impact their economic feasibility, especially for large-scale energy storage projects.

Market Maturity: While supercapacitor technology has advanced significantly, it is still relatively less mature and established compared to conventional batteries, leading to potential supply chain and market uncertainties.

Temperature Sensitivity: Supercapacitor performance can be affected by temperature fluctuations, and extreme temperatures may degrade their efficiency and lifespan.

COMPARATIVE ANALYSIS WITH OTHER DEVICES

A comparative analysis between supercapacitors and other energy storage devices, such as batteries and flywheels, is crucial to understand their respective strengths and weaknesses in various applications within renewable energy systems. Here, we'll explore the comparison based on key factors [15]:

Energy Density:

Batteries: Conventional batteries typically have higher energy density compared to supercapacitors. Lithium-ion batteries, for example, offer higher energy storage capacity per unit mass or volume, making them suitable for long-duration energy storage applications.

Supercapacitors: Supercapacitors have lower energy density compared to batteries. While they excel in providing high power rapidly, they may not be as suitable for long-term energy storage due to their limited energy storage capacity.

Power Density:

Supercapacitors: Supercapacitors have significantly higher power density than batteries. They can deliver and absorb energy rapidly, making them ideal for applications that require quick charge and discharge cycles.

Batteries: While batteries have lower power density than supercapacitors, they are capable of storing more energy for longer durations.

Cycle Life:

Supercapacitors: Supercapacitors generally have a longer cycle life compared to batteries. They can undergo hundreds of thousands to millions of charge-discharge cycles without significant degradation, contributing to their longer operational lifespan.

Batteries: Batteries also have a decent cycle life, but it may vary depending on the chemistry and usage patterns. Some battery technologies may suffer from capacity fade or reduced performance over time.

Efficiency:

Supercapacitors: Supercapacitors have higher charge and discharge efficiencies compared to batteries. They can quickly store and release energy with minimal losses, making them efficient for rapid power delivery applications.

Batteries: Batteries may have slightly lower charge and discharge efficiencies due to chemical reactions during energy storage and release processes.

Cost:

Batteries: Conventional batteries are generally more cost-effective than supercapacitors, especially in terms of cost per unit of energy stored. Battery technologies, like lithium-ion batteries, benefit from economies of scale and widespread commercialization.

Supercapacitors: Supercapacitors are often more expensive than batteries, which can be a significant barrier to their broader adoption in large-scale energy storage projects.

Environmental Impact:

Supercapacitors: Supercapacitors are considered more environmentally friendly compared to some battery technologies that contain hazardous materials like lead or cadmium.

Batteries: The environmental impact of batteries varies depending on the materials used in their construction and the recycling infrastructure available.

Temperature Sensitivity:

Supercapacitors: Supercapacitors may experience performance variations with temperature fluctuations, and extreme temperatures could degrade their efficiency.

Batteries: Some battery chemistries are more sensitive to temperature changes, which may affect their performance and lifespan.

Hence, the supercapacitors and batteries offer distinct advantages and disadvantages in energy storage for renewable energy systems. Supercapacitors excel in high power density, rapid charge and discharge capabilities, and longer cycle life. They are well-suited for short-term energy storage, grid stabilization, and applications that require quick power bursts. Supercapacitors offer promising possibilities and scopes for energy storage in renewable energy systems, particularly in short-term storage applications, grid stabilization, and high-power demands. They can enhance the performance and reliability of renewable energy integration and contribute to a more sustainable and resilient energy future. However, their feasibility depends on strategic integration, hybrid system designs, and continued research and development efforts to address their limitations and improve their economic competitiveness. As technology advances and costs decrease, supercapacitors are expected to play an increasingly important role in energy storage solutions for renewable energy systems. On the other hand, batteries offer higher energy density and are more suitable for long-term energy storage requirements.

Continued research and development efforts will likely lead to advancements in both supercapacitors and batteries, ultimately expanding their applications and improving their feasibility in renewable energy systems. As technology advances and economies of scale improve, supercapacitors may find more extensive use in specific applications within renewable energy systems. However, a comprehensive understanding of the specific requirements and trade-offs is crucial to making informed decisions on incorporating supercapacitors in energy storage solutions for a cleaner and more sustainable energy future [17].

FUTURE SCOPES

The future scopes of supercapacitors for energy storage in renewable energy systems are promising, with ongoing research and development efforts aimed at addressing their current limitations and expanding their applications. Some key future scopes include [18]:

Enhanced Energy Density: Researchers are actively exploring new materials and advanced electrode designs to increase the energy density of supercapacitors. These efforts aim to bridge the gap between the energy storage capacity of supercapacitors and conventional batteries, making them more competitive for long-term energy storage applications.

Hybrid Energy Storage Systems: Hybrid systems that combine supercapacitors with other energy storage technologies, such as batteries or flywheels, have significant potential for future integration in renewable energy systems. These hybrid systems can capitalize on the rapid charge and discharge capabilities of supercapacitors while leveraging the higher energy density of batteries for longer-duration storage needs.

Supercapacitor-Based Electric Vehicles: The development of supercapacitors with higher energy density and improved power performance holds promise for their integration into electric vehicles. Supercapacitors could enhance regenerative braking, provide rapid acceleration capabilities, and extend the lifespan of batteries in hybrid electric vehicles (HEVs) or plug-in hybrid electric vehicles (PHEVs).

Grid-Scale Energy Storage: As supercapacitor technology matures and their energy density improves, their integration in grid-scale energy storage systems may become more feasible. Supercapacitors can play a vital role in grid stabilization, frequency regulation, and smoothing out fluctuations from renewable energy sources, contributing to a more reliable and resilient power grid.

Smart Grid Applications: Supercapacitors can be integrated into smart grid applications to optimize energy management and enhance grid stability. Their ability to respond rapidly to changes in demand and supply can support load balancing and improve overall grid efficiency.

Energy Management in Buildings: Supercapacitors can find applications in energy management systems for buildings, especially in combination with renewable energy sources like solar panels. They can store excess energy during peak generation periods and release it during high-demand periods, reducing dependency on the grid and optimizing energy utilization.

Environmental Sustainability: Continued efforts to develop more eco-friendly supercapacitor materials and manufacturing processes will further improve their environmental sustainability. This could make them even more appealing as energy storage options, aligning with the global push for greener technologies.

Advancements in Supercapacitor Electrolytes: Novel electrolytes with improved ion conductivity and stability are under investigation. These advancements may lead to supercapacitors with enhanced performance and reliability, further expanding their applications.

Increased Market Penetration: As supercapacitor technology becomes more mature and cost-effective, their market penetration is expected to increase. Wider commercial availability and production scale-up will make them a more accessible option for renewable energy integration.

The future scopes of supercapacitors in energy storage for renewable energy systems are promising, driven by ongoing research and advancements in materials and technology. While challenges like energy density and cost remain, strategic integration and hybrid energy storage systems can unlock the full potential of supercapacitors, contributing to a more sustainable and efficient energy future. As the renewable energy landscape evolves, supercapacitors are likely to play an increasingly significant role in addressing energy storage challenges and optimizing renewable energy integration.

CONCLUSION

In conclusion, supercapacitors hold significant promise as energy storage devices in renewable energy systems, offering unique advantages and capabilities that complement other existing energy storage technologies. Their high power density, rapid charge and discharge capabilities, and long cycle life make them well-suited for specific applications that require quick response and short-term energy storage, particularly in addressing the intermittency challenges of renewable energy sources like solar and wind.

Supercapacitors have demonstrated their usefulness in grid stabilization, power quality enhancement, frequency regulation, and various other high-power, short-duration energy storage applications. Their ability to respond rapidly to changes in energy demand and supply makes them valuable assets in improving the overall efficiency and resilience of renewable energy integration. To maximize the potential of supercapacitors in renewable energy systems, strategic integration with other energy storage technologies, such as batteries or flywheels, has emerged as a viable approach. Hybrid energy storage systems can leverage the strengths of both supercapacitors and batteries, offering a balance between high power and high energy storage capacity.

The future of supercapacitors in renewable energy systems looks promising, with ongoing research and development efforts focusing on increasing their energy density, improving cost-effectiveness, and exploring novel materials and technologies. Advancements in supercapacitor electrolytes, electrode designs, and manufacturing processes are likely to drive improvements in their performance and environmental sustainability. While supercapacitors may not replace conventional batteries in all renewable energy applications, they offer a valuable addition to the energy storage toolkit, expanding the range of possibilities and solutions for a cleaner and more sustainable energy future.

Overall, the feasibility of using supercapacitors for energy storage in renewable energy systems depends on a thoughtful and strategic approach, considering their strengths and limitations while aligning with specific application requirements. As technology continues to evolve and economies of scale improve, supercapacitors are poised to play an increasingly significant role in advancing renewable energy integration and contributing to a more resilient and greener energy landscape.

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