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(Review Article)

Optimizing energy storage for electric grids: Advances in hybrid technologies

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Abstract

The increasing integration of renewable energy sources and the rising demand for efficient and reliable power supply have positioned Hybrid Energy Storage Systems (HESS) as a pivotal innovation in modern electric grids. HESS synergistically combine multiple energy storage technologies, such as batteries, supercapacitors, and flywheels, to leverage their complementary strengths in energy and power density, response time, and cycle life. This review comprehensively explores the critical role of HESS in addressing contemporary grid challenges, including variability in renewable generation, peak load management, and grid stability. The paper begins by elucidating the components of HESS, emphasizing the contributions of advanced batteries, supercapacitors, flywheels, and emerging storage technologies in enhancing performance metrics. Subsequently, it delves into the design considerations necessary for HESS optimization, including configuration strategies, control methodologies, and scalability. Technological advancements, such as the integration of artificial intelligence, machine learning, and smart grid compatibility, are highlighted as transformative enablers for efficient energy management and predictive maintenance in HESS applications. Real-world implementations of HESS in grid-connected systems and microgrids are analyzed to showcase their practicality and impact in diverse energy ecosystems. Moreover, the economic and environmental dimensions of HESS are critically examined, with a focus on cost-benefit analyses and ecological considerations. Challenges, including technical, regulatory, and economic hurdles, are discussed alongside future directions for research and innovation, underscoring the need for policy alignment and sustained technological development. Looking forward, the evolution of HESS is poised to redefine energy storage paradigms, playing a central role in the global transition toward sustainable and resilient power systems. By addressing the multifaceted challenges of grid modernization, HESS hold the promise of revolutionizing energy storage, fostering greater renewable energy adoption, and securing a low-carbon energy future.

Keywords: Hybrid Energy Storage Systems (HESS); Renewable Energy Integration; Grid Stability and Resilience; Energy Management Strategies; Smart Grid Technology; Sustainable Energy Storage Solutions

1. Introduction

The increasing integration of renewable energy sources into electric grids has introduced complexities due to their intermittent nature, necessitating advanced energy storage solutions to maintain grid stability and reliability. Traditional single-technology storage systems often fall short in meeting the dynamic demands of modern power grids,

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leading to a growing interest in Hybrid Energy Storage Systems (HESS). HESS combine multiple storage technologies, such as batteries and supercapacitors, to leverage their complementary strengths, offering enhanced performance and flexibility in grid applications [1-4].

Recent research buttresses the significance of HESS in optimizing energy storage for electric grids. For instance, a comprehensive review by Hemmati and Saboori [5] highlights the emergence of HESS in renewable energy and transport applications, emphasizing their potential to address the limitations of single storage systems. The authors discuss various configurations and control strategies that enhance the efficiency and reliability of HESS, providing a foundation for future developments in this field.

Furthermore, a study by Zhao et al. [6] examines the role of energy storage systems in supporting wind power integration. The authors analyze different storage technologies and their suitability for mitigating the variability of wind energy, concluding that hybrid systems offer superior performance in balancing supply and demand fluctuations. Their findings suggest that HESS can significantly enhance the stability of grids with high renewable energy penetration.

In addition, research by Guezgouz et al. [4] focuses on the optimal design of hybrid pumped hydro-battery storage systems. The study presents a methodology for determining the optimal sizing and operation of such systems to improve grid reliability and economic performance. The authors demonstrate that integrating batteries with pumped hydro storage can effectively address the limitations of each technology when used independently, leading to more efficient energy management in electric grids.

These studies, among others, highlight the advancements in HESS technologies and their pivotal role in modernizing electric grids. By combining the strengths of various storage technologies, HESS provide a more resilient and adaptable solution to the challenges posed by renewable energy integration, paving the way for a more sustainable and efficient energy future.

1.1. Background on Energy Storage in Electric Grids

Energy storage systems (ESS) are integral to the stability and reliability of modern electric grids, especially as the integration of renewable energy sources increases. The primary function of ESS is to balance supply and demand, ensuring consistent power delivery even when generation or consumption fluctuates. This balancing act is crucial for maintaining grid frequency and preventing disturbances that could lead to outages [7,8].

One of the key roles of energy storage is to provide a buffer that absorbs excess energy during periods of low demand and releases it during peak times. This capability not only enhances grid reliability but also improves efficiency by reducing the need for peaking power plants, which are often less efficient and more polluting. Additionally, ESS can offer ancillary services such as frequency regulation, voltage support, and reactive power compensation, all of which are essential for the smooth operation of the grid.

The importance of energy storage becomes even more pronounced with the increasing penetration of renewable energy sources like wind and solar power. These sources are inherently intermittent, leading to challenges in maintaining a stable and reliable power supply. ESS can mitigate these challenges by storing surplus energy generated during periods of high renewable output and discharging it when generation is low, thereby smoothing out the variability and ensuring a continuous power supply [9].

Recent advancements in energy storage technologies have further enhanced their role in grid stability. For instance, large-scale battery storage systems have been deployed to provide rapid response to grid disturbances, effectively maintaining frequency and preventing cascading failures. Moreover, the development of hybrid energy storage systems, which combine different storage technologies, offers improved performance by leveraging the strengths of each component. These systems can provide both high power and high energy capacity, making them versatile tools for grid management [10,11].

In essence, energy storage systems are vital components of modern electric grids, playing a crucial role in maintaining stability and reliability. Their ability to balance supply and demand, provide ancillary services, and integrate renewable energy sources makes them indispensable in the evolving energy landscape. As technology continues to advance, the role of energy storage in grid management is expected to become even more significant, paving the way for a more resilient and sustainable energy future.

1.2. Emergence of Hybrid Energy Storage Systems (HESS)

Hybrid Energy Storage Systems (HESS) represent an innovative approach in modern electric grids, combining multiple energy storage technologies to capitalize on their respective strengths and mitigate individual limitations. Typically, a HESS integrates high-energy-density components, such as batteries, with high-power-density elements like supercapacitors. This combination enables the system to efficiently manage both energy-intensive and power-intensive tasks, enhancing overall grid performance [12].

The significance of HESS in contemporary grids is multifaceted. By merging different storage technologies, HESS can provide rapid response to transient power demands while also offering sustained energy supply over longer durations. This dual capability is particularly beneficial for accommodating the variable nature of renewable energy sources, such as wind and solar power, which can cause fluctuations in grid stability. For instance, supercapacitors can address short-term power spikes, while batteries manage longer-term energy storage needs, ensuring a balanced and reliable power supply [10,13,14].

Recent advancements in HESS have demonstrated their potential to enhance grid reliability and efficiency. A study by Zugschwert et al. [15] developed a multi-timescale method for classifying HESS in grid applications, highlighting the advantages of hybrid systems over conventional single-energy storage solutions. The research emphasized that HESS could effectively address challenges arising from the temporal and spatial decoupling of energy generation and consumption, particularly in scenarios with high renewable energy penetration.

Moreover, the integration of HESS into microgrids has shown promise in improving energy management and resilience. The UltraBattery, for example, combines the features of a lead-acid battery and a supercapacitor, offering both high energy and power capabilities [16]. Its application in microgrids has demonstrated improved efficiency in smoothing and shifting renewable energy, thereby enhancing the predictability and reliability of power availability [15,16].

In principle, the emergence of Hybrid Energy Storage Systems marks a significant advancement in the evolution of modern electric grids. By leveraging the complementary characteristics of various storage technologies, HESS provide a versatile and robust solution to the challenges posed by renewable energy integration and fluctuating power demands. As research and development in this field continue to progress, HESS are poised to play an increasingly pivotal role in achieving a stable, efficient, and sustainable energy future.

2. Components of Hybrid Energy Storage Systems

Hybrid Energy Storage Systems (HESS) are engineered to integrate multiple energy storage technologies, each with distinct characteristics as detailed in Table 1, to meet the diverse demands of modern electric grids. By combining components such as batteries, supercapacitors, and other storage devices, HESS can effectively manage both high-energy and high-power requirements, enhancing grid stability and efficiency [13]. Understanding the individual components and their synergistic interactions within a HESS is essential for optimizing performance and ensuring seamless integration into the power infrastructure. The architecture of a HESS is designed to leverage the complementary strengths of its components, ensuring efficient energy management and improved grid reliability [13,17]. By intelligently controlling the operation of each storage element, HESS can respond dynamically to varying energy demands and supply conditions, thereby enhancing the overall stability and efficiency of the electric grid.

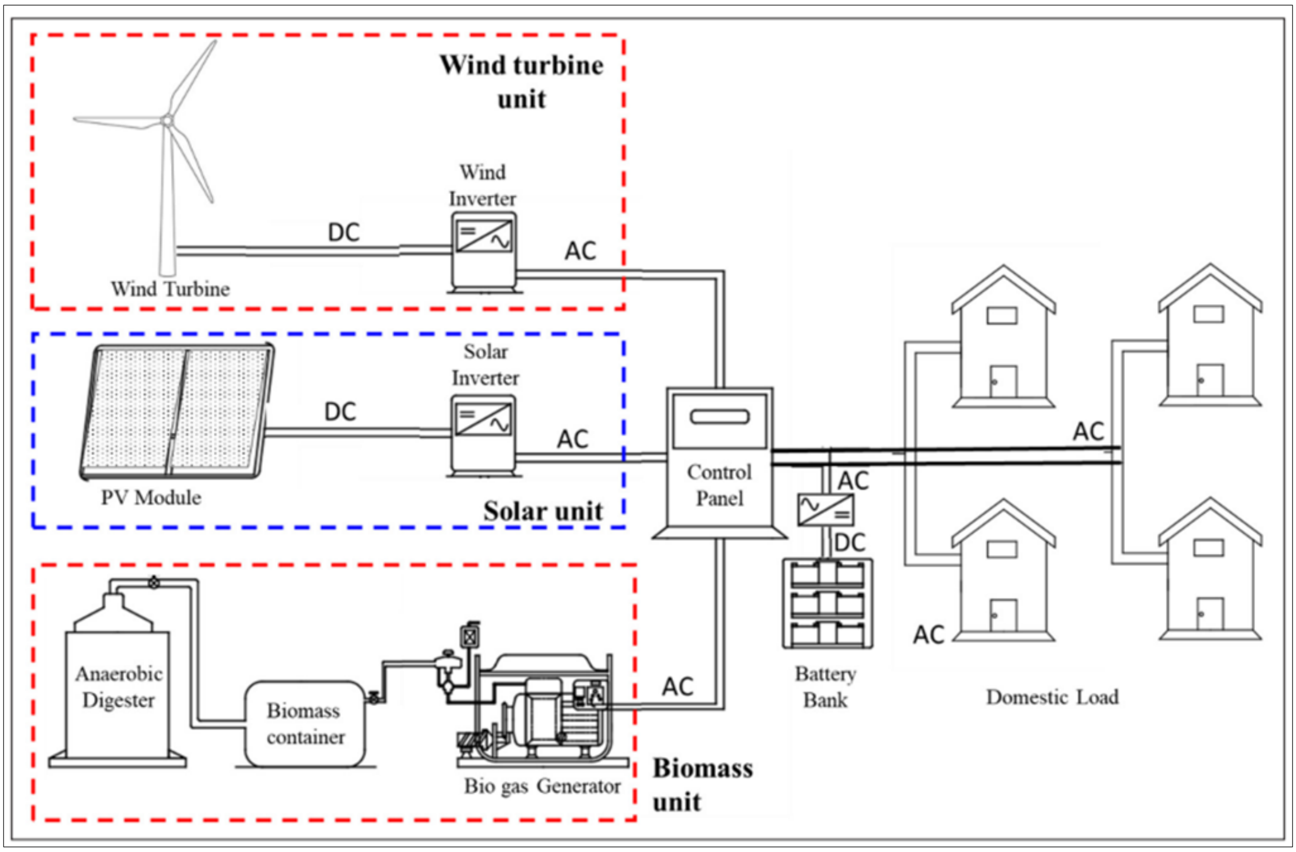

Figure 1 Schematic Diagram of an Integrated Hybrid Energy Storage System (HESS) Architecture. Reproduced from Ref [17] with permission

Table 1 Comparison of Various Energy Storage Technologies Commonly Utilized in Hybrid Energy Storage Systems (HESS)

Technology	Energy Density (Wh/kg)	Power Density (W/kg)	Efficiency (%)	Lifespan (cycles)	Response Time	Cost ($/kWh)	Advantages	Disadvantages
Lithium-Ion Batteries	150–200	250–340	90–95	1,000–10,000	Milliseconds	200–400	High energy density, high efficiency, fast response, declining costs	Thermal runaway risk, degradation over time, resource constraints
Supercapacitors	5–10	10,000	95	>1,000,000	Microseconds	10,000	Exceptional power density, rapid charge/discharge, extremely long cycle life	Low energy density, high cost per energy unit
Flywheels	20–80	500–10,000	85–95	>20,000	Milliseconds	500–1,000	High power density, long cycle life, rapid response, minimal maintenance	Self-discharge, mechanical complexity, site-specific installation requirements
Lead-Acid Batteries	30–50	180	70–80	500–2,000	Seconds	150–300	Low cost, mature technology, reliable	Low energy density, limited cycle life, environmental concerns due to lead content
Sodium-Sulfur Batteries	150–240	150–230	85–90	2,500–4,500	Milliseconds	200–500	High energy density, suitable for large-scale applications	High operating temperatures, safety concerns, complex thermal management
Vanadium Redox Flow Batteries	15–50	100–150	75–85	>10,000	Seconds	150–300	Scalability, long cycle life, easy refurbishment	Low energy density, large footprint, high upfront costs
Nickel-Cadmium Batteries	40–60	150–300	60–70	1,500–2,500	Seconds	500–1,500	Reliable performance in extreme temperatures, moderate energy density	Memory effect, environmental concerns due to cadmium toxicity, higher cost
Compressed Air Energy Storage	2–6	60–75	40–55	>10,000	Minutes	2–50	Large-scale energy storage, long lifespan, low operational costs	Low efficiency, geographical limitations, complex infrastructure requirements

2.1. Batteries

Batteries play a central role in Hybrid Energy Storage Systems (HESS) due to their ability to store substantial amounts of energy over extended periods. Their primary function in HESS is to provide long-duration energy storage, which is essential for balancing the intermittent nature of renewable energy sources and stabilizing the grid. Batteries allow for the absorption of excess energy during periods of low demand and its release when demand peaks, making them a crucial component in maintaining grid stability and reliability. The combination of batteries with other high-power storage technologies, such as supercapacitors, enables HESS to handle both energy and power demands efficiently [18].

2.1.1 Overview of Battery Technologies in HESS

Several types of batteries are used in HESS, each selected based on specific performance characteristics, cost considerations, and application requirements. Among the most commonly used are:

- **Lithium-ion Batteries**: Known for their high energy density, long cycle life, and relatively fast charging times, lithium-ion batteries are the most widely used battery technology in HESS. They are well-suited for applications requiring both high power and energy density, such as electric vehicles and grid-scale energy storage. The efficiency and maturity of lithium-ion technology have led to its dominance in both commercial and research settings [19,20].
- **Vanadium Redox Flow Batteries (VRFBs)**: These batteries are particularly beneficial for large-scale storage due to their ability to scale easily and provide long discharge durations. VRFBs are ideal for applications where energy storage needs are more about duration than power output, as they separate the energy and power components of the system, offering flexibility in storage sizing [21]. Research by Zugschwert et al. [15] has shown that VRFBs can be integrated with lithium-ion batteries to enhance the overall efficiency and lifespan of HESS.
- **Sodium-ion Batteries**: Sodium-ion batteries are emerging as a lower-cost and more environmentally friendly alternative to lithium-ion batteries. While they generally offer lower energy density, recent advances in sodium-ion battery technology have shown promise in reducing their energy gap relative to lithium-ion batteries. These advancements position sodium-ion batteries as a viable option for large-scale energy storage systems, particularly where cost and material availability are key considerations [22,23].
- **Flow Batteries**: In addition to VRFBs, other flow battery technologies, such as zinc-bromine and all-vanadium systems, are being explored for use in HESS. Flow batteries are particularly advantageous for long-duration storage because of their ability to maintain high efficiency over many cycles without degradation. These batteries are also scalable, which makes them ideal for large energy storage applications where long-term reliability and performance are crucial [24].

2.1.2 The Role of Batteries in HESS

In the context of HESS, batteries primarily function to store energy during periods of low demand and discharge it when demand rises. This capability is especially important for supporting renewable energy systems, where fluctuations in generation due to variable weather conditions can cause imbalances in power supply. Batteries help smooth out these fluctuations, ensuring that electricity supply remains consistent and reliable [25]. Furthermore, batteries in HESS can also provide ancillary services, such as frequency regulation and voltage support, both of which are essential for maintaining grid stability. Their high energy density allows them to store significant amounts of power, making them an effective tool for large-scale energy storage applications [26]. Recent advancements in battery technology have led to improved energy densities, faster charge-discharge cycles, and longer cycle lives. Research into hybrid systems that combine different types of batteries has demonstrated enhanced performance. For instance, integrating vanadium redox flow batteries with lithium-ion batteries can extend the operational life of the system while ensuring that both high power and long-duration energy storage needs are met efficiently [27,28].

Principally, batteries remain a crucial element in Hybrid Energy Storage Systems, providing reliable, long-duration storage and contributing to overall grid stability. With ongoing innovations, battery technologies are expected to play an even more significant role in the transition to sustainable energy systems, offering more efficient and cost-effective solutions for energy storage at scale.

2.2. Supercapacitors

Supercapacitors, also known as ultracapacitors, are energy storage devices that stand out due to their ability to deliver high power output, rapid charge and discharge capabilities, and exceptional cycle life. These characteristics make them invaluable components in Hybrid Energy Storage Systems (HESS), where they complement other storage technologies like batteries to optimize the performance of the entire system. Unlike batteries, which are designed for long-duration energy storage, supercapacitors excel in providing instantaneous power, handling short-term fluctuations and high-power demands efficiently. Their unique ability to quickly absorb and release energy enables them to perform effectively in hybrid configurations where rapid power delivery and absorption are crucial [29].

2.2.1 Role in Hybrid Energy Storage Systems

In Hybrid Energy Storage Systems, supercapacitors mainly address the need for high power density and rapid energy exchange. While batteries are ideal for providing sustained energy over longer periods, supercapacitors are designed to handle power fluctuations and transient spikes that batteries may not be equipped to manage. For instance, in applications such as electric vehicles or grid stabilization, supercapacitors can supply quick bursts of power during sudden demand spikes, which allows batteries to focus on delivering energy over longer durations [30]. This division of labor between the two energy storage devices ensures that the system operates more efficiently, as the batteries are relieved of the task of dealing with rapid power demands, thus reducing their wear and extending their operational life. Additionally, supercapacitors help maintain a stable power supply by quickly absorbing energy from regenerative braking systems in vehicles or from excess energy generated during periods of low demand in grid applications [30-33].

2.2.2 Benefits in Hybrid Configurations

The integration of supercapacitors into Hybrid Energy Storage Systems provides several notable benefits. One of the key advantages is that they significantly extend the lifespan of batteries by reducing the frequency of high-power demand on the batteries themselves. By absorbing quick power surges, supercapacitors prevent batteries from being subjected to rapid charge-discharge cycles, which can degrade their performance over time [30]. Furthermore, supercapacitors are highly efficient in capturing and storing energy during regenerative processes, ensuring that no energy is wasted and that the system's overall efficiency is maximized. This is particularly valuable in applications like electric vehicles, where energy recovery is crucial for improving overall efficiency. Another significant benefit of supercapacitors in HESS is their compact design. With their high power density, supercapacitors enable the creation of energy storage systems that are both lightweight and space-efficient, which is an essential factor in industries where weight and space are limited, such as in electric vehicles. Additionally, the use of supercapacitors can lower the overall cost of energy storage systems by reducing the reliance on batteries, which are typically more expensive [30,34].

2.2.3 Applications and Integration

Supercapacitors are widely used in a variety of applications within Hybrid Energy Storage Systems, including in electric and hybrid vehicles, renewable energy systems, and grid stabilization. In electric vehicles, supercapacitors provide the necessary power during acceleration and help capture energy during braking, significantly enhancing vehicle performance and energy efficiency. They also support grid stabilization by smoothing out voltage fluctuations and providing power during sudden load changes, ensuring that the grid remains balanced and resilient [35,36]. In renewable energy systems, supercapacitors help manage the intermittency of power generation from sources like wind and solar by quickly storing excess energy and releasing it during periods of low generation. This capability is especially useful in maintaining a consistent power supply and improving the efficiency of renewable energy systems [37].

Recent advancements in supercapacitor technology have further strengthened their role in HESS. For instance, improvements in materials such as graphene and carbon nanotubes have enhanced the energy storage capacity and charge-discharge rates of supercapacitors, making them even more effective in hybrid systems. These advancements have led to more compact and powerful supercapacitors that can handle larger power loads, making them increasingly attractive for large-scale applications like grid stabilization and electric vehicles [34]. As research continues, it is expected that the efficiency and energy density of supercapacitors will improve even further, reinforcing their position as a crucial element in the next generation of energy storage solutions.

2.3. Flywheels: Application and Integration in HESS

Flywheels are mechanical energy storage devices that store energy in the form of rotational kinetic energy. They are increasingly being integrated into Hybrid Energy Storage Systems (HESS) for applications where high power density, rapid response time, and long cycle life are critical. The fundamental principle behind flywheel energy storage involves accelerating a rotor to a high speed and maintaining that speed to store energy. When the stored energy is needed, the rotational speed is reduced, and the energy is converted back into electrical power. Flywheels offer distinct advantages in energy storage, including high power output, robustness, and efficiency, making them valuable in various energy applications, particularly when combined with batteries or supercapacitors in HESS [35,36].

2.3.1 Flywheel Technology Overview

Flywheels consist of a rotor, a bearing system, a motor/generator, and a controller. The rotor, typically made from materials such as steel or carbon fiber, is the component that spins to store energy. The rotor's rotational speed directly correlates to the amount of energy stored. The bearing system ensures minimal friction, allowing the rotor to spin for extended periods with little energy loss. The motor/generator unit is responsible for converting electrical energy into kinetic energy during the charging process and converting kinetic energy back into electrical energy during discharge. The flywheel energy storage system is enclosed within a sealed casing, maintaining a high vacuum environment to minimize aerodynamic drag and safeguard the rotor system during operation (see Figure 2). This technology offers several advantages, including high energy storage density, exceptional energy conversion efficiency of up to 90%, and a lifespan that is not affected by the depth of charge and discharge cycles. Additionally, it is an environmentally friendly solution with no associated emissions [37]. Flywheel systems are widely utilized in various applications, such as power systems—including renewable energy integration and frequency regulation—rail transportation, uninterruptible power supplies (UPS), and aerospace technology. The working principle of the flywheel is basically simple. During the charging phase, the motor accelerates the flywheel, transforming electrical energy into rotational kinetic energy for storage. When power is required, the flywheel slows down, and the stored mechanical energy is converted back into electricity via the generator to supply external loads. In recent years, advanced materials and magnetic bearings have been used to enhance flywheel performance, increasing energy density and reducing mechanical losses [37,38].

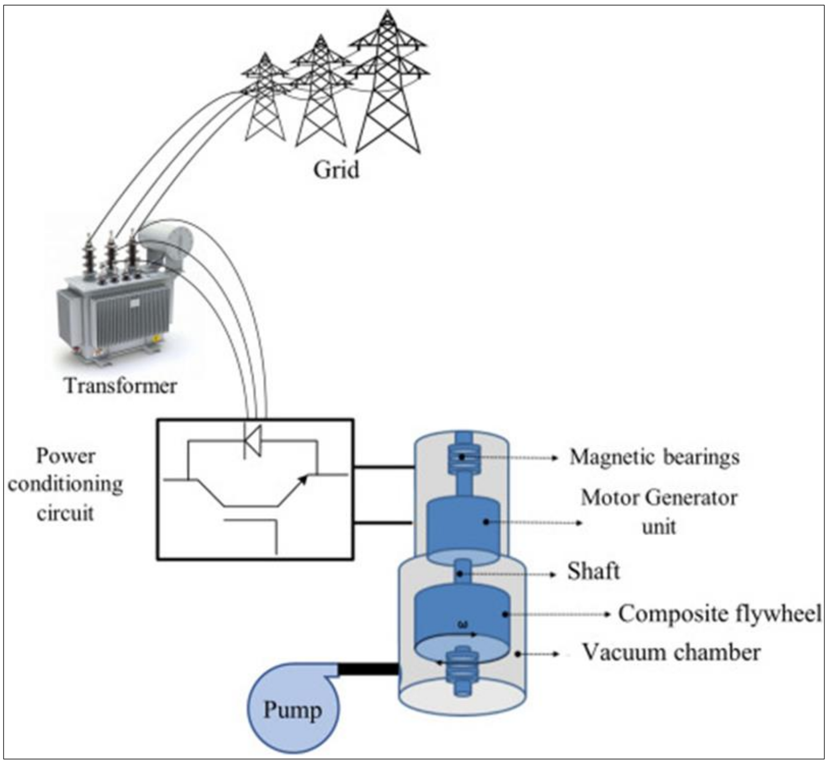

Figure 2 Schematic Diagram of a Flywheel Energy Storage System (FESS) Showing Key Components and Grid Integration. Reproduced from Ref [37] with permission

2.3.2 Role of Flywheels in Hybrid Energy Storage Systems

In Hybrid Energy Storage Systems, flywheels are typically used to meet high power demands over short durations. Unlike batteries or supercapacitors, which are better suited for either energy storage or rapid discharge, flywheels provide both. This dual capability makes them ideal for bridging the gap between short-term high-power needs and long-term energy storage. Flywheels are particularly effective in providing power during transient events, such as power outages, frequency regulation, or short-term spikes in demand. Their ability to respond almost instantaneously makes them a valuable asset for ensuring grid stability [35,37].

2.3.3 Advantages of Flywheels in HESS

One of the primary advantages of integrating flywheels into HESS is their ability to provide a rapid response to power fluctuations [36]. This is particularly beneficial in renewable energy applications where variability in generation can lead to sudden changes in power output. Flywheels can quickly absorb excess energy when generation exceeds demand and can rapidly release stored energy when demand spikes. This capacity to handle high-frequency fluctuations and provide power during these critical times enhances the stability of the grid [38]. In addition, flywheels have a long lifespan and can withstand millions of charge-discharge cycles without significant degradation. This is in stark contrast to conventional battery systems, which tend to degrade more rapidly when subjected to frequent cycling. Flywheels also require relatively low maintenance due to their simple mechanical structure, which contributes to their long-term cost-effectiveness. The lack of chemical reactions in flywheel systems means they are not subject to issues like battery memory effect or capacity degradation over time [39].

Another significant benefit is the high round-trip efficiency of flywheels. When designed with high-performance materials and optimized for minimal friction, flywheels can achieve efficiency levels upwards of 90%, which makes them an effective means of storing and utilizing energy with minimal losses. Furthermore, unlike batteries, flywheels are not prone to temperature sensitivity, which allows them to operate efficiently across a wide range of temperatures, an advantage in environments where temperature fluctuations are common [36,40].

2.3.4 Integration with Other Storage Technologies

Flywheels are often integrated with other energy storage technologies, such as batteries and supercapacitors, to form a hybrid system that leverages the strengths of each component. For instance, in an HESS, flywheels can be used in conjunction with lithium-ion batteries, where the flywheel manages high-power demands while the battery stores and provides energy over longer durations. In this configuration, the battery supports the system by providing energy during periods of low demand, while the flywheel responds to immediate power needs. This hybrid system maximizes the overall performance, ensuring that both energy and power demands are efficiently met [37,39].

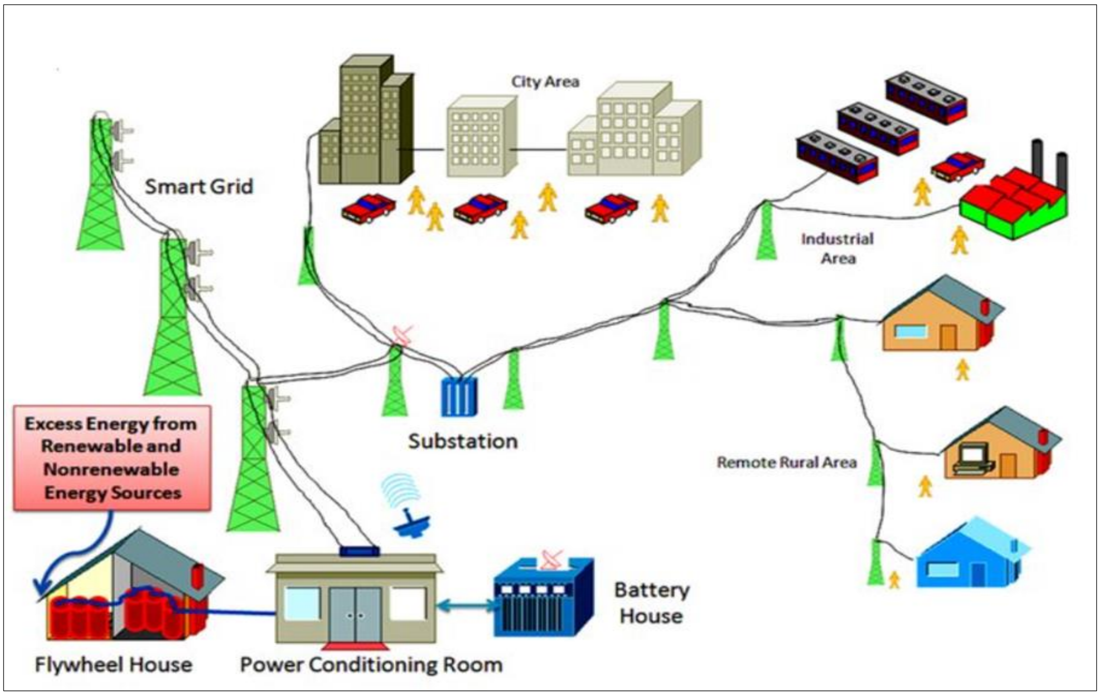

Figure 3 Schematic Representation of Flywheel Energy Storage System (FESS) Integration with Battery Storage and Smart Grid Infrastructure. Reproduced from Ref [39] with permission

Flywheels can also be combined with supercapacitors in a similar manner. Supercapacitors, with their high-power density, are suited to short, high-intensity bursts of energy, while flywheels provide the medium-term power that sustains the system. The combination of flywheels and supercapacitors enables rapid energy delivery over a wide range of timescales, from milliseconds to minutes, thus ensuring that both the energy and power requirements of the grid or application are met with minimal delay [40]. Figure 3 illustrates the integration of flywheel energy storage systems (FESS) with other energy storage technologies, such as battery systems, within a smart grid infrastructure. The schematic demonstrates how excess energy from renewable and non-renewable sources is managed through substations and power conditioning units, ensuring efficient energy distribution to diverse consumer sectors, including urban, industrial, and rural areas. This figure highlights the complementary role of flywheels in enhancing grid stability, energy efficiency, and system reliability when integrated with other storage solutions.

2.3.5 Applications of Flywheels in HESS

Flywheels are employed in a variety of HESS applications, ranging from grid stabilization to electric vehicle power systems. In grid applications, flywheels are used for frequency regulation and balancing energy supply and demand. By rapidly releasing or absorbing energy, flywheels help maintain the frequency of the grid, which is crucial for preventing power outages or equipment damage. Flywheels are also used in microgrids and off-grid systems, where they provide energy storage and backup power, particularly in remote locations where traditional grid infrastructure is unavailable [41,42]. In the transportation sector, flywheels have found application in hybrid electric vehicles (HEVs) and trains, where they store and release energy during acceleration and braking. In these systems, flywheels are used to recapture energy during braking (regenerative braking) and provide extra power during acceleration, improving fuel efficiency and reducing emissions. The use of flywheels in this context enhances the performance of electric propulsion systems, particularly in heavy-duty transport and public transit systems [43].

2.4. Other Storage Technologies

While batteries, supercapacitors, and flywheels represent some of the most well-established energy storage technologies in Hybrid Energy Storage Systems (HESS), there is a growing interest in emerging storage solutions that offer complementary benefits. These new technologies are designed to address the limitations of traditional storage systems, such as energy density, efficiency, cost, and environmental impact. As the demand for more sustainable, efficient, and high-performance energy storage solutions increases, several alternative technologies have gained attention in recent years. These technologies, including pumped hydro storage, compressed air energy storage (CAES), solid-state batteries, and advanced thermal storage systems, offer unique advantages that can be integrated into HESS for a more versatile and efficient energy storage solution.

2.4.1 Pumped Hydro Storage (PHS)

Pumped hydro storage (PHS) is one of the oldest and most reliable forms of large-scale energy storage, and it continues to play a crucial role in balancing supply and demand on the grid. In PHS systems, water is pumped from a lower reservoir to a higher one using excess electricity during periods of low demand. When there is a need for power, the stored water is released from the upper reservoir, flowing through turbines to generate electricity. This technology has a high round-trip efficiency and is capable of storing vast amounts of energy over long durations. However, its implementation is geographically dependent, requiring suitable topography and significant capital investment for infrastructure [44,45].

Despite its limitations, PHS remains a cornerstone of large-scale energy storage and is being increasingly integrated into hybrid systems alongside other technologies like batteries and supercapacitors to create more flexible and sustainable energy storage solutions. By coupling PHS with newer technologies, HESS can combine the benefits of long-duration storage from PHS with the rapid discharge and high-power capabilities of other systems, creating a more balanced and resilient grid [46].

2.4.2 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) is another emerging technology that holds promise for hybrid energy systems. In a CAES system, excess electricity is used to compress air and store it in underground caverns or above-ground storage tanks. When energy is needed, the compressed air is released, heated, and expanded through a turbine to generate electricity. CAES systems offer the advantage of providing large-scale storage over long durations, similar to pumped hydro storage. The efficiency of CAES systems has been significantly improved in recent years with the advent of adiabatic CAES (A-CAES) and diabatic CAES (D-CAES) technologies, which reduce the energy losses associated with the compression and expansion cycles [48].

The main benefit of CAES systems lies in their ability to store energy for extended periods, making them ideal for integrating intermittent renewable energy sources, such as wind and solar power, into the grid. By pairing CAES with other energy storage systems that can handle rapid power fluctuations (such as supercapacitors or flywheels), HESS can provide both long-term storage and rapid-response capabilities, addressing the intermittency and variability of renewable energy generation [13,49]. However, CAES is still in the early stages of commercialization, and its widespread adoption may be limited by factors such as location-specific infrastructure and high capital costs.

2.4.3 Solid-State Batteries

Solid-state batteries are a next-generation battery technology that promises to revolutionize energy storage with higher energy densities, improved safety, and longer lifespans compared to conventional lithium-ion batteries. Unlike traditional lithium-ion batteries, which use liquid electrolytes, solid-state batteries utilize a solid electrolyte. This design eliminates many of the risks associated with liquid electrolytes, such as leakage, flammability, and dendrite formation. Solid-state batteries also offer the potential for greater energy densities, which could significantly increase the storage capacity of HESS without requiring larger or more costly systems [50,51].

The integration of solid-state batteries into hybrid energy storage systems is still in the experimental and early commercialization phases, with many challenges to be addressed, including manufacturing scalability, cost reduction, and long-term stability. However, researchers are optimistic about the potential of solid-state batteries to complement other storage technologies in HESS. Their higher energy density and safety features could make them ideal for applications requiring both high energy storage and compact design, such as in electric vehicles and stationary grid storage systems [50,52].

2.4.4 Advanced Thermal Energy Storage

Advanced thermal energy storage (TES) systems store energy in the form of heat rather than electrical energy. These systems capture excess energy during periods of low demand and convert it into heat, which can later be converted back into electricity when needed. Various methods of thermal energy storage exist, including molten salt, phase change materials (PCMs), and solid-state heat storage systems. Among these, molten salt TES has become the most widely used in concentrating solar power plants, where excess heat is stored in molten salts and then used to generate electricity during cloudy periods or at night [53-55].

In the context of Hybrid Energy Storage Systems, advanced thermal storage solutions are being explored for their ability to provide long-duration energy storage. These systems can store large quantities of energy at relatively low costs, making them an attractive option for grid-scale applications. When integrated with other storage systems, such as batteries and flywheels, advanced thermal storage can provide complementary long-duration energy storage, balancing short-term power fluctuations with stable, large-scale energy reserves [56,57].

2.4.5 Hydrogen Energy Storage

Hydrogen energy storage is another emerging technology gaining attention in the context of Hybrid Energy Storage Systems. In a hydrogen-based storage system, electricity is used to split water molecules into hydrogen and oxygen through a process known as electrolysis. The hydrogen gas can then be stored and, when needed, used in fuel cells to generate electricity. Hydrogen offers a high energy density and can be stored for long periods, making it an attractive option for both grid-scale and off-grid energy storage applications [58].

The integration of hydrogen storage with other energy storage technologies, such as batteries or supercapacitors, can provide a hybrid solution that combines the benefits of both rapid power delivery and long-duration energy storage. However, hydrogen storage is currently limited by high costs, efficiency losses in the electrolysis process, and the need for specialized infrastructure. Nevertheless, ongoing research into improving electrolyzer efficiency, reducing storage costs, and enhancing fuel cell performance is likely to make hydrogen storage a more viable option for future HESS configurations [58].

3. Design Considerations for HESS in Grid Applications

Designing a Hybrid Energy Storage System (HESS) for grid applications requires careful consideration of various technical, economic, and operational factors to ensure that the system meets the specific demands of grid stability, reliability, and efficiency. HESS combines different storage technologies to optimize energy management by addressing the inherent challenges posed by fluctuating renewable energy sources, peak demand periods, and grid disturbances. Key design considerations include the selection of appropriate storage technologies, system sizing, efficiency optimization, cost-effectiveness, and the ability to integrate seamlessly with existing grid infrastructure. This section explores the critical factors involved in designing effective and sustainable HESS solutions for grid applications, drawing from recent research and industry practices.

3.1. Configuration Optimization

The configuration of Hybrid Energy Storage Systems (HESS) is a critical aspect in ensuring that multiple storage technologies are optimally integrated to provide reliable and efficient performance in grid applications. HESS combine two or more energy storage technologies, such as batteries, supercapacitors, flywheels, or compressed air, to leverage their complementary strengths. The primary goal of configuration optimization is to design a system that maximizes the benefits of each storage technology, minimizing their respective weaknesses, and achieving superior performance in terms of energy efficiency, cost, and system flexibility [59].

3.1.1 Integration of Complementary Storage Technologies

The fundamental challenge in optimizing HESS configuration lies in selecting the right combination of storage technologies that complement each other. Each storage technology has distinct characteristics, including power density, energy density, response time, and cycle life. For example, batteries, such as lithium-ion, offer high energy density and are well-suited for long-duration storage, while supercapacitors excel in high power density and can deliver rapid bursts of energy over short durations. Flywheels, on the other hand, can provide high power outputs with fast response times and can handle rapid cycling, while technologies like pumped hydro storage offer long-duration, large-scale energy storage [60,61].

The key to effective integration is understanding the role that each storage technology will play in the overall system. In a typical HESS configuration, batteries are often used for longer-duration energy storage, while supercapacitors or flywheels are employed to handle short-duration power surges. By strategically selecting technologies that can work in tandem to balance both energy and power demands, HESS can deliver greater performance than any individual technology could achieve alone [18]. For example, a combination of lithium-ion batteries for energy storage and supercapacitors for rapid discharge may be ideal for smoothing out intermittent renewable energy production while ensuring grid stability [62].

3.1.2 Power and Energy Sizing

An essential consideration in the optimization of HESS configurations is determining the appropriate sizing of each storage technology to meet the specific needs of grid applications. Power and energy sizing are critical for ensuring that the system can both deliver sufficient power during peak demand periods and store adequate energy during off-peak times [59]. The balance between power and energy must be carefully calculated, as over-sizing one component can lead to inefficiencies and unnecessary costs, while under-sizing may result in poor system performance.

To achieve optimal sizing, advanced modeling and simulation techniques are often employed. These models take into account factors such as load profiles, renewable energy generation patterns, and grid requirements. By simulating various configurations under different operational conditions, it is possible to identify the most efficient and cost-effective configuration that meets both power and energy demands without overburdening any single technology [63]. Moreover, the sizing of storage systems must also consider the expected lifespan of each technology, ensuring that the system maintains a high level of efficiency throughout its operational life.

3.1.3 System Control and Management Strategies

The successful operation of an HESS relies heavily on sophisticated control and management strategies to ensure that each component operates at peak efficiency. In a hybrid system, the storage devices must be able to charge and discharge independently, and the system must intelligently manage energy flow to balance supply and demand. The control strategy needs to determine when to deploy each technology based on factors such as state of charge, energy demand, and the availability of renewable energy sources [64,65].

One of the most common approaches to managing energy flow in HESS is through the use of power management algorithms that dynamically allocate energy between the different storage devices. These algorithms monitor grid conditions in real time and make decisions based on predefined operational parameters. For instance, during periods of high energy demand or low renewable generation, the algorithm may prioritize the discharge of batteries to provide sustained power. Conversely, when rapid power delivery is needed, such as during transient disturbances or spikes in demand, the algorithm might engage supercapacitors or flywheels to provide instantaneous support [63].

The control system must also optimize the charging and discharging cycles of each storage device to extend the overall lifespan of the system. For example, batteries degrade more quickly under high power loads, so the system might prioritize supercapacitors or flywheels for handling short, high-intensity bursts of energy, while the batteries are used for more prolonged discharges. Effective management algorithms must balance these factors, ensuring that the HESS operates efficiently while minimizing wear on each storage component [65].

3.1.4 Cost-Effectiveness and Economic Optimization

The economic optimization of a HESS configuration is a significant factor in its design, particularly for grid-scale applications where cost-effectiveness is essential. While HESS can provide superior performance compared to single-storage systems, they also come with increased initial capital costs due to the need for multiple storage technologies, as well as more complex control systems. Therefore, the optimization of configuration must consider both the upfront costs and the long-term operational savings [63].

To optimize the economic performance, the system design must account for factors such as capital investment, maintenance costs, and the potential revenue generation from services such as frequency regulation or demand response. Moreover, the operating costs of different storage technologies should be evaluated, including energy losses, maintenance requirements, and the expected degradation of each storage device over time. Economic models are often used to perform a cost-benefit analysis of various HESS configurations, taking into consideration the expected return on investment and the lifetime of the system. These models help identify the most cost-efficient design that provides the best balance between performance and financial feasibility [66,67].

3.1.5 Flexibility and Scalability

Another important aspect of configuration optimization is ensuring that the HESS is flexible and scalable to adapt to future changes in grid demand and renewable energy integration. As the energy landscape continues to evolve with increasing shares of intermittent renewable generation, it is essential for energy storage systems to be scalable and adaptable to these changes. Configuration optimization involves designing systems that can be easily expanded or modified to accommodate additional storage capacity or new technologies as they become available [13].

Scalability also pertains to the ability of the system to operate across various scales, from smaller microgrids to large utility-scale grids. A well-optimized HESS should be able to integrate seamlessly into different grid infrastructures, providing reliable storage and power management capabilities regardless of the grid size or complexity. As renewable energy technologies advance and energy demand patterns change, having a flexible and scalable HESS configuration ensures that the system remains relevant and effective over the long term [13,68].

3.2. Control Strategies: Advanced Control Methods for Efficient Energy Management

Efficient energy management in Hybrid Energy Storage Systems (HESS) is integral to the reliable functioning of grid applications. Control strategies are essential for optimizing the charging, discharging, and overall coordination of multiple energy storage technologies within a hybrid system. Figure 4 illustrates a comprehensive control strategy for a Hybrid Energy Storage System (HESS) integrated with renewable energy sources. The diagram highlights the role of a central controller in managing energy flows between solar panels, wind turbines, and storage units while ensuring optimal distribution to AC and DC loads. The power flow directions, control signals, and communication lines depict a coordinated approach to enhance system efficiency and stability. By implementing such control methodologies, HESS can dynamically respond to fluctuations in generation and load demand, thus improving overall grid reliability and energy utilization. These strategies ensure that the system operates at peak performance while balancing energy supply and demand, minimizing operational costs, extending the lifespan of the storage components, and enhancing grid stability [13]. Given the complexity of hybrid systems, advanced control methods (see Table 2) are employed to manage the dynamic interactions between storage devices and to respond effectively to real-time grid conditions. This section explores the primary advanced control strategies used in HESS, including their mechanisms, benefits, and the role of artificial intelligence and machine learning in enhancing these strategies [69].

Table 2 Comparison of Control Strategies for HESS

Control Strategy	Description	Effectiveness in Different Scenarios	Challenges
Predictive Control	Utilizes models to forecast future energy demands and system states, allowing for proactive management of energy storage components. This approach often employs Model Predictive Control (MPC) algorithms to optimize	- **Renewable Integration:** Effectively manages the variability of renewable energy sources by anticipating fluctuations and adjusting storage utilization accordingly. - **Load Following:** Enhances	- **Model Accuracy:** Requires precise system models for accurate predictions, which can be complex to develop. - **Computational Demand:** Involves significant computational resources for real-time optimization,

	performance over a specified future horizon.	the system's ability to meet dynamic load demands by predicting and preparing for changes in consumption patterns. - **Peak Shaving:** Reduces peak demand charges by forecasting high-demand periods and strategically discharging storage systems.	potentially limiting applicability in systems with limited processing capabilities. - **Uncertainty Handling:** Challenges arise in accounting for unforeseen events or rapid changes in system conditions.
Real-Time Optimization	Involves continuous assessment and adjustment of energy storage operations based on real-time data inputs. This strategy aims to optimize performance metrics such as efficiency, cost, and system stability by responding promptly to current conditions.	- **Dynamic Environments:** Well-suited for applications where system conditions change rapidly, necessitating immediate responses to maintain optimal performance. - **Energy Market Participation:** Enables systems to capitalize on real-time energy pricing by adjusting storage utilization to maximize economic benefits. - **Grid Support:** Provides ancillary services such as frequency regulation by swiftly responding to grid fluctuations.	- **Data Dependency:** Relies heavily on the availability and accuracy of real-time data, which may be challenging in certain environments. - **System Complexity:** The need for continuous monitoring and adjustment increases system complexity and may require sophisticated control infrastructure. - **Stability Concerns:** Rapid decision-making processes must be carefully managed to avoid instability due to overreactions to transient conditions.
Distributed Control	Employs a decentralized approach where multiple controllers manage different components or subsystems independently. This strategy enhances scalability and resilience by reducing reliance on a central controller.	- **Large-Scale Systems:** Ideal for extensive HESS installations where centralized control is impractical due to communication delays or single points of failure. - **Modular Architectures:** Facilitates the integration of diverse storage technologies by allowing tailored control strategies for each module. - **Fault Tolerance:** Improves system resilience by isolating faults to individual controllers, preventing widespread system disruptions.	- **Coordination Complexity:** Ensuring harmonious operation among distributed controllers can be challenging, particularly in maintaining overall system objectives. - **Communication Overhead:** Requires robust communication networks to facilitate information exchange between controllers, which can introduce latency and reliability issues. - **Consistency Maintenance:** Achieving consistent performance across distributed controllers necessitates sophisticated synchronization mechanisms.

3.2.1 Energy Management Algorithms

At the core of any HESS are energy management algorithms that govern the interaction between different storage technologies to optimize their operation. These algorithms are designed to ensure that energy is stored or released at the right time, based on the energy demands of the grid and the characteristics of the storage devices involved. The key objective of energy management is to maximize the system’s overall efficiency by appropriately distributing the energy flow between the components, preventing energy losses, and avoiding overuse of any single storage technology [61,70].

For example, during periods of high renewable energy generation, such as when solar or wind output peaks, the algorithm will prioritize the charging of batteries to store surplus energy. During periods of high demand or low renewable generation, the algorithm will deploy energy stored in the batteries to maintain grid stability [71]. At the same time, supercapacitors or flywheels might be engaged to deliver rapid bursts of energy to balance short-term fluctuations in demand. One of the challenges in energy management is to minimize the wear on storage technologies, particularly batteries, which degrade faster when subjected to frequent high-power cycles. Therefore, the energy management strategy must consider the limitations and performance characteristics of each technology, ensuring that the system remains reliable and cost-effective over its lifecycle [70,72].

Energy management algorithms rely on sophisticated optimization techniques, such as linear programming, dynamic programming, and model predictive control, to find the most efficient distribution of energy. These techniques enable the system to adapt to varying conditions, such as fluctuating electricity prices, grid frequency disturbances, and varying renewable generation rates, while minimizing the overall operating costs of the HESS. In addition, the algorithms must integrate real-time monitoring data from the grid and storage devices to make accurate predictions about energy usage and to optimize system performance on the fly [68,71,73].

3.2.2 Predictive Control Strategies

Predictive control strategies are a key advancement in HESS management, leveraging predictive algorithms to forecast future energy demand and generation patterns. Unlike traditional reactive control systems, which respond to changes in real-time, predictive control strategies analyze historical data, weather forecasts, and grid conditions to anticipate future energy needs. By making predictions about energy consumption and renewable generation, predictive control strategies can preemptively adjust the operation of storage devices to avoid inefficiencies and to ensure that the system is prepared for upcoming fluctuations in energy demand [74].

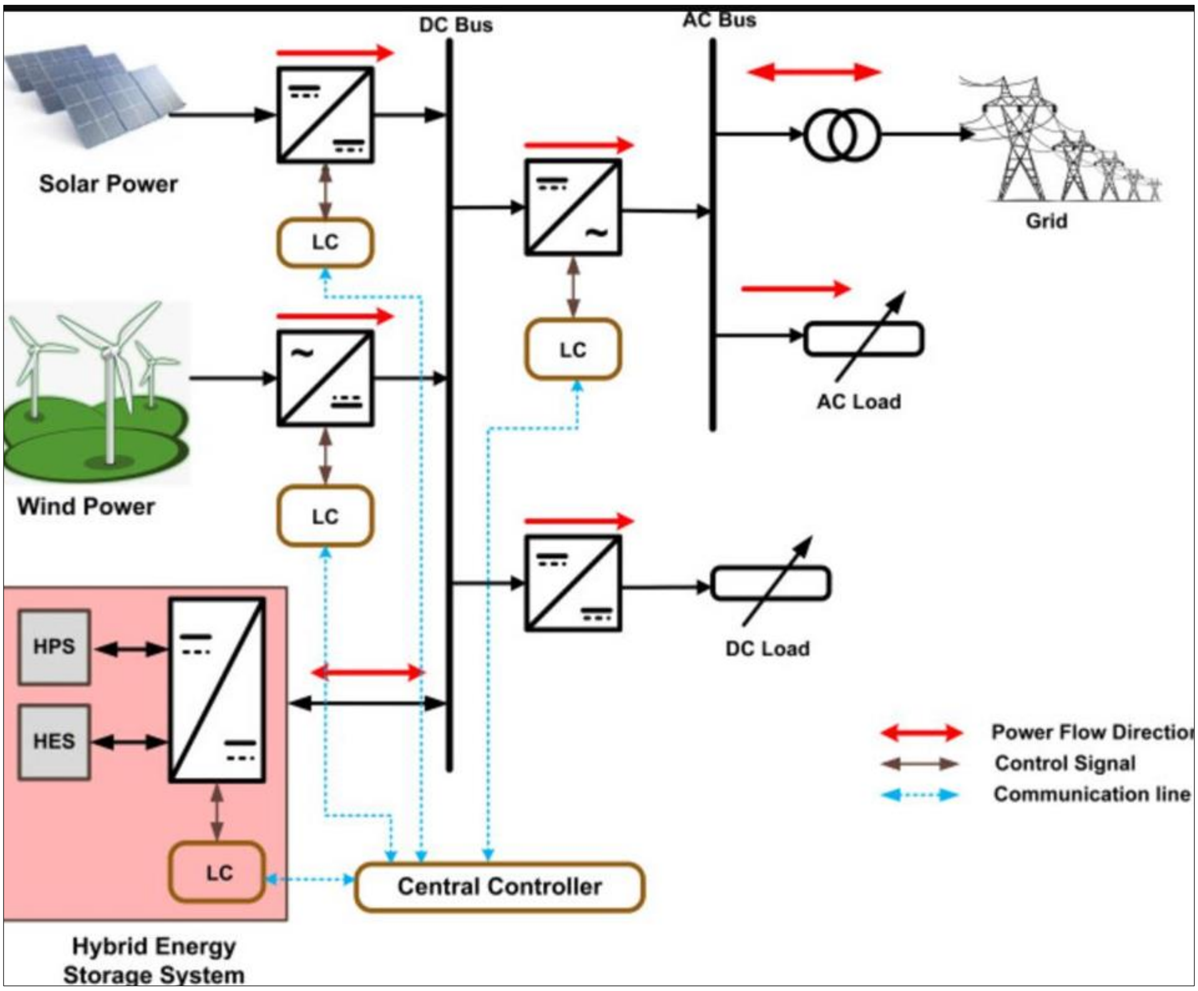

Figure 4 Schematic Representation of Hybrid Energy Storage System (HESS) Control Strategy Integrating Renewable Energy Sources. Reproduced from Ref [65] with permission

For example, by predicting a peak in electricity demand or a period of low renewable generation, the predictive control system can preemptively discharge batteries or store energy in anticipation of these changes. This not only improves the efficiency of the system but also enhances grid reliability by ensuring that energy is available when it is needed most. Predictive control methods are particularly beneficial in managing the intermittency of renewable energy sources, as they allow the system to adjust in advance, minimizing the reliance on fossil-fuel-based peaking power plants [73,75].

The implementation of predictive control strategies in HESS often requires the use of advanced forecasting models, which incorporate real-time weather data, grid load forecasts, and historical trends. Machine learning and data-driven approaches are increasingly being integrated into predictive models to improve the accuracy of forecasts and enable more responsive control strategies. These models can also adapt to changes in grid conditions, ensuring that the system remains optimized even in the face of uncertain or fluctuating energy demands [75].

3.2.3 Distributed Control Systems

In large-scale HESS applications, particularly those involving multiple distributed energy storage units, centralized control may not be feasible due to the complexity and scale of the system. Distributed control systems (DCS) offer an effective solution by decentralizing the control process and enabling each storage unit to operate independently while still adhering to the overall system objectives. In a distributed control strategy, local controllers within each storage unit communicate with one another to share information about system performance, energy demand, and other relevant data, allowing for real-time coordination across the entire HESS [76].

The advantage of distributed control lies in its ability to reduce the communication burden on central controllers and enhance the system's scalability and flexibility. For example, in a large grid-connected HESS, multiple storage devices located at different points in the grid may be managed by local controllers that adjust their operation based on localized conditions. These local controllers use shared data and feedback from neighboring units to optimize the collective performance of the HESS, ensuring that energy is stored or released in the most efficient manner across the entire system [77,78]. Distributed control systems can also improve the robustness and resilience of HESS in the event of a failure or malfunction of one of the components. Since each storage device operates autonomously, the failure of one unit does not necessarily compromise the performance of the entire system. This decentralization enhances the overall reliability of the grid, allowing it to continue functioning even if one part of the energy storage system is unavailable [78].

3.2.4 Role of Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) are increasingly being integrated into the control strategies of HESS to enhance their performance and adaptability. AI and ML techniques enable energy management systems to learn from historical data, predict future conditions, and autonomously adjust the system's operation in real-time to improve efficiency and minimize costs. These technologies are particularly useful in dynamic and complex environments, where traditional control methods may struggle to adapt to rapidly changing conditions [79,80]. For instance, machine learning algorithms can analyze vast amounts of data from the grid, storage devices, and environmental sensors to predict trends in energy demand, renewable generation, and system performance. By identifying patterns in the data, the system can predict periods of high demand or low generation and adjust its charging and discharging strategies accordingly [80]. Additionally, AI-based control systems can optimize energy flow by learning from previous cycles and making real-time adjustments to improve efficiency, thereby reducing the wear on storage devices and extending their lifespan [81].

Machine learning can also be used to enhance predictive control strategies, improving the accuracy of forecasts and enabling better decision-making. These systems can be trained on large datasets, including weather patterns, grid load forecasts, and energy production data, to develop more precise models that anticipate future conditions with higher accuracy. The adaptability of AI and ML systems ensures that HESS can continue to optimize their operation as grid conditions evolve over time, making them an essential component of future energy storage solutions [13, 80].

3.3. Sizing and Scalability: Determining Appropriate System Size and Scalability Factors

Sizing and scalability are fundamental considerations in the design of Hybrid Energy Storage Systems (HESS) for grid applications. These factors directly influence the system's effectiveness, economic viability, and ability to meet the dynamic needs of modern electrical grids. The challenge lies in determining the optimal size of the energy storage system to meet specific operational goals, such as grid stability, renewable energy integration, and peak shaving, while ensuring scalability for future growth [82]. This subtopic delves into the key elements that affect sizing and scalability, including the capacity of individual storage technologies, system modularity, and factors that impact the scalability of HESS in grid applications [83].

3.3.1 Determining System Size

The size of a Hybrid Energy Storage System must be tailored to meet the energy demands of the grid while considering the unique characteristics of each storage technology within the hybrid configuration [84]. A key factor in sizing is the total energy storage capacity required to support grid applications, such as load leveling, renewable energy integration, or frequency regulation. According to the findings of Yang et al. [85], the size of the battery storage component in HESS is typically determined by factors such as the duration of energy supply needed, the rate of energy discharge, and the operational lifespan of the battery. For instance, when using lithium-ion batteries in HESS, the energy capacity is often defined by the amount of energy that can be stored for hours to days, depending on the specific needs of the grid.

Additionally, for applications such as peak shaving, the power rating of the storage system, which defines the maximum energy output over a short period, is equally important. According to studies by Rao et al. [86], batteries are commonly chosen for long-duration storage applications, whereas supercapacitors or flywheels are more suitable for short-duration, high-power applications. This dual-use nature of HESS, combining batteries for energy storage and fast-acting devices like supercapacitors for short-term power bursts, requires a careful balance in determining the overall size of the system. Researchers have emphasized the importance of modeling energy demand profiles and operational constraints, such as grid frequency requirements and power quality standards, to accurately size each component of the system [86].

The sizing process also involves a trade-off between cost, efficiency, and operational flexibility. According to Ahmad et al. [87], over-sizing a system to ensure reliability may lead to excessive capital expenditure, while under-sizing could result in insufficient capacity to meet the grid's needs during peak load conditions or periods of low renewable energy generation. Therefore, detailed load forecasting and simulation studies are crucial in accurately determining the optimal size of each storage technology to ensure reliable and cost-effective system performance [87].

3.3.2 Factors Affecting Scalability

Scalability refers to the ability of a Hybrid Energy Storage System to grow and adapt to increasing energy demands over time. This capability is particularly important in grid applications, where future energy demands are often uncertain due to factors such as population growth, increased electrification, and the growing penetration of renewable energy sources. To ensure that HESS systems are adaptable, scalability factors must be integrated into the design phase, taking into account both technological and operational aspects [88].

One of the primary factors that influence the scalability of HESS is the modularity of the individual storage components. Modularity enables the system to be expanded by adding more storage units as demand grows, without requiring significant changes to the existing infrastructure. For instance, as highlighted by Rothgang et al. [89], battery systems with standardized designs can be easily scaled by adding more batteries to the configuration. This modularity not only facilitates the expansion of the system but also allows for easier maintenance, as individual components can be replaced or upgraded without disrupting the overall operation of the HESS.

Moreover, the integration of storage technologies with different energy capacities and discharge rates allows for a flexible, scalable approach to HESS design. For example, the inclusion of both batteries and supercapacitors in a hybrid configuration enables the system to meet both long-duration and short-duration energy storage requirements. According to Lund et al. [90], this flexibility can be key when scaling up a system to accommodate growing energy demands or higher renewable energy generation rates. By incorporating multiple types of storage technologies that are optimized for different time scales and power demands, the system can evolve to meet future grid requirements without overhauling the entire setup.

Another factor influencing scalability is the ability to integrate emerging energy storage technologies into existing HESS configurations. As new storage technologies such as solid-state batteries, advanced flywheels, or compressed air energy storage systems become more commercially viable, HESS can be designed to accommodate these innovations. According to the research of Cavus et al. [91], the adaptability of a hybrid system to integrate next-generation storage technologies is essential to future-proofing the grid, ensuring that the system can scale as new advancements in energy storage technologies emerge. From a grid infrastructure perspective, scalability is also influenced by the capacity of the grid itself to accommodate additional storage units. The ability of the grid to integrate large-scale storage solutions is determined by its current infrastructure, the presence of smart grid technologies, and the capacity of grid operators to manage distributed storage systems. Smart grid technologies, including advanced metering infrastructure, real-time data communication, and automated control systems, enable better coordination between storage devices and grid operators, allowing for more seamless scalability. In a recent review, Ekechukwu et al. [92] stressed that the deployment of smart grids is crucial for enabling scalable HESS systems, as it facilitates the real-time monitoring and optimization required to integrate a growing number of energy storage units.

3.3.3 Modelling and Simulation for Sizing and Scalability

Modeling and simulation play a critical role in determining both the size and scalability of HESS. By using simulation tools, grid operators and system designers can predict the performance of different storage configurations under various scenarios, such as fluctuations in renewable energy generation or changes in grid demand. These models incorporate parameters such as load profiles, weather forecasts, and energy generation patterns to simulate how HESS will respond to real-world conditions. According to the research of Lin et al. [93], simulation models are vital for optimizing the sizing of each component within the system, ensuring that the HESS operates efficiently and cost-effectively under all possible operating conditions.

Simulation studies also enable the scalability of HESS to be assessed over time, providing insights into how the system will perform as energy demand grows. For example, simulations can help determine the optimal expansion strategy for a HESS, indicating when and how to add additional storage units to maintain optimal performance. These models can also help identify potential bottlenecks in the system's scalability, such as limitations in grid infrastructure or control system capabilities, and suggest ways to mitigate these issues [93].

4. Technological Advancements in HESS

As the global energy landscape shifts toward renewable sources, the demand for more sophisticated and efficient Hybrid Energy Storage Systems (HESS) has grown exponentially. Traditional energy storage systems, while effective in specific applications, often fall short in addressing the diverse and dynamic requirements of modern grids. HESS have emerged as a versatile solution, leveraging the complementary strengths of different storage technologies. However, their effectiveness depends heavily on continuous technological advancements to overcome existing limitations and enhance their integration into complex energy systems [94].

Recent innovations have focused on improving the performance, reliability, and scalability of HESS [60,72]. Developments in advanced materials, smart grid integration, and artificial intelligence-driven control strategies have significantly enhanced the efficiency and adaptability of these systems. Furthermore, breakthroughs in power electronics and energy management systems have enabled seamless coordination between different storage components, optimizing energy usage and minimizing losses. These technological strides (see Table 3) are not only enabling HESS to meet present-day grid requirements but also paving the way for their role in future energy systems characterized by higher renewable penetration and decentralized energy networks [50].

Table 3 Key Technological Advancements in Hybrid Energy Storage Systems

Advancement	**Description**	**Benefits**	**Challenges**
Advanced Energy Management Systems (EMS)	Integration of sophisticated EMS utilizing artificial intelligence and machine learning algorithms to optimize the operation of HESS components. These systems predict energy demand, manage charge-discharge cycles, and enhance overall system efficiency.	- Enhanced performance by utilizing strengths of each technology - Increased flexibility in energy management - Improved system efficiency	- Enhanced performance by utilizing strengths of each technology - Increased flexibility in energy management - Improved system efficiency
Integration of Renewable Energy Sources	Seamless integration of renewable energy sources like solar and wind with HESS to manage their intermittent nature. Advanced control strategies are employed to balance supply and demand, ensuring a stable power output.	- Increased utilization of renewable energy - Reduction in greenhouse gas emissions	- Increased utilization of renewable energy - Reduction in greenhouse gas emissions

		- Enhanced grid stability	- Enhanced grid stability
Advancements in Power Electronics	Development of advanced power electronic converters and inverters to efficiently manage the flow of energy between different storage components and the grid. These advancements enable better control, higher efficiency, and improved reliability of HESS.	- Improved energy conversion efficiency - Enhanced system reliability - Greater flexibility in system design	- Improved energy conversion efficiency - Enhanced system reliability - Greater flexibility in system design
Implementation of Smart Grid Technologies	Incorporation of smart grid technologies to enable real-time monitoring, control, and optimization of HESS. This includes the use of advanced sensors, communication networks, and data analytics to enhance system performance.	- Real-time system monitoring and control - Improved demand response capabilities - Enhanced fault detection and system diagnostics	- High implementation costs - Cybersecurity risks - Need for standardization and interoperability among devices

This section delves into the latest technological advancements in HESS, exploring innovations in energy management, control algorithms, material science, and system integration. By examining these advancements, it highlights how cutting-edge research and engineering are shaping the future of hybrid energy storage, making it a cornerstone of sustainable and resilient grid infrastructure.

4.1. Integration with Renewable Energy Sources

The integration of renewable energy sources (RES) into the electrical grid presents challenges due to their inherent intermittency and variability. Hybrid Energy Storage Systems (HESS) have emerged as a pivotal solution to mitigate these challenges, enhancing the reliability and efficiency of renewable energy integration [5,17,13,59]. This section explores the role of HESS in facilitating renewable integration, examining technological advancements, control strategies, and real-world applications that underscore their effectiveness.

4.1.1 Role of HESS in Renewable Integration

Renewable energy sources like solar and wind are characterized by fluctuations that can disrupt grid stability. HESS, which combine multiple energy storage technologies such as batteries and supercapacitors, offer a means to balance these fluctuations. According to a review by Zhang et al. [95], HESS can effectively smooth out the power output from RES, providing both short-term and long-term energy storage solutions that accommodate the variable nature of renewables.

4.1.2 Technological Advancements in HESS

Recent technological advancements have significantly enhanced the capabilities of HESS in renewable integration. Innovations in battery technology, such as the development of sodium-ion batteries, have improved energy storage efficiency and safety. Stigliano et al. [96] have developed safer and more sustainable battery materials, including sodium-based batteries, which avoid the flammability issues of traditional lithium-ion batteries. Additionally, advancements in control algorithms have optimized the operation of HESS. Samende et al. [94] introduced a deep reinforcement learning-based control strategy to optimize the scheduling of hybrid energy storage systems and energy demand in real-time, improving renewable energy utilization and minimizing energy costs and carbon emissions.

4.1.3 Control Strategies for HESS

Effective control strategies are essential for maximizing the benefits of HESS in renewable integration. The implementation of advanced energy management systems enables real-time optimization of energy storage and distribution. Farah and Andresen [98] proposed an investment-based optimization method for sizing of electricity-hydrogen hybrid energy storage microgrids, enhancing the competitiveness of emerging energy storage technologies and reducing reliance on batteries in renewable energy systems. Moreover, the integration of smart grid technologies facilitates better coordination between HESS and renewable energy sources. Aghmadi et al. [18] emphasized that the deployment of smart grids is crucial for enabling scalable HESS systems, as it facilitates the real-time monitoring and optimization required to integrate a growing number of energy storage units.

4.1.4 Real-World Applications and Case Studies

The practical application of HESS in renewable integration is evident in various projects worldwide. In Australia, large-scale battery storage systems are being deployed to support the decarbonization of the energy sector and enhance grid stability. Akaysha Energy, backed by BlackRock, is implementing a network of large batteries across the country, including a $200 million project in Queensland with the capacity to power 300,000 homes [99,100]. This project is crucial for supporting the integration of renewable energy sources and improving the stability of the electrical grid. In the United Kingdom, the government is set to support pumped hydro energy storage projects to manage supply and demand volatility as more renewable power enters the grid. These projects will receive subsidies through a "cap and floor" mechanism, guaranteeing minimum revenue and preventing excessive charges. Pumped hydro stores energy by pumping water to an upper reservoir when electricity is cheap and releasing it to generate power during peak demand, thus facilitating the integration of renewable energy sources [99].

Despite the advancements, challenges remain in the widespread adoption of HESS for renewable integration. Issues such as high initial costs, technological complexity, and the need for standardized protocols require ongoing research and development. Future directions include the exploration of novel materials for energy storage, the development of more efficient control algorithms, and the integration of emerging technologies such as hydrogen storage. Researchers are also focusing on the economic and energetic assessment of hybrid energy storage systems. Foles et al. [101] investigated control combinations for a vanadium redox flow battery and a lithium-ion battery in a hybrid storage solution, evaluating performance through specific energy and economic key performance indicators. Their findings indicate that customized energy management strategies render the characteristics of different battery technologies complementary, enhancing the competitiveness of hybrid energy storage systems.

4.2. Smart Grid Compatibility: Role of HESS in Smart Grid Environments

The transition from conventional power grids to smart grids represents a paradigm shift in energy management, emphasizing efficiency, reliability, and sustainability. Smart grids integrate advanced communication and automation technologies, enabling real-time monitoring, adaptive control, and the seamless integration of distributed energy resources (DERs). Hybrid Energy Storage Systems (HESS) have emerged as pivotal components in achieving the operational and sustainability goals of smart grids, offering a robust solution to energy variability and enhancing grid compatibility [101-103].

4.2.1 Enhancing Operational Efficiency and Grid Stability

The cornerstone of smart grid functionality is its ability to dynamically adapt to fluctuating energy demands and supplies. HESS are uniquely suited to address this requirement by combining complementary storage technologies such as batteries, supercapacitors, and flywheels. According to Adeyinka et al. [13], this synergy enables HESS to deliver both rapid-response energy and sustained power, optimizing frequency regulation and voltage stability. The authors demonstrated that integrating HESS into smart grids reduces energy losses and enhances overall grid efficiency, particularly in managing peak demand scenarios. This dual-functionality aligns with the operational flexibility demanded by modern grids.

4.2.2 Facilitating Renewable Energy Integration

The integration of renewable energy sources (RES) such as wind and solar is a critical component of smart grid architecture. However, the inherent intermittency of RES poses significant challenges to grid reliability and energy consistency. HESS play a critical role in mitigating these challenges. Studies by Elkholy et al. [104] revealed that HESS improve the reliability of renewable energy integration by storing surplus energy during high generation periods and discharging during low production or high-demand intervals. This functionality ensures that energy supply remains consistent and reduces reliance on fossil-fuel-based peaking plants. Additionally, Elkholy et al. [104] emphasized the importance of optimized energy management strategies in maximizing the lifecycle benefits of HESS, making them indispensable for sustainable smart grid operations.

4.2.3 Advanced Control and Communication Strategies

The efficiency of HESS in smart grids is heavily reliant on advanced control mechanisms and communication protocols. Real-time energy management systems employing machine learning and predictive algorithms have been shown to optimize HESS performance. For example, Abdelghany et al. [105] developed a multi-layer control architecture that integrates HESS into smart grids, balancing energy supply and demand with minimal operational losses. Their findings revealed that predictive models based on historical data could enhance the scheduling and dispatch of energy storage resources, further improving grid reliability. These innovations demonstrate the critical role of intelligent control strategies in ensuring the compatibility of HESS with smart grids.

4.2.4 Real-World Successful Implementations

Globally, the deployment of HESS in smart grid environments has showcased significant operational and economic benefits. In the European Union, projects such as the Smarter Network Storage initiative have successfully integrated HESS to manage energy variability, reduce carbon emissions, and stabilize grids. The Smarter Network Storage (SNS) project was a notable initiative in the United Kingdom aimed at demonstrating the role of large-scale energy storage in managing energy variability, reducing carbon emissions, and stabilizing the grid. While the SNS project itself was UK-based, its findings have been influential across the European Union [106-108]. In the broader EU context, the integration of Hybrid Energy Storage Systems (HESS) has been a focal point in various projects to enhance grid stability and support renewable energy sources. For instance, INEGI has joined a consortium to develop an innovative HESS designed to support the electricity grid, contributing to European goals for a sustainable energy future [106]. Additionally, the European Union has been actively promoting smart sector integration to facilitate the decarbonization of the economy. This includes initiatives that allow new low-carbon energy carriers, such as hydrogen, to emerge and support the progressive decarbonization of various sectors, including the gas sector [107]. Furthermore, the BRIDGE initiative, as detailed in its 2024 brochure, encompasses various projects that align with the EU's climate and energy policies aimed at reducing net greenhouse gas emissions [108]. These efforts collectively highlight the EU's commitment to integrating advanced energy storage solutions like HESS to manage energy variability, reduce carbon emissions, and stabilize the grid.

Similarly, in the United States, utilities like Pacific Gas & Electric (PG&E) have implemented large-scale HESS solutions to provide ancillary services such as black start capability and grid inertia [109]. Regarding black start capabilities, PG&E has acknowledged the need for additional resources in the Bay Area to enhance system restoration times. In a 2015 issue paper, PG&E supported the California Independent System Operator's (CAISO) initiative to procure more black start resources, emphasizing the importance of improving restoration times and procuring services cost-effectively [110]. These implementations underline the practical feasibility and transformative impact of HESS in smart grid contexts.

Despite their evident advantages, the integration of HESS into smart grids is not without challenges. High initial capital costs, the complexity of multi-technology integration, and the lack of standardized protocols remain significant barriers. Research by Foles et al. [101] suggests that addressing these challenges will require advancements in materials science, scalable manufacturing processes, and the development of unified communication standards. Moreover, future research must focus on enhancing the energy density, efficiency, and durability of individual storage technologies within HESS. Emerging trends such as vehicle-to-grid (V2G) systems and hydrogen-based storage solutions present exciting avenues for expanding the role of HESS in smart grids [101]. By incorporating such innovations, HESS can further enhance grid compatibility, offering solutions that are not only efficient but also adaptable to evolving energy demands.

4.3. Artificial Intelligence and Machine Learning Applications

The integration of Artificial Intelligence (AI) and Machine Learning (ML) into Hybrid Energy Storage Systems (HESS) has revolutionized their functionality and efficiency. By leveraging advanced computational algorithms, AI/ML enables predictive maintenance, real-time optimization, and enhanced decision-making processes. These technologies address the complex challenges of energy storage management, including dynamic energy demands, wear-and-tear of components, and optimal energy dispatch, thus transforming HESS into smarter, more adaptable systems for modern grid applications [111,112]. Figure 5 illustrates the integration of Artificial Intelligence (AI) and Machine Learning (ML) in the management of Hybrid Energy Storage Systems (HESS). AI-powered data analysis facilitates deep learning and machine learning applications, optimizing energy storage operations and enhancing decision-making. The figure highlights the role of AI in enabling peer-to-peer energy trading, IoT-driven smart homes, and energy hubs, leading to more efficient energy management and the implementation of dynamic tariffs. These advancements contribute to enhanced grid stability, cost efficiency, and real-time adaptability to demand fluctuations.

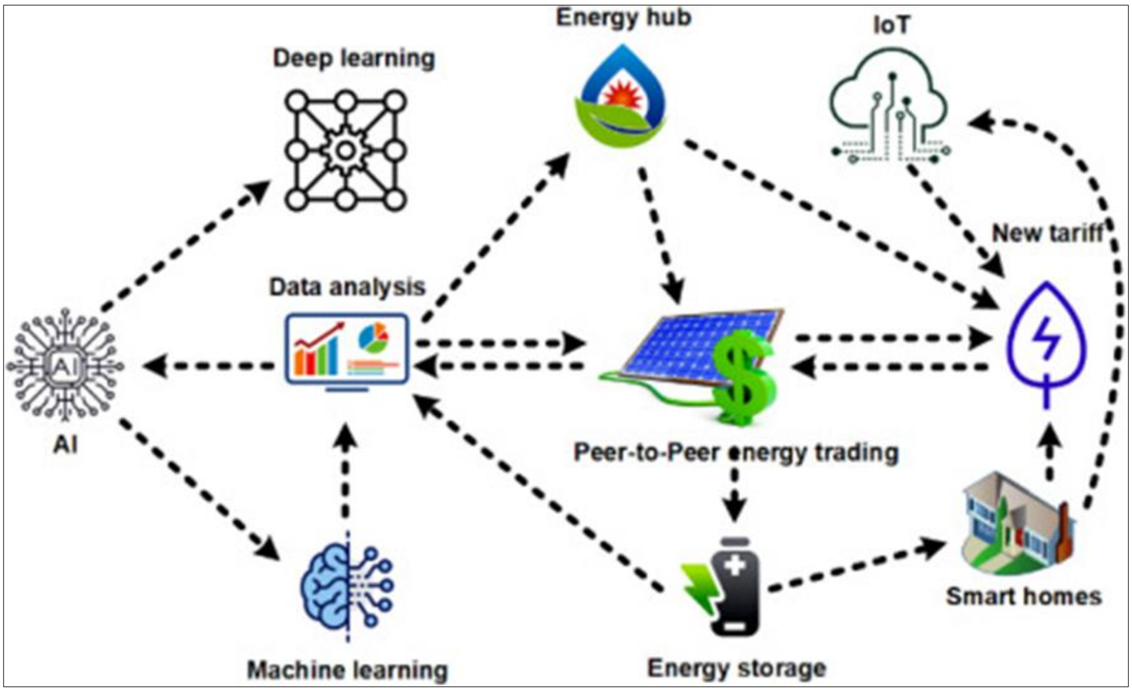

Figure 5 AI and Machine Learning Integration in Hybrid Energy Storage System (HESS) Management for Smart Energy Optimization. Reproduced from Ref [112]

4.3.1 *Predictive Maintenance and Reliability Enhancement*

AI/ML algorithms have demonstrated exceptional capabilities in predicting the operational lifespan and potential failures of energy storage components within HESS. These systems employ data collected from sensors embedded in batteries, supercapacitors, and other storage units to identify degradation patterns and impending faults. According to Sharma et al. [113], machine learning models such as decision trees and neural networks have achieved over 90% accuracy in predicting battery state of health (SOH) and remaining useful life (RUL). This predictive ability allows operators to schedule maintenance proactively, reducing downtime and associated costs [113]. Moreover, AI-driven maintenance strategies enhance system reliability by minimizing the risk of catastrophic failures. In a case study conducted by Ukoba et al. [114], integrating AI-powered predictive analytics into a HESS operating in a renewable-integrated grid reduced unplanned outages by 25%, thereby increasing overall grid stability and reliability.

4.3.2 *Real-Time Optimization and Energy Management*

AI/ML technologies also play a crucial role in optimizing the real-time performance of HESS. By analyzing grid conditions, energy demands, and storage capacities, machine learning models can dynamically allocate energy between different storage units to maximize efficiency. For instance, deep reinforcement learning, as employed by Meydani et al. [115], has proven effective in optimizing energy dispatch in hybrid configurations, ensuring that high-power devices like supercapacitors handle short-term fluctuations, while batteries manage sustained energy supply.

Furthermore, AI algorithms excel in forecasting energy generation and consumption patterns, especially in grids with high renewable energy penetration. By integrating weather and consumption data, predictive models enable HESS to adaptively manage storage and discharge cycles, minimizing energy wastage and ensuring a balanced supply-demand equilibrium. These capabilities underscore the transformative potential of AI/ML in making HESS more adaptive and responsive to dynamic grid conditions [114,115].

4.3.3 *Advanced Decision-Making and Control Strategies*

The complex interactions between multiple energy storage technologies within a HESS require advanced decision-making processes, which AI/ML efficiently provide. Techniques such as fuzzy logic and support vector machines have been applied to develop hybrid control strategies, as highlighted in the work of Ashraf et al. [116]. These systems can evaluate various operational scenarios and recommend optimal strategies for energy storage, discharge, and ancillary service provisioning, such as frequency regulation and load balancing.

AI/ML also facilitates self-learning mechanisms, allowing HESS to improve performance over time. According to Wang et al. [117], the incorporation of federated learning into HESS control systems enables decentralized and collaborative learning among storage units, further enhancing their operational synergy. This innovation not only improves efficiency but also reduces the computational burden on central controllers, paving the way for scalable and distributed HESS deployments.

4.3.4 Practical Implementations and Success Stories

The application of AI/ML in HESS has gained traction in various real-world scenarios. For example, the California Independent System Operator (CAISO) has employed AI-driven optimization tools to manage hybrid storage systems integrated into its renewable-heavy grid. A notable example is the deployment of Fluence's Mosaic™ AI-powered bidding software, which optimizes hybrid renewable and storage assets in CAISO's wholesale power market. As of early 2024, Mosaic™ is anticipated to manage 75 MW / 300 MWh of hybrid assets, enhancing grid efficiency and reliability [118-120]. These tools have been instrumental in reducing energy curtailment and improving storage utilization.

Despite its potential, the integration of AI/ML into HESS faces challenges such as data security, model scalability, and computational requirements. Addressing these issues will require advancements in data encryption, the development of lightweight AI models, and the establishment of standardized frameworks for AI integration in energy systems. Additionally, future research must focus on enhancing the interpretability of AI/ML models, ensuring that operators can understand and trust the decisions made by these systems. Emerging trends such as the integration of AI with blockchain technology and the use of edge computing for real-time data processing hold promise for further enhancing the capabilities of HESS. These innovations, combined with ongoing research and development, are set to solidify the role of AI/ML as indispensable tools in the optimization and management of hybrid energy storage systems.

5. Case Studies and Real-World Applications

The practical deployment of Hybrid Energy Storage Systems (HESS) represents the culmination of theoretical advancements, design considerations, and technological innovations. Real-world applications highlight the effectiveness of HESS in addressing challenges such as intermittent renewable energy generation, grid instability, and energy demand fluctuations. Case studies provide valuable insights into the design, implementation, and performance of these systems under varying environmental, economic, and technological conditions. By examining successful deployments globally as briefly summarized in Table 5, this section underscores the transformative potential of HESS in modernizing energy infrastructure and achieving sustainability goals [121,122].

Table 4 Summary of Global Case Studies of HESS Deployment

Project Name	Location	Storage Technologies	Capacity	Purpose	Outcomes
Fluence Energy Storage Projects	Various (16 countries)	Lithium-ion batteries	Varies by project	Grid stability, renewable integration	Enhanced grid stability and increased renewable energy integration across multiple regions. Notable projects include a 40 MW storage facility for San Diego Gas & Electric and six storage projects across Germany providing grid stabilization.
Blue Grass Solar Farm Expansion	Chinchilla, Queensland, Australia	Battery Energy Storage System (BESS)	148 MW	Renewable integration, grid resiliency	The expansion includes a 148 MW BESS, enabling the farm to store excess energy and release it during high demand or low solar generation periods, supporting grid resiliency and mitigating price volatility.

Energy Vault's Gravity Energy Storage Solution (GESS)	China (first commercial-scale project)	Gravity-based energy storage using massive concrete blocks	Varies by project	Long-duration energy storage, renewable integration	Provides long-duration storage for renewable energy, avoiding the use of lithium-ion batteries. The system uses excess renewable energy to elevate heavy blocks, which are lowered to generate electricity as needed.
Ometepe Island Renewable Energy System	Ometepe, Nicaragua	Geothermal, hydro, wind, photovoltaic (PV), and pumped storage hydropower	Designed for 100% renewable supply	Renewable integration, energy independence	Evaluated a hybrid system comprising geothermal, hydro, wind, PV, and energy storage in an extinct volcano to achieve a 100% renewable energy supply for the island. The study demonstrated the feasibility of such a system in isolated regions.

5.1. Grid-Connected HESS Implementations

Grid-connected Hybrid Energy Storage Systems (HESS) have emerged as critical components of modern energy infrastructure, particularly in regions aiming to increase renewable energy penetration and improve grid stability. These systems leverage the complementary strengths of different energy storage technologies, such as batteries, supercapacitors, and flywheels, to address the limitations of standalone storage solutions. This subsection explores successful HESS implementations worldwide, focusing on their design, operational outcomes, and contributions to energy systems [122].

5.1.1 HESS in Europe: Pioneering Renewable Integration

Europe has been at the forefront of grid-connected HESS deployments, driven by aggressive renewable energy targets and supportive policies. One notable example is the SuKoBa research project. In the SuKoBa research project, Skeleton Technologies collaborated with AVL Deutschland GmbH and the Fraunhofer Institute for Energy Economics and Energy System Technology, both in Germany, to develop hybrid energy storage systems combining lithium-ion batteries (LIBs) and supercapacitors (SCs). The project aimed to create a software toolbox to determine the optimal combination of these technologies for various applications. The research demonstrated that integrating supercapacitors with lithium-ion batteries in high-power applications, such as mining trucks, extended battery life by over 20% and reduced electrical losses by 6% and thermal losses by 10%, leading to significant improvements in overall system efficiency [123]. These findings highlight the potential of hybrid storage systems to enhance performance and longevity in applications requiring rapid energy discharge and recharge.

Similarly, The UK's Smarter Network Storage (SNS) project, led by UK Power Networks, was a pioneering initiative aimed at exploring the role of large-scale energy storage in enhancing grid efficiency and reliability. The project focused on integrating a 6MW/10MWh lithium-ion battery storage system into the UK electricity network to provide various grid support services and to explore the multi-purpose application of large-scale energy storage, including providing services such as frequency regulation and peak shaving. The SNS project successfully demonstrated the scalability and flexibility of hybrid energy storage systems (HESS). The findings from the project indicated that such systems could lead to significant cost savings for grid operators and improve energy dispatch efficiency [124,125].

5.1.2 North America: Advancing Grid Resilience and Flexibility

In North America, the emphasis on grid resilience has spurred the adoption of HESS. The Imperial Irrigation District (IID) project in California serves as a benchmark for HESS deployment in areas with high renewable energy penetration. This system combines lithium-ion batteries and flywheels to stabilize the grid and manage peak demand. The Imperial Irrigation District (IID) in California has implemented a 30-megawatt (MW), 20-megawatt-hour (MWh) lithium-ion battery energy storage system (BESS) to enhance grid reliability and support the integration of renewable energy sources. This system provides operational support across IID's balancing authority by facilitating solar integration, frequency regulation, and power balancing. The BESS enables IID to balance power supply and demand, integrate renewable energy resources, and provide spinning reserve and black start capabilities.

Another example is the Beacon Power flywheel system in New York, which operates alongside traditional battery storage to offer ancillary services such as frequency regulation. Beacon Power operates a 20-megawatt flywheel energy storage plant in Stephentown, New York, designed to provide frequency regulation services to the New York Independent System Operator (NYISO). This facility utilizes 200 flywheels to absorb excess electricity from the grid, storing it as kinetic energy, and releasing it back when needed to maintain grid stability [127].

5.1.3 Asia-Pacific: Innovations in Emerging Markets

In the Asia-Pacific region, HESS deployments have focused on addressing challenges unique to emerging markets, such as energy access and infrastructure limitations. For instance, Gansu Zhongboyuan Energy Technology in China announced the successful grid connection of a 50 MW/200 MWh vanadium flow battery energy storage system in Shandan County, Gansu. This system comprises 16 units of 3 MW/12 MWh storage subsystems and one 2 MW/8 MWh storage subsystem. The project aims to enhance the absorption of renewable energy in the region and improve grid efficiency [128].

Similarly, The Indian Army, in collaboration with NTPC, has set up a solar hydrogen-based microgrid project in Ladakh, located at Chushul, a remote off-grid area. This initiative aims to address the region's energy needs by integrating solar energy with hydrogen-based storage, enhancing power stability and ensuring a reliable supply for isolated military stations. The success of this project has been evident in several ways. It has improved energy access in a previously power-deficient area, reduced dependence on traditional fuel supplies, and provided a sustainable alternative through renewable energy. The microgrid has also contributed to reducing carbon emissions, making it a key step in India's energy transition efforts. Furthermore, it serves as a model for future off-grid renewable energy solutions in other remote regions across the country. This initiative aims to provide a stable power supply to off-grid locations, highlighting the potential of hybrid energy storage systems (HESS) in remote applications [129].

5.1.4 Lessons Learned and Implications for Future Deployments

The success of grid-connected HESS implementations underscores several key lessons for future projects. First, the choice of storage technologies and their integration must align with the specific energy challenges and grid conditions of the region. Second, advanced control strategies, including AI-driven energy management systems, are crucial for maximizing the performance and efficiency of HESS. Third, supportive policies and financial incentives play a vital role in encouraging the adoption of these systems, particularly in regions transitioning to renewable energy.

6. Challenges and Future Directions

The integration of Hybrid Energy Storage Systems (HESS) in modern energy systems offers substantial benefits, including enhanced grid stability, renewable energy utilization, and efficient energy management. However, the widespread adoption of HESS is constrained by various technical, policy, and economic challenges. Addressing these barriers is crucial for unlocking the full potential of HESS and ensuring their effective deployment in energy infrastructures. This section explores the key technical challenges, the influence of policy and regulatory frameworks, and the opportunities for future research and innovation that could shape the trajectory of HESS development.

Table 5 Economic and Environmental Benefits of HESS over Conventional Storage Systems

Benefit Category	**Metric**	**Conventional Storage Systems**	**Hybrid Energy Storage Systems (HESS)**
Cost Savings	Capital Expenditure (CapEx)	Typically higher due to reliance on a single storage technology, leading to over-sizing to meet diverse energy demands.	Optimized CapEx by combining multiple storage technologies, each tailored to specific operational needs, reducing overall system size and cost.
	Operational Expenditure (OpEx)	Higher maintenance and replacement costs due to the limitations of single technology performance and lifespan.	Reduced OpEx through improved efficiency and extended lifespan of components by distributing the load among various storage technologies.

	Levelized Cost of Storage (LCOS)	Generally higher LCOS due to suboptimal utilization and frequent cycling of a single storage system.	Lower LCOS achieved by optimizing the use of each storage technology according to its strengths, leading to enhanced system efficiency.
Emission Reductions	Greenhouse Gas (GHG) Emissions	Limited reduction potential, especially if the storage system is charged using non-renewable energy sources.	Significant GHG emission reductions by facilitating higher integration of renewable energy sources and optimizing energy usage.
	Fossil Fuel Dependency	Continued reliance on fossil fuels for energy generation and storage in certain scenarios.	Decreased fossil fuel dependency by enhancing the efficiency and reliability of renewable energy integration.
Energy Efficiency Improvements	Round-Trip Efficiency	Varies depending on technology; some conventional systems exhibit lower efficiency due to energy losses in conversion and storage processes.	Improved round-trip efficiency by leveraging the complementary characteristics of different storage technologies to minimize energy losses.
	System Flexibility and Responsiveness	Limited flexibility in responding to rapid changes in energy demand and supply, potentially leading to inefficiencies.	Enhanced flexibility and responsiveness, allowing for better matching of energy supply and demand, thus improving overall system efficiency.

6.1. Technical Challenges

The deployment of HESS faces significant technical challenges that arise from the complexity of integrating multiple energy storage technologies with distinct operational characteristics. One critical issue is achieving seamless synchronization between different storage units, such as batteries, supercapacitors, and flywheels. According to Molzahn et al. [130], the inherent differences in energy density, power capacity, and response times of these technologies complicate the design of control algorithms that ensure optimal energy flow and system reliability. Their study highlights the need for advanced control systems capable of real-time adjustments to accommodate dynamic grid demands.

Another prominent technical hurdle is the development of robust energy management systems (EMS) that can handle large-scale HESS deployments. As noted by Recalde et al. [131], existing EMS frameworks often struggle with the computational demands of optimizing energy distribution across heterogeneous storage units while considering grid constraints and economic factors. Advanced algorithms that incorporate machine learning and artificial intelligence are being explored to address these limitations, though their implementation is still in nascent stages.

Furthermore, the issue of scalability remains a major concern. While HESS can be effectively deployed at pilot scales, their expansion to grid-wide applications often encounters obstacles related to interconnection standards and thermal management. Research by Kwon et al. [132] demonstrates that thermal runaway in battery components and inefficiencies in cooling systems can significantly reduce the lifespan of HESS, necessitating advancements in thermal management technologies.

6.2. Policy and Regulatory Frameworks

The policy and regulatory environment plays a pivotal role in shaping the adoption of HESS. The absence of standardized guidelines for integrating HESS into grid operations creates uncertainty for utilities and developers. According to the World Energy Transitions Outlook 2023 report by the International Renewable Energy Agency (IRENA), which discusses the global energy transition and the need for integrated policies to support renewable energy systems, the challenge of inconsistent interconnection and safety standards, largely impedes the large-scale deployment of energy storage systems like HESS. The report calls for comprehensive policies that address safety, performance, and interoperability to overcome these barriers [133].

Moreover, the financial incentives for HESS adoption are often insufficient or inconsistent across regions. Research by Midford et al. [134] illustrates how policies such as feed-in tariffs and subsidies for renewable energy have accelerated solar and wind adoption but have yet to be effectively extended to HESS technologies. Their analysis suggests that introducing dedicated incentives for hybrid systems could catalyze their adoption by mitigating upfront costs.

Grid access policies also play a critical role. In many regions, regulatory barriers limit the participation of HESS in ancillary service markets, such as frequency regulation and demand response. Studies by Ameriekhtiar et al. [135] advocate for policy reforms that enable hybrid systems to compete fairly in these markets, thereby unlocking their potential to provide grid services and generate revenue.

6.3. Research and Development Opportunities

Ongoing research and development (R&D) efforts are critical for overcoming the challenges associated with HESS and driving innovation. One promising area is the development of next-generation materials for storage technologies. According to the detailed review study carried out by Jayaprabakar et al. [136], advanced materials such as solid-state electrolytes and nanostructured electrodes offer the potential to enhance the performance and durability of battery components in HESS.

Another avenue of research involves the integration of HESS with renewable energy forecasting models. Accurate predictions of renewable generation are essential for optimizing the operation of hybrid systems. As highlighted by Sarwar et al. [137], machine learning-based forecasting methods are being integrated with HESS to improve scheduling and energy dispatch, leading to better utilization of storage resources. Additionally, the concept of modular HESS is gaining traction as a means to enhance scalability and flexibility. Modular systems allow for incremental additions of storage capacity, reducing the need for large upfront investments [138,139].

The exploration of decentralized HESS for microgrid applications also represents a significant R&D opportunity. Studies suggest that decentralized architectures can enhance system resilience and facilitate the integration of local renewable resources. Their work emphasizes the need for intelligent control systems that can coordinate the operation of distributed HESS units in a decentralized framework [13,140]

7. Conclusion

Hybrid Energy Storage Systems (HESS) represent a transformative solution to the increasing challenges faced by electric grids, particularly as the integration of renewable energy sources becomes more widespread. This review has highlighted the significant advantages of HESS in enhancing grid reliability, enabling efficient energy management, and facilitating the integration of intermittent renewable energy. By combining the strengths of diverse storage technologies, such as batteries, supercapacitors, and flywheels, HESS provide a flexible, scalable, and efficient means of addressing the varying demands of modern grids. Key findings from the review underscore the importance of optimizing HESS configuration, employing advanced control strategies, and ensuring scalability for long-term deployment. The integration of these systems into both large-scale grid-connected and decentralized microgrid applications demonstrates their potential in stabilizing grid fluctuations, supporting peak load management, and offering ancillary services. The advancement of smart grid technologies, machine learning algorithms, and improved energy forecasting further enhance the operational efficiency of HESS, solidifying their place in future energy infrastructures.

However, several challenges persist, including high upfront costs, technical complexities in integrating multiple storage technologies, and regulatory barriers that hinder the broader adoption of HESS. While the environmental benefits of HESS are substantial, addressing lifecycle concerns and ensuring sustainable material sourcing are critical to minimizing their ecological footprint. As research continues to address these challenges, the future potential of HESS as a core component of global energy systems remains promising.

Looking forward, the continued evolution of HESS technology is expected to play a pivotal role in advancing the goals of grid modernization and renewable energy adoption. Future research should focus on enhancing the efficiency and longevity of storage components, exploring innovative system configurations, and addressing the scalability challenges for large-scale deployment. Moreover, policy frameworks will need to evolve in tandem to incentivize the adoption of HESS, streamline regulatory processes, and support investments in research and development. As the world increasingly pivots toward a sustainable energy future, HESS will undoubtedly be central in shaping the next generation of energy storage solutions and ensuring the resilience of global electric grids.

Compliance with ethical standards

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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