Sustainable Energy Research

REVIEW

Open Access

Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration

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Abstract

The global energy sector is currently undergoing a transformative shift mainly driven by the ongoing and increasing demand for clean, sustainable, and reliable energy solutions. However, integrating renewable energy sources (RES), such as wind, solar, and hydropower, introduces major challenges due to the intermittent and variable nature of RES, affecting grid stability and reliability. Hybrid energy storage systems (HESS), which combine multiple energy storage devices (ESDs), present a promising solution by leveraging the complementary strengths of each technology involved. This comprehensive review examines recent advancements in grid-connected HESS, focusing on their components, design considerations, control strategies, and applications. It provides a detailed analysis of technological progress in various ESDs and the critical role of power conversion, control, energy management, and cooling systems in optimizing HESS performance. Highlighting case studies of some notable and successful HESS implementations across the globe, we illustrate practical applications and identify the benefits and challenges encountered. By addressing these challenges, HESS can significantly enhance the efficiency and reliability of RES, supporting the shift towards a sustainable and resilient energy infrastructure. The paper concludes by identifying future research directions, highlighting the development of intelligent control systems, sustainable materials, and efficient recycling processes to ensure the widespread adoption and long-term viability of HESS.

Keywords Hybrid energy storage system, Renewable energy source, Energy storage device, Intelligent control system, Grid stability and reliability

Introduction

The global energy sector is facing critical challenges due to increasing energy demand and the need to combat climate change (Adediji et al., 2023; Adeyinka et al., 2023; Mbelu et al., 2024). Traditional fossil fuel-based energy infrastructure is increasingly recognized as unsustainable due to its significant environmental impact (Cowell & De Laurentis, 2022). The combustion of coal, oil, and natural gas for energy is a leading cause of global warming and air pollution, contributing to health issues and environmental degradation (Jiang et al., 2023). The release of carbon dioxide (CO_2) and other greenhouse gases (GHGs) from fossil fuel combustion increases the greenhouse effect, leading to higher global temperatures and more frequent extreme weather events (Singh et al., 2023). These environmental changes endanger ecosystems, human health, water resources, and agriculture, necessitating urgent action to mitigate their impacts (Weiskopf et al., 2020).

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The urgency to transition to cleaner energy systems is driven by international agreements such as the Paris Agreement and Sustainable Development Goals, which call for substantial reductions in GHG emissions to reduce global temperature rise (McCollum et al., 2018). These agreements highlight the global consensus on the need to limit temperature rise to significantly less than 2 °C above pre-industrial levels, with efforts to limit the increase to 1.5 °C to avoid the most catastrophic impacts of climate change (Gao et al., 2017; Warren et al., 2022). Achieving these targets necessitates a shift away from fossil fuels towards RES, which are abundant, sustainable, and environmentally benign (Sharma et al., 2023).

The global push for renewable energy has been driven by both environmental concerns and the economic potential of green technologies. Renewable energy sources have emerged as crucial alternatives to fossil fuels because they contribute to energy security by diversifying the energy supply, reducing reliance on fossil fuels, lowering GHG emissions, and mitigating the impacts of climate change (Chen et al., 2023). In recent years, the installation of renewable energy systems has accelerated dramatically. According to the International Renewable Energy Agency (IRENA), the total capacity for renewable energy reached 2813 gigawatts (GW) by the end of 2020, with solar and wind power experiencing the most significant growth (IRENA, 2023) and estimated to reach 7 300 GW by 2028 (IEA, 2023), further highlighting the momentum behind the global energy transition.

Solar power has seen remarkable growth, contributing to three-quarters of renewable capacity installations globally (IEA, 2023). The rapid decline in the levelized cost of electricity (LCOE) of photovoltaic (PV) technology has made solar energy increasingly competitive with traditional energy sources (G. He et al., 2020). Innovations in PV materials, manufacturing processes, and installation techniques have improved efficiency and reduced costs, enabling widespread adoption (Schmela et al., 2023). Similarly, wind power continues to expand, with a global capacity of around 1000 GW at the end of 2023. Technological advancements in materials, turbine design, and control systems have significantly improved the cost-effectiveness and efficiency of wind energy (Alex, 2024).

Despite these advancements, integrating RES into the existing power grid presents challenges due to their intermittent and variable nature (Ayamolowo et al., 2020; Purkait et al., 2024). Unlike traditional fossil fuel plants, which can provide a reliable and controllable power output, renewable energy generation fluctuates with the weather and time of day, leading to periods when energy production is either insufficient or excessively high compared to demand (Deguenon et al., 2023). This variability can cause instability and reliability issues in the power grid, which has traditionally been designed for the steady output of fossil fuel plants (Benzohra et al., 2020). The intermittency of power generated from RES can lead to challenges for grid integration due to mismatches between energy supply and demand (Mlilo et al., 2021). These often require grid operators to balance these fluctuations in real time to avoid frequency deviations, voltage drops, and power outages (Khalid, 2024).

Energy storage devices (ESDs) are essential in addressing these challenges by saving excess energy generated during periods of high production and making it available during periods of low production (Kebede et al., 2022). ESD, such as batteries, pumped hydro storage, and flywheels, provides various benefits, including load leveling, frequency regulation, and backup power during outages, enhancing grid stability and reliability (Chong et al., 2016; Tan et al., 2021). However, no single storage technology can effectively address all grid stability and reliability requirements. This is where the hybrid energy storage systems come into play. HESS combines different energy storage technologies to provide short-term high power output and long-term energy storage solutions (Y. Wang et al., 2020). By buffering the intermittency of RES, HESS enhances grid stability, improves energy reliability, and reduces the dependence on auxiliary fossil fuel power plants, thereby facilitating a smoother transition to a renewable energy-dominated grid.

Furthermore, HESS is particularly crucial for non-interconnected power systems, such as those found on isolated islands. Fotopoulou et al. (2024) emphasize the importance of HESS in these environments, highlighting their role in mitigating power quality issues and providing essential ancillary services like frequency regulation, voltage control, and black start capabilities. The versatility and reliability of HESS make them an indispensable component for enhancing the sustainability and operational efficiency of isolated grids, which face unique challenges compared to interconnected systems (Fotopoulou et al., 2024).

Table 1 provides an overview of review studies on HESS. Even though few reviews on some important HESS concepts have been published (Abo-Khalil et al., 2023; Arsad et al., 2022; Chatzigeorgiou et al., 2024; Emrani & Berrada, 2024; Lei et al., 2023a, 2023b; Lin & Zamora, 2022; Modu et al., 2023; Rezaei et al., 2022; Wali et al., 2023; Wang et al., 2022), a detailed understanding of the advances in HESS and their role in enhancing renewable energy integration into the power grid and case studies of successful installation of grid-connected HESS were not considered. Consequently, a timely and contemporary review of grid-connected HESS is vital for information and knowledge updates.

Table 1 Critical review of recent studies on HESS

Refs.	Year	ESD	Highlights from the paper	Area of review focus			
				Technology	Control system	RES integration	Case studies for grid application
(Chatzigeorgiou et al., 2024)	2024	BESS	Reviewed applications, developments, and research trends in hybrid installations for end-users; highlighted the growing importance of BESS in integrating renewable energy sources	✓	✓	✓	
(Emrani & Berrada, 2024)	2024	All ESDs	Elucidated the integral role of energy storage devices in optimizing hybrid photovoltaic/wind power systems, focused on recent technical advancements and economic factors influencing their adoption and implementation	✓		✓	
(Abo-Khalil et al., 2023)	2023	All ESDs	Emphasized the benefits of integrating various energy storage technologies to enhance system performance and reliability; discussed traditional and intelligent control techniques	✓	✓		
(Lei et al., 2023a, 2023b)	2023	BESS, SC, FC, SMES, Flywheel	Focused on components, powertrain topologies, and control methods; emphasized the integration of different energy storage devices to optimize performance and extend vehicle range	✓	✓		
(Wali et al., 2023)	2023	Hydrogen storage	Introduced a novel 'usage count' indicator for identifying impactful research in hydrogen-based HESS; emphasized hydrogen's high energy density and storage capacity and its role in decarbonization	✓		✓	
(Modu et al., 2023)	2023	Hydrogen storage	Highlighted recent advancements in the integration of hydrogen storage within HRES; examined various optimization techniques and energy management systems	✓		✓	

Table 1 (continued)

Refs.	Year	ESD	Highlights from the paper	Area of review focus			
				Technology	Control system	RES integration	Case studies for grid application
(Rezaei et al., 2022)	2022	BESS, UC	Categorized energy management systems into optimization-based, frequency-based, and rule-based approaches; highlighted practical applications and potential for future improvements	✓	✓		
(Wang et al., 2022)	2022	BESS, SC	Analyzed various topologies, such as non-isolated and isolated converters, and emphasized their roles in voltage matching and power decoupling	✓			
(Lin & Zamora, 2022)	2022	BESS, SC	Categorized control strategies into centralized, decentralized, and distributed methods; highlighted future trends in control strategies for HESS	✓	✓		
(Arsad et al., 2022)	2022	Hydrogen storage	Utilized bibliometric analysis to identify research trends and future directions; highlighted the potential of hydrogen storage for energy sustainability and examined highly cited articles	✓			
This review	2024	All ESDs	Comprehensive review of advances in HESS technologies, control systems, RES integration and case studies of grid-connected HESS	✓	✓	✓	✓

By examining the current state of HESS, its applications, benefits, and challenges, this paper will provide a comprehensive overview of how these systems can support the transition to a sustainable energy infrastructure. The organization structure of this article is as follows: the overview of the technology, components, design considerations, types of hybrid systems, control systems, topologies, and applications of HESS are reviewed in Sect. "An overview of hybrid energy storage systems". The recent technological development focusing on advanced control strategies for enhancing renewable energy integration are discussed in Sect. "Technological advancements in HESS control strategies for enhancing renewable energy integration". Sect. "Case studies of successful implementation of HESS" explores the case studies of the successful implementation of HESS around the world. Finally, the challenges and future directions for research and development are discussed in Chapter 5.

An overview of hybrid energy storage systems

Hybrid energy storage systems are advanced energy storage solutions that provide a more versatile and efficient approach to managing energy storage and distribution, addressing the varying demands of the power grid more effectively than single-technology systems. HESS has transformed from conceptual frameworks into advanced systems integrating multiple energy storage technologies, evolving through continuous advancements and innovations. The development trend of HESS results from the growing demand for efficient and reliable energy storage solutions to tackle the challenges posed by modern energy systems. Figure 1 provides an overview of the technological development of HESS. The technological roadmap illustrates the evolution and future directions of hybrid energy storage technologies. It provides a visual representation of milestones, advancements, trends and projects for future advancements in the development of HESS.

Components of HESS

Each component in a HESS has distinct functions that enhance the reliability and efficiency of the system. Figure 2 provides an overview of the interconnectivity between the components of HESS. The primary elements of HESS and their functions are:

Energy storage devices (ESD)

Energy storage devices are the core components of HESS, responsible for saving excess energy generated during periods of high production and supplying it during periods of high demand (Hassan et al., 2023a, 2023b). This ensures a stable and reliable energy supply, meeting load balancing, grid stabilization, and energy management needs. Different types of ESD are integrated into HESS to leverage their unique strengths and mitigate their weaknesses. These include batteries, supercapacitors, flywheels, pumped hydro, super magnets, compressed air, and hydrogen, which are used to store energy in various forms (Gusain et al., 2021; Worku et al., 2022; Zhang et al., 2021a, 2021b). Table 2 provides a comparison of different ESDs reviewed in this study, focusing on metrics such as energy density, power density, efficiency, cost, and the times required for charging and discharging.

Power conversion system

The power conversion system (PCS) converts energy between different forms to ensure compatibility and efficient integration with the power grid (Atawi et al., 2023). The PCS includes bidirectional inverters, rectifiers, and converters that convert direct current from energy storage devices to alternating current for grid supply and vice versa. This bidirectional capability enables seamless energy flow management and allows the charging and discharging of ESDs. The PCS is essential for maintaining voltage stability and regulating the frequency of the electricity supplied to the grid (Jarosz, 2024). By interfacing with the ESDs, the control system and the energy management system (EMS), the PCS ensures that energy is efficiently converted and delivered to meet real-time demand.

Control system

The control system is a critical component of HESS, responsible for managing and regulating the operation of the ESDs and ensuring their optimal performance (Lin & Zamora, 2022). The control system uses advanced

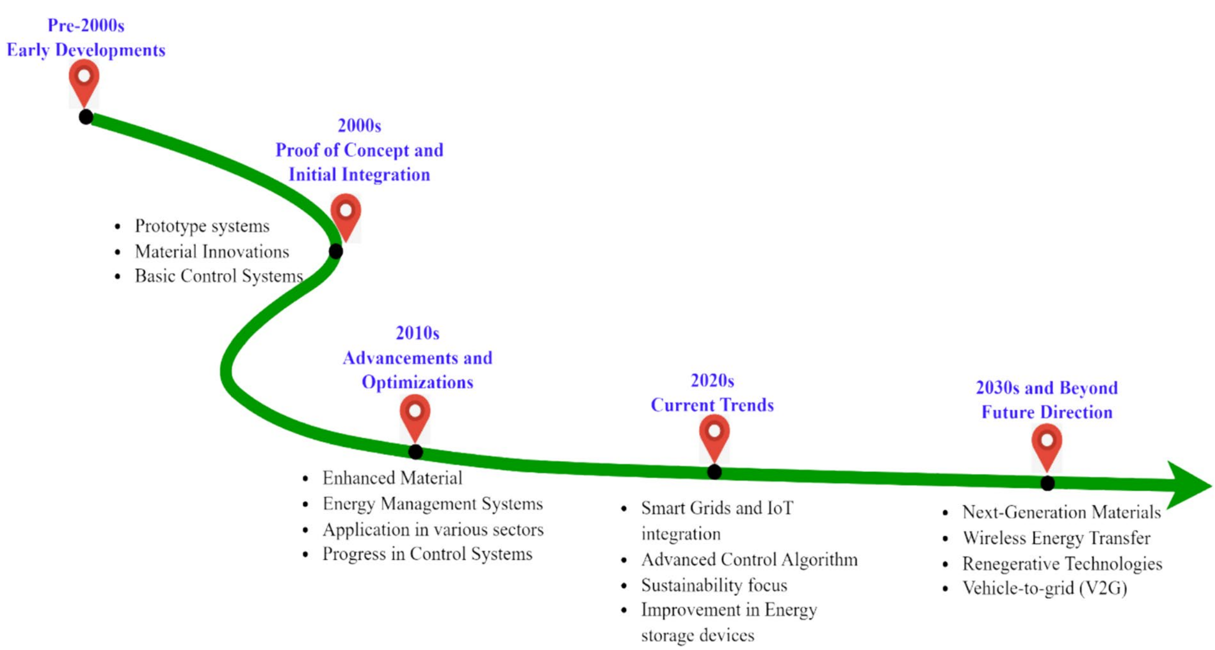

Fig. 1 Technological roadmap for HESS

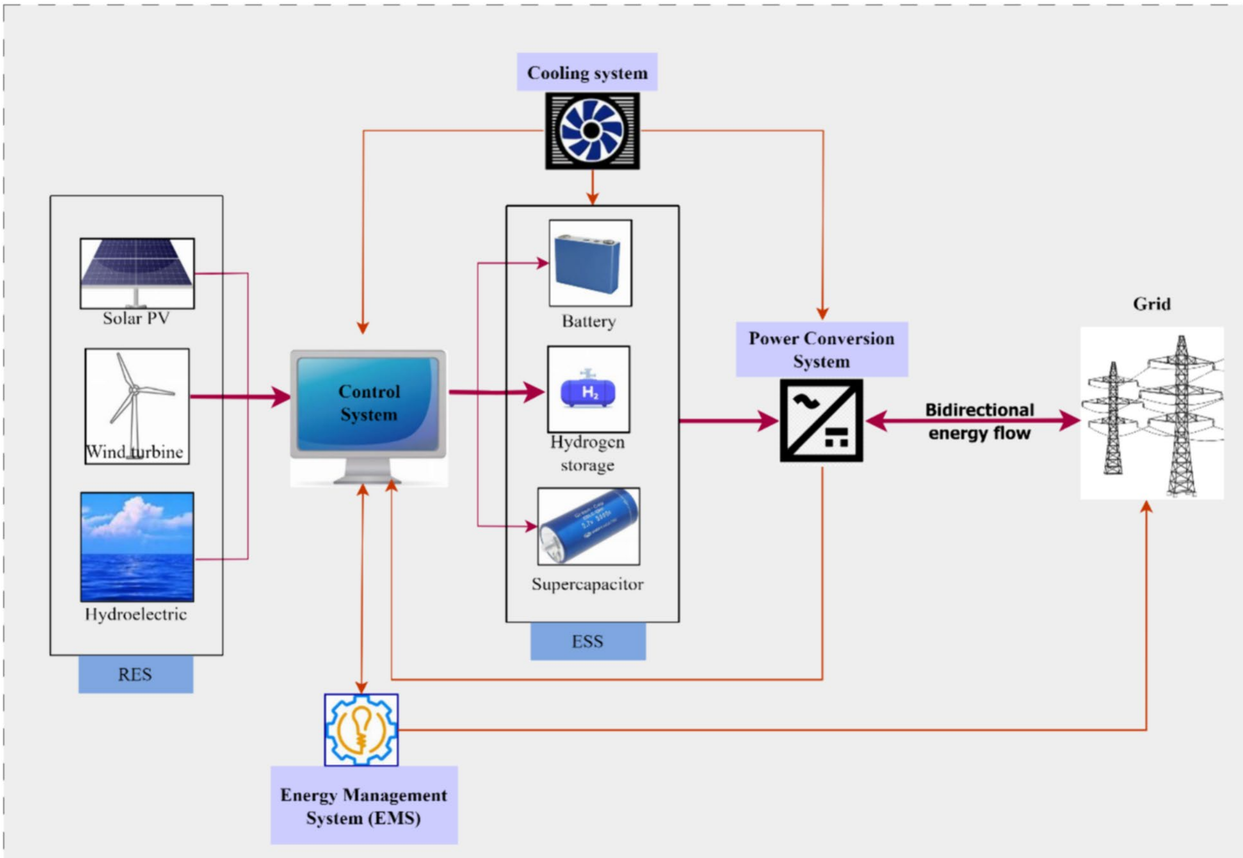

Fig. 2 An overview of hybrid energy storage systems and their components

control algorithms and safety protocols to continuously monitor the status of the energy storage devices, including state of charge, health, and operating conditions. It uses this information to make real-time decisions about when to charge or discharge the storage devices to prevent overcharging, deep discharging, and overheating issues (Hajiaghasi et al., 2019). Furthermore, the control system coordinates the operation of the power conversion system (PCS) and the energy management system (EMS) to ensure a balanced and stable energy supply. For instance, the control system can rapidly respond to short-term power fluctuations by adjusting the output of the storage devices, helping to stabilize the grid and prevent outages or frequency deviations. The control system also interfaces with the cooling system to manage the thermal conditions of the storage devices, ensuring they operate within safe temperature limits.

Energy management system

The energy management system (EMS) uses advanced algorithms and forecasting techniques to predict energy demand and supply, enabling it to dynamically adjust the charging and discharging schedules of ESD (Meliani et al., 2021). One of the primary functions of the EMS is load forecasting. By analyzing historical data, weather conditions, and usage patterns, the EMS can predict future energy demand accurately. This allows it to optimize the charging and discharging cycles of the ESDs (Wazirali et al., 2023). By working in conjunction with the control system, the EMS monitors the status of the ESDs, making real-time adjustments to maintain optimal performance and prevent issues such as overcharging, deep discharging, and overheating.

Cooling system

The cooling system maintains the optimal operating temperature of the ESDs, PCS, and control system to ensure efficiency and longevity. Effective thermal management is needed to prevent overheating, which can degrade performance, reduce efficiency, and shorten the lifespan of ESDs (Nadjahi et al., 2018). The cooling system utilizes various methods, such as air cooling, liquid cooling, and heat sinks, to dissipate excess heat produced during charging and discharging cycles. By keeping the temperature within safe limits, the cooling system ensures that the ESDs operate efficiently and reliably (Zhang

Table 2 Comparative analysis of different energy storage devices

Energy storage devices	Energy density	Power density	Efficiency	Charge/discharge time	Cost	Primary use	Advantages	Disadvantages	Refs
Lithium-ion batteries	High	Moderate	High (~ 90–95%)	Hours	Moderate	Portable electronics, EVs, grid storage	High energy density, well-understood	Degradation with use, sensitive to temperature	(Goodenough & Kim, 2010)
Lead-acid batteries	Low	Low	Moderate (~ 70–80%)	Hours	Low	UPS, grid storage, automotive	Low cost, reliable, well-established	Low energy density, heavy, environmental issues	(Lopes & Stamenkovic, 2020)
Supercapacitors	Low	Very high	Very high (> 95%)	Seconds to minutes	High	Regenerative braking, power quality	Very fast charge/discharge, very long lifespan	Low energy density, high cost per energy unit	(X. He & Zhang, 2022)
Flywheels	Moderate	High	High (~ 85–95%)	Seconds to minutes	High	Frequency regulation, UPS	No chemical degradation, rapid response	High mechanical maintenance, energy loss over time	(Ji et al., 2024; Rahman et al., 2021)
Flow batteries	Moderate	Low to moderate	Moderate (~ 70–85%)	Minutes to hours	Moderate	Long-duration grid storage	Scalable energy capacity, long discharge duration	Complex plumbing and maintenance	(Esan et al., 2020)
Compressed air energy storage (CAES)	Low	Low	Moderate (~ 40–75%)	Hours to days	Moderate	Grid energy storage, load leveling	Large-scale energy storage, long lifespan	Requires specific geological formations	(Olabi et al., 2021; X. Zhang et al., 2024)
Thermal energy storage (TES)	Variable	Variable	Variable	Hours to days	Variable	Building heating/cooling, industrial processes	Flexible application scope	Efficiency varies with installation	(Cabeza et al., 2015; Guelpa & Verda, 2019)
Hydrogen storage (via electrolysis)	Low	Low	Low (~ 35–55%)	Hours	High	Fuel for vehicles, grid storage	High capacity for large-scale storage	High costs, requires advanced infrastructure	(Hassan et al., 2023a, 2023b; Terlouw et al., 2022)
Superconducting magnetic energy storage (SMES)	Low	Very high	Very high (> 95%)	Instantaneous	Very high	Power quality, grid stability	Extremely fast response time, very high efficiency	High cost, complex cryogenics	(Adetokun et al., 2022)
Pumped hydro storage	Low	Low	High (~ 70–85%)	Hours to days	Low	Grid energy storage, load leveling	Long lifespan, large-scale storage	Geographic and environmental constraints	(Hoffstaedt et al., 2022; Rehman et al., 2015)

et al., 2021a, 2021b). Furthermore, the cooling system is integrated with the control system to dynamically adjust cooling efforts based on real-time temperature data and operational conditions.

Key design considerations for HESS

Designing HESS requires careful consideration of several key factors to ensure optimal performance, efficiency, and reliability. The following are critical design considerations.

Technology compatibility

HESS should be designed for seamless compatibility with existing power systems, renewable generation units, and grid interfaces (R. & Kowsalya, 2024). Ensuring effective communication and adaptation with current grid management tools and demand response systems is critical. The selected combination of storage technologies should complement each other to optimize performance (see Fig. 3 for suggested compatibility and effectiveness of various ESDs for potential HESS configuration). For example, batteries with high energy capacity but limited cycle life can be paired with supercapacitors with high power output and rapid cycling capability. This synergistic approach should be adapted to the specific energy profiles and operational demands of the application, enhancing the overall efficiency and reliability of the HESS.

Capacity sizing

Capacity sizing involves a detailed analysis of energy requirements (kWh) and power demand (kW) over specific periods based on historical data, anticipated growth, and the variability in energy production from renewable sources (Colak & Ahmed, 2021). Recent progress has been made in software-based capacity sizing for hybrid systems, which leverages advanced computational tools and algorithms to optimize system performance and cost-effectiveness (Lian et al., 2019). Tools like RETScreen, Hybrid Optimization by Genetic Algorithms

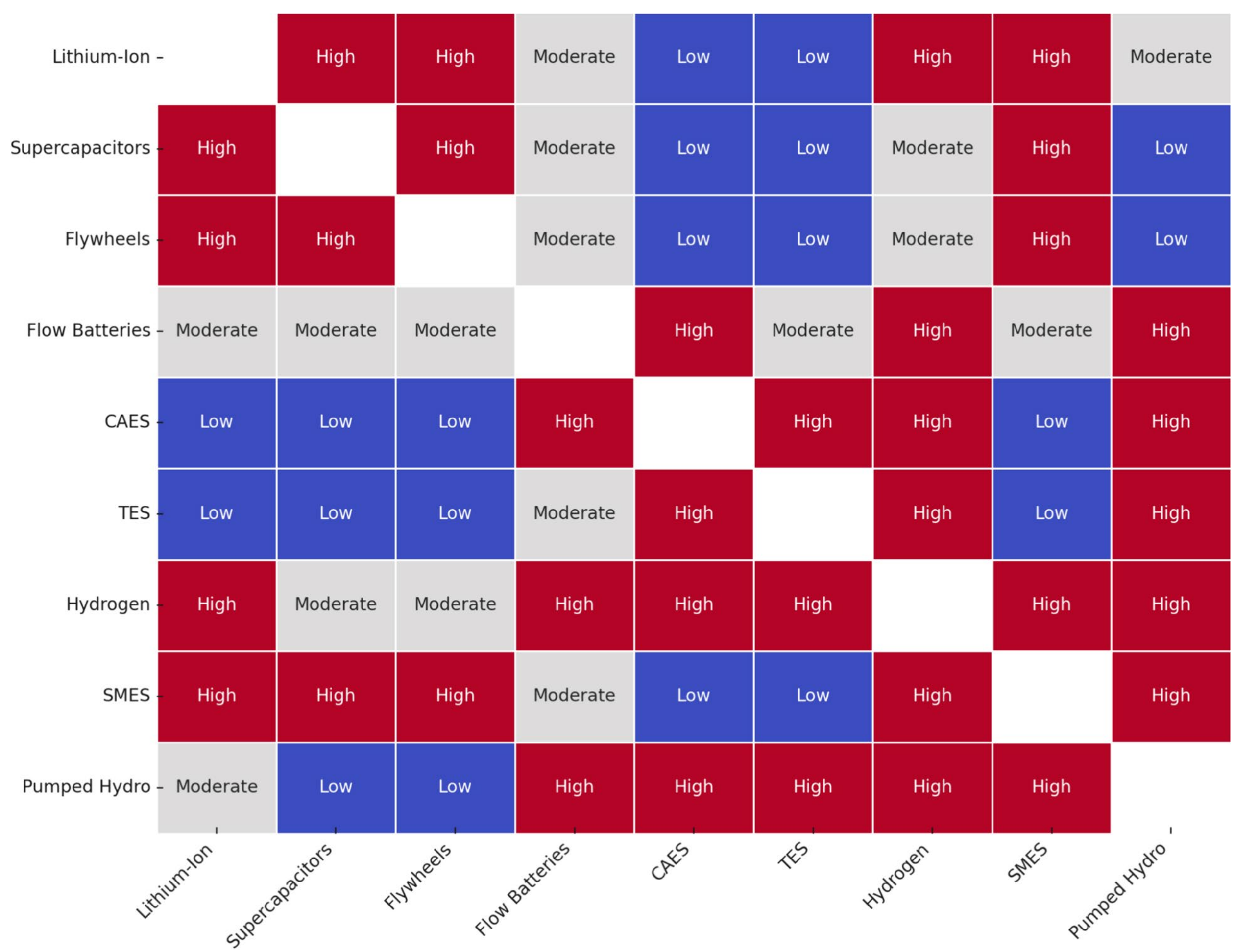

Fig. 3 Heatmap of different forms of HESS combinations

(iHOGA), and Integrated Simulation Environment Language (INSEL) provide comprehensive energy management, efficiency analysis, and scenario simulations to handle the complexities of renewable energy integration and storage management (Adeyinka & Kareem, 2018; Canada, 2021; Hoarcă et al., 2023; Sinha & Chandel, 2014). Artificial Intelligence capacity sizing approaches utilizing advanced techniques such as genetic algorithms, neural networks, and fuzzy logic have been increasingly adopted to optimize HESS (Bajpai & Dash, 2012; Zahraee et al., 2016). These AI methods are adept at handling complex, nonlinear relationships in energy systems and can adapt to dynamic conditions, ensuring precise and flexible optimization of storage capacity (Tang et al., 2021). Proper capacity sizing ensures that the HESS can handle peak loads and maintain supply during periods of low energy generation.

System reliability and safety

Designing HESS for reliability and safety involves integrating redundancy to enhance system resilience against failures or unexpected demand spikes and implementing robust safety protocols to manage risks associated with high-energy systems (Reveles-Miranda et al., 2024). This includes measures to prevent thermal runaway in batteries, such as integrating advanced thermal management systems, fail-safe mechanisms, and robust containment strategies to prevent overheating and mitigate failures (A. M. Adeyinka & Olaleke, 2020). Continuous monitoring systems are critical for maintaining the reliability and safety of HESS by using sensors and real-time data analytics to detect and diagnose potential issues, enabling predictive maintenance that extends the life of ESDs and avoids unexpected failures.

Environmental impact

Considering the environmental impact throughout the system's lifecycle is crucial when designing HESS (Hassan et al., 2023a, 2023b). This involves evaluating the materials used in batteries and other components, focusing on their manufacturability, recyclability, and disposal (Ijaola et al., 2022). Selecting environmentally friendly materials and technologies is essential to minimize the ecological footprint of HESS. Lifecycle assessments should be conducted to assess the environmental impact from production to disposal, ensuring that the design choices contribute to sustainability. These assessments consider factors such as the extraction of raw materials, manufacturing processes, operational efficiency, and end-of-life disposal or recycling. Additionally, integrating recycling strategies that recover valuable materials from used components can reduce the demand for new raw materials and mitigate environmental degradation.

Cost factors

When designing HESS, it is crucial to consider the cost factors, which include upfront capital costs, operational and maintenance costs, and potential replacement costs, which vary significantly based on the technology used (Abo-Khalil et al., 2023). Scalability and potential for future upgrades to adapt to evolving energy demands and integrate new technological advancements, ensuring long-term cost-effectiveness, should be considered (Lei et al., 2023a, 2023b). Furthermore, assessing the economic viability includes considering financial incentives and revenue generation opportunities through mechanisms like energy arbitrage and demand response programs, which can significantly offset the initial and operating costs (Gudlaugsson et al., 2023).

Types of hybrid systems

Hybrid systems integrate the strengths of various storage devices to address specific energy storage needs and enhance the overall functionality of energy systems. The heatmap in Fig. 3 illustrates the applications and effectiveness of various combinations of energy storage devices (ESDs) in HESS. The colors indicate the relevance and performance of each combination, with "High", "Moderate", and "Low" representing the effectiveness of each pairing.

The heatmap shows that certain combinations, such as lithium-ion with supercapacitors or CAES with flow batteries, exhibit high performance in terms of efficiency and reliability, as indicated by the red areas. These high-performing combinations leverage the unique strengths of each technology to deliver superior results in specific applications, such as grid stabilization, renewable energy integration, and quick response scenarios. However, it is important to consider other factors beyond performance when designing and selecting HESS configurations. The availability of RES, cost, maintenance requirements, and environmental impact are critical factors that influence the overall feasibility and sustainability of HESS. Hence, a comprehensive economic, environmental, and resource availability analysis should be conducted to make informed decisions about deploying HESS.

Recent technological advancements have significantly enhanced the performance, safety, and scalability of various energy storage solutions. These innovations are critical for integrating RES into the grid, mitigating intermittency issues, and ensuring a stable, reliable power supply.

Pumped hydro storage

Pumped hydro storage remains one of the most mature and widely used energy storage technologies. Recent advancements focus on increasing efficiency and reducing environmental impact. Innovations include variable-speed pump-turbine units, which offer greater flexibility and efficiency in energy conversion (Zhao et al., 2022). Additionally, closed-loop systems that do not rely on natural water bodies have been introduced, reducing environmental impacts and expanding the potential for PHS deployment in various geographic locations (Nikolaos et al., 2023). Research into underground pumped hydro storage, using abandoned mines and other subterranean spaces (Lyu et al., 2022) is also underway, offering new possibilities for PHS implementation in regions lacking suitable surface topography. These innovations continue to make PHS a critical component in supporting renewable energy integration and ensuring grid stability.

Compressed air energy storage (CAES)

Recent developments in CAES focus on increasing efficiency and reducing environmental impact. Innovations include adiabatic CAES, which captures and stores the heat generated during compression, improving overall system efficiency (Sarmast et al., 2024). Advanced thermodynamic modeling has also been explored to optimize the design and operation of CAES systems (Zhang et al., 2024). Additionally, developments in cavern storage and the use of abandoned mines for CAES have expanded the potential sites for implementation, addressing geographical limitations and reducing environmental impacts.

Flywheel energy storage systems (FESS)

Flywheels have benefitted from advancements in high-strength materials and magnetic bearing technology (Li & Palazzolo, 2022). Developing composite materials for the flywheel rotor has improved energy storage capacity and efficiency by allowing higher rotational speeds. Additionally, magnetic bearings reduce friction and wear, enhancing overall durability and reducing maintenance requirements (Hiroshima et al., 2015). These improvements make flywheels viable for stabilizing grid frequency and providing short-term energy storage.

Battery energy storage system (BESS)

One of the most promising progresses in this area is the development of solid-state batteries. These batteries use solid electrolytes instead of the liquid ones found in conventional lithium-ion batteries, enhancing safety by reducing the likelihood of leakage and thermal runaway (Janek & Zeier, 2023). They offer higher energy densities, so they can store more energy in a smaller space, making them ideal for stationary and mobile applications. Their improved safety profiles and energy densities make solid-state batteries a key component in the next generation of HESS.

Flow batteries are also gaining significant attention for their potential in grid-scale applications. These batteries store energy in liquid electrolytes in external tanks, allowing for scalable energy storage capacities (Zhang et al., 2022). The modular nature of flow batteries enables easy scaling by increasing the electrolyte tanks, making them highly adaptable for large-scale energy storage needs. Moreover, flow batteries can maintain their capacity and efficiency over many charge–discharge cycles, which is crucial for long-term, reliable operation in renewable energy systems. Their ability to provide long-duration energy storage is essential for balancing intermittent RES, ensuring a stable and reliable power supply.

Superconducting magnetic energy storage (SMES)

SMES systems have improved with advancements in high-temperature superconductors (HTS) and cryogenic technologies. The development of HTS materials that operate at higher temperatures reduces the cooling requirements and operational costs of SMES systems (Rong & Barnes, 2017). Additionally, improvements in cryogenic cooling systems and magnetic field containment have enhanced the efficiency and safety of SMES (Mitali et al., 2022). These advancements have made SMES a promising option for applications requiring rapid response times and high power density, such as grid stabilization, frequency regulation, and uninterruptible power supplies.

Supercapacitors

Supercapacitors have seen significant advancements in electrode materials and fabrication methods. Incorporating graphene and carbon nanotubes has significantly increased their energy density and lifespan (Pandya et al., 2023). Researchers are also exploring hybrid supercapacitors that combine the high power density of capacitors with the high energy density of batteries, providing an efficient solution for applications requiring quick energy bursts and frequent cycling (Chatterjee & Nandi, 2021).

Hydrogen storage systems

Recent advancements in hydrogen storage systems have significantly improved their efficiency and capacity. Enhanced electrolysis technologies, such as proton exchange membrane (PEM) and solid oxide electrolyzers, have boosted hydrogen production efficiency (Sebastian et al., 2023). Innovations in storage materials, including metal hydrides and porous materials, have increased storage capacity and safety by enabling higher-density storage at lower pressures (Firuznia et al., 2023). Additionally, the development of high-strength composite materials for storage tanks has allowed safer and more efficient high-pressure hydrogen storage.

Thermal energy storage (TES)

Recent advancements in TES have significantly improved efficiency and application potential. Key developments include the use of advanced phase change materials (PCMs) with higher thermal conductivity and stability, enabling more efficient heat storage and retrieval (Wong et al., 2023). Innovations in molten salt storage for concentrated solar power (CSP) plants have enhanced thermal capacity and operational reliability (Ali et al., 2024). Compact thermal energy storage systems have been developed for residential and industrial applications, optimizing space and energy use. Additionally, advancements in thermochemical storage methods, which store energy through reversible chemical reactions, have shown promise for long-term energy storage with high energy density (De Rosa et al., 2021).

HESS topology

HESS topology can be categorized into several structural configurations, each with unique characteristics and operational principles. These configurations are:

Passive structure

In a passive structure, the ESDs are connected directly to the load without active control. Since the terminal voltage of the ESDs is not controlled, the power distribution between different ESDs is governed by their inherent electrical characteristics (Babu et al., 2020). Passive structures are simple and cost-effective, but they may not fully optimize the performance of each storage technology, as there is no active management of power flow or state-of-charge (SOC) balancing.

Semi-active structure

Semi-active structures incorporate a PCS connected to one of the ESDs while the other is connected directly to the direct current (DC) bus (Song et al., 2015). Semi-active structures improve the overall system performance by providing some level of control over the power distribution without the complexity and cost of fully active systems.

Series active topology

In a series active structure, the energy storage devices are connected in series with active control elements, such as converters or inverters, which manage the power flow and ensure optimal operation of each ESD. This structure allows accurate control over the energy distribution and SOC balancing, improving efficiency, and performance.

Parallel active topology

Parallel active structures use active control elements to manage the power flow between parallel-connected storage devices. Each ESD is connected to the DC bus through a converter or inverter, allowing independent control of each component (Ju et al., 2016). This configuration provides high flexibility and efficiency, as each ESD can be operated at its optimal point.

Cascaded active topology

Cascaded active structures connect multiple ESDs in a cascade configuration, with each device managed by its active control element. This setup allows for hierarchical control and energy flow optimization, improving overall system performance and reliability.

Multi-level active topology

Multi-level active structures combine several storage devices in a multi-level configuration, with each level managed by active control elements, as shown in Fig. 4f. This structure provides high efficiency and flexibility, enhancing the overall system reliability and performance of each ESD (Bharadwaj & Maiti, 2017). Each level in the configuration can operate independently or in coordination with others, allowing for accurate control over energy distribution and state of charge (SOC) balancing across the entire system.

Table 3 presents a detailed comparison of various HESS topologies, highlighting their control mechanisms, complexity, cost, performance, reliability, and applications.

Ancillary services offered by grid-connected HESS

HESS offers numerous benefits that significantly enhance energy storage and distribution performance, reliability, and efficiency. By combining multiple ESDs, HESS can address various challenges associated with renewable energy integration, grid stability, enhanced reliability and improving energy efficiency. Some of the ancillary services offered by implementing HESS in modern energy systems are summarized as follows:

- Energy arbitrage: By buying electricity during off-peak times and selling it during high-peak times, HESS can effectively manage and reduce energy costs (Gbadegesin et al., 2020).
- Load leveling: Balances out the load on the power grid by storing excess energy during low demand and releasing it during high demand periods (Danish et al., 2020; Londák et al., 2023).
- Transient stability: HESS enhances transient stability by rapidly responding to sudden changes in load

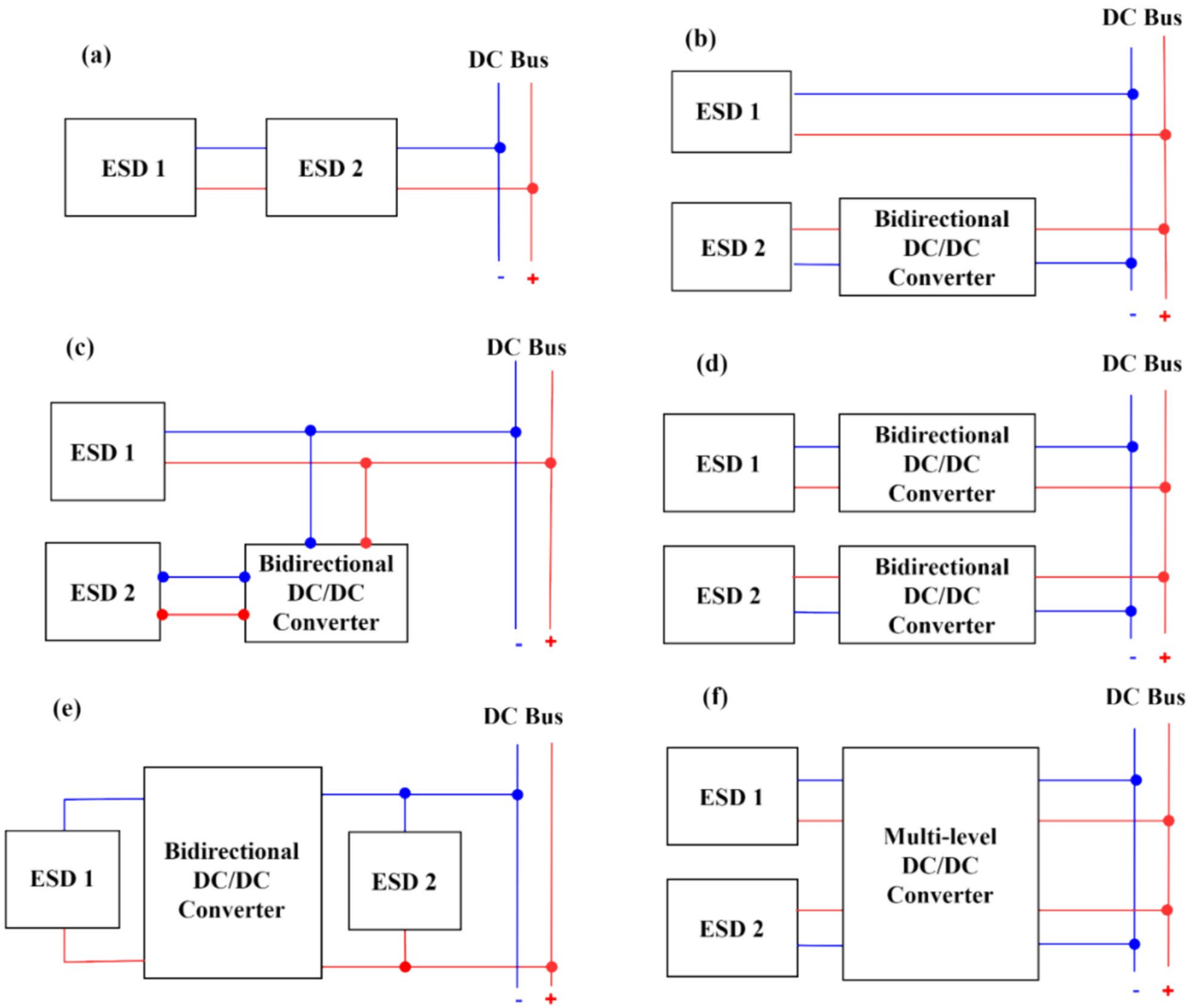

Fig. 4 HESS topologies

Table 3 Comparison of HESS topologies (Abo-Khalil et al., 2023; Hajiaghasi et al., 2019; Lin & Zamora, 2022)

Feature	Passive structure	Semi-active structure	Series active structure	Parallel full active structure	Cascaded active structure	Multi-level active structure
Control mechanism	No active control	Simple control	Active converters/inverters	Independent converters/inverters	Hierarchical active control	Multi-level active control
Complexity	Low	Moderate	High	High	High	Very high
cost	Low	Moderate	High	High	High	Very high
Performance optimization	Limited	Improved	High	High	Very high	Very high
Reliability	Moderate	Moderate to high	High	Very high	Very high	Very high
Scalability	Limited	Moderate	High	High	Very high	Very high
Applications	Simple, low-cost solutions	Enhanced performance over passive	Precise control in complex systems	High flexibility and efficiency	Hierarchical systems requiring optimization	Complex systems with high flexibility
Example use cases	Small-scale residential	Small- to medium-scale commercial	Industrial applications	Large-scale grid storage	Advanced grid and industrial applications	Smart grids, advanced renewable integration

or generation, thereby maintaining system stability and preventing outages (Khan & Khalid, 2021).

- Frequency regulation: HESS facilitates rapid response to changes in grid frequency, either by absorbing excess power or by injecting power into the grid, making them highly effective in maintaining the grid's frequency within the desired range (Swapna & Gayatri, 2021).
- Voltage support: HESS manages the reactive power to maintain the voltage levels within specified limits across the power system, thereby ensuring the quality and reliability of power supply (Abo-Khalil et al., 2023).

Technological advancements in HESS control strategies for enhancing renewable energy integration

Technological advancements in HESS involve optimizing energy management systems, enhancing the efficiency of energy storage devices, and developing advanced control strategies. The primary aim of control strategies in HESS is to enhance system performance, reliability, and efficiency by preventing battery deep discharge, reducing peak power demand, managing charge/discharge cycles, minimizing operational and maintenance costs, maintaining stable DC voltage, and ensuring effective frequency regulation. Figure 5 summarizes the control techniques used in HESS.

Classical control

Droop control

Droop control is a widely used decentralized control strategy for power-sharing and voltage or frequency regulation in HESS and microgrids. It functions by adjusting the output power of individual ESDs based on their respective droop characteristics, which are predefined relationships between the output power and either voltage or frequency (Lu et al., 2014). The purpose of the droop function is to stabilize voltage or frequency within the HESS during load variations or power supply interruptions (Abo-Khalil et al., 2023). Droop control is advantageous due to its simplicity, robustness, and scalability. It allows for plug-and-play operation, where additional storage units can be integrated into the system with minimal configuration, enhancing the flexibility and modularity of the energy storage network (Cingoz et al., 2015; Tayab et al., 2017). However, droop control also has some limitations. It may not accurately share power among units with different characteristics, such as varying capacities or states of charge, and its fixed settings can lead to suboptimal performance under varying conditions. To address this, intelligent droop control strategies, such as adaptive droop control or virtual impedance techniques (Jin et al., 2022), have been developed to enhance the performance and accuracy of power sharing.

Dead beat control (DBC)

Dead beat control (DBC) is used in HESS to rapidly and precisely control power distribution and voltage regulation. Researchers have employed DBC in HESS to

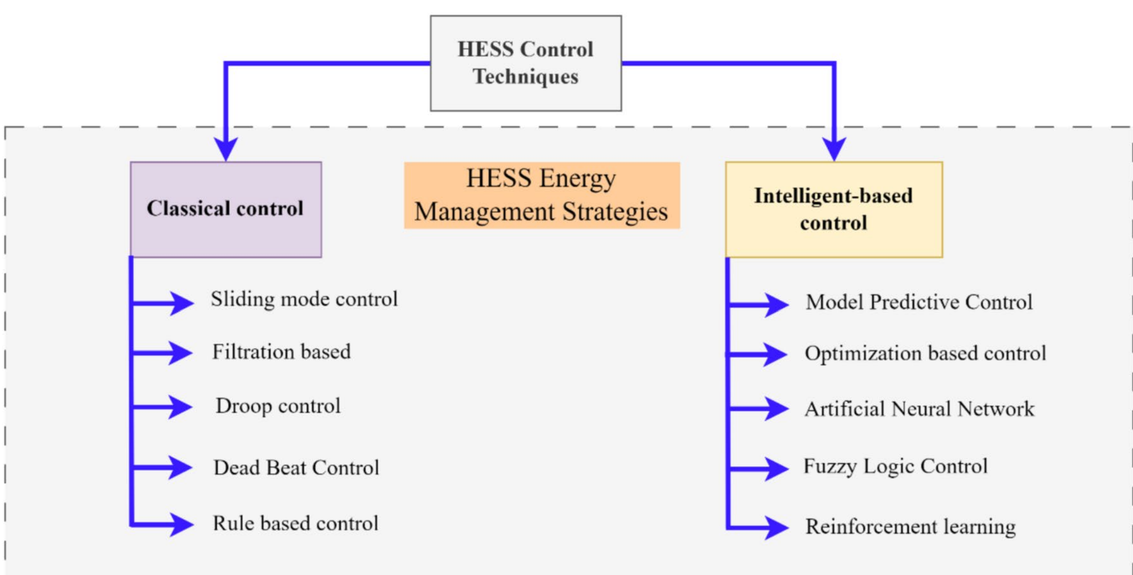

Fig. 5 HESS control techniques

manage the dynamic interactions between different storage components, ensuring fast response to fluctuating load demand and renewable energy inputs (Wang et al., 2019). The advantages of DBC include its fast transient response, high accuracy, and ability to eliminate steady-state error. Wang et al. (Wang et al., 2019) developed a deadbeat control strategy for battery–supercapacitor HESS combination in a DC microgrid. Their result showed that the DBC responds faster to sudden power demand than PI controllers. It reduces battery stress and strictly maintains bus voltage with high precision while minimizing hardware costs by requiring fewer current sensors. However, DBC is limited by its sensitivity to model inaccuracies and noise, requiring precise system modeling and noise filtering to maintain performance (De Carolis et al., 2017). Despite these challenges, DBC remains a powerful tool for optimizing the performance and reliability of HESS, particularly in applications requiring fast and accurate control.

Filtration-based control (FBC)

FBCs are commonly used in HESS due to their simplicity and minimal computational requirement (Chong et al., 2016). (Gee et al., 2013) presented a low-pass filter (LPF) method to extend battery life in a small-scale wind-power system using a battery/supercapacitor HESS. Song et al. (Song et al., 2013) proposed an energy management system for HESS based on wavelet transform FBC and neural networks. The hybrid power system comprises solar and wind power subsystems with lithium-ion battery banks and supercapacitors. Their controller maintained the DC voltage and kept the SOC of batteries within the safe range, thus protecting against overcharge and deep discharge. FBC strategies are suitable for a single HESS but require additional power distribution controllers for effective and adaptable multi-HESS operations. This is because FBC cannot distribute proportional power between multiple HESS systems and potential communication delays. Advances in this field focus on developing adaptive and real-time filtering techniques to enhance the robustness and efficiency of FBC.

Sliding mode control (SMC)

Sliding mode control (SMC) is an adaptive control technique for handling nonlinear systems, external disturbances, and system uncertainties (Liu et al., 2020). It operates by driving system states toward a predefined sliding surface and maintaining them there for all subsequent times using high-frequency switching control (Shtessel et al., 2023). SMC has been applied in HESS to manage interactions between different storage components and the power grid, including state of charge regulation, power distribution control, and overall stability and performance (Abo-Khalil et al., 2023). Morstyn et al. (Morstyn et al., 2018) developed a novel use of multi-agent SMC for SOC balancing of battery ESD distributed in a DC microgrid. Their model was able to eliminate circulating current and reach faster SOC balancing, thereby avoiding overloading the battery ESD during periods of high load. Armghan et al. (Armghan et al., 2020) designed SMC for a hybrid AC/DC microgrid to maintain the bus voltages by controlling the frequency during islanding and grid-connected mode. Despite the strength of SMC, challenges like chattering and the need for accurate system modeling remain (Oliveira et al., 2022), prompting future research directions such as developing advanced algorithms to minimize chattering, integrating SMC with AI techniques for adaptive tuning, and expanding its application in distributed energy management (DER) systems.

Rule-based control (RBC)

Rule-based control is a straightforward and intuitive control strategy that operates based on predefined rules and logical conditions to manage the operation of systems. In HESS, rule-based control employs a set of if–then-else rules to determine the actions of different ESDs (Nejabatkhah et al., 2012) based on real-time data like SOC, power demand, and grid conditions. For example, a rule might dictate that if the SOC of a battery falls below a certain threshold, the system should switch to discharging a supercapacitor to maintain power supply. Researchers have utilized rule-based control in HESS for its simplicity, ease of implementation, and ability to integrate expert knowledge into the control process. (Aktaş & Kırçiçek, 2020) presented a novel RBC for battery–supercapacitor HESS in nine modes of operations for off-grid applications. (Thomas & Mishra, 2019) proposed a power management strategy (PMS) for a standalone DC microgrid with PV and wind sources combined with a battery–supercapacitor HESS to regulate the DC bus voltage under varying irradiations and wind power conditions.

The primary advantage of RBC is its simplicity, making it easy to design, understand, and modify. It allows for quick decision-making without complex computations, making it suitable for real-time applications (Liu et al., 2010). Additionally, it is flexible and can be designed for specific system requirements and operational scenarios. However, rule-based control has limitations, including its lack of adaptability and inability to handle unforeseen situations or dynamic changes in the system environment. It relies heavily on the accuracy of the predefined rules, which may not cover all possible scenarios, potentially leading to suboptimal performance or system instability.

Intelligent-based control

Model predictive control (MPC)

Model predictive control (MPC) is an advanced control strategy that uses a dynamic model of the system to forecast future system behavior and optimize control actions within a set time horizon. MPC is employed in HESS to manage the charging and discharging cycles of various storage units, optimize power flow, and enhance overall system efficiency (R. & Kowsalya, 2024). By solving an optimization problem at each control step, MPC can account for system constraints, forecasted energy demand, and renewable energy generation, ensuring optimal performance under varying conditions (Schwenzer et al., 2021). Researchers have successfully applied MPC in HESS for tasks such as state of charge (SOC) balancing (Liu et al., 2023), peak load shaving (Zhang et al., 2018), and energy cost minimization, demonstrating significant improvements in system reliability and operational efficiency. The advantages of MPC include its ability to handle multivariable systems, incorporate constraints directly into the control process, and provide predictive capabilities for proactive decision-making (Darby & Nikolaou, 2012). However, MPC is computationally complex and demanding for real-time applications.

Optimization-based control (OBC)

Optimization-based control (OBC) is an advanced control strategy that formulates the control problem as an optimization problem, aiming to find the best control actions that maximize or minimize a defined objective function under given constraints. OBC uses mathematical algorithms and optimization techniques like dynamic programming, linear programming, nonlinear programming, and metaheuristic approaches to determine the optimal control actions (Babu et al., 2020). In HESS, OBC is employed to optimize power distribution, minimize energy costs, maximize efficiency, balance the state of charge, and enhance the lifespan of ESDs (Shao et al., 2023). For example, an optimization objective might be to minimize the total operating cost by determining the best times to charge and discharge batteries based on electricity price signals. Tetuko et al. (Tetuko et al., 2022) proposed optimal scheduling using nonlinear programming for battery-flywheel HESS for off-grid power generation with renewable energy sources comprising PV and wind turbines. Their approach was to perform power-sharing for each ESD based on minimizing the total project cost, operation and maintenance cost, and life cycle of each ESD. OBC offers a systematic approach to achieving optimal performance of complex, multivariable systems and can adjust to changing conditions and constraints. However, OBC is limited by its high computational complexity, making real-time implementation challenging. It requires accurate models of the system and the environment, and its performance can be sensitive to the quality of these models and the accuracy of the input data.

Fuzzy logic control (FLC)

Fuzzy logic control (FLC) is a powerful and flexible control strategy that uses fuzzy logic to handle the uncertainties and nonlinearities in complex systems (Arcos-Aviles et al., 2019). FLC is used in HESS to manage the charging and discharging processes, balance the SOC across different storage units, and maintain overall system stability (García et al., 2014). An FLC algorithm was implemented to operate the battery and supercapacitor-based HESS optimally (Gamage et al., 2018). Their fuzzy inference system determines the HESS's optimal charging and discharging rate based on the SOC constraints of the battery and supercapacitor. Zahedi and Ardehali (Zahedi & Ardehali, 2020) developed multiple optimally designed FLCs to manage the power of ESD by minimizing the operational cost of a battery/supercapacitor/fuel cell/wind turbines/photovoltaic collectors HESS system. Vivas et al. (Vivas et al., 2022) proposed a multivariable and multistage fuzzy logic energy management system for grid-connected residential DC microgrids with HESS aimed at optimizing power management and extending the lifespan and performance of the system components. FLC is particularly suitable for a single HESS. However, additional power distribution controllers are required to enhance the effectiveness and adaptability of multiple HESS. Despite its benefits, FLC has limitations, such as the complexity of designing and tuning the fuzzy rules and membership functions, which can become cumbersome for large-scale systems. It may also require extensive simulation and testing to ensure optimal performance across different operating scenarios (Sadollah, 2018).

Artificial neural network (ANN)

ANNs are valuable in HESS because they can learn complex and nonlinear relationships from data, making them effective for SOC estimation, fault detection, and predictive maintenance tasks. An efficient power sharing and management system was developed for battery/supercapacitor PV systems using ANN to balance demand, maintain SOC, and manage DC bus voltage (Singh & Lather, 2020). An ANN energy management controller was developed for a HESS with a multi-source inverter (MSI) to manage the current distribution between a lithium-ion battery and an ultracapacitor by actively controlling the MSI's operating modes (Ramoul et al., 2018). (Faria et al., 2019) developed a novel ANN-based HESS power management scheme to reduce lithium-ion battery stress under dynamic power exchange conditions. Their proposed power management strategy was able to manage the power flow of the ESDs and charge or discharge power based on their SOC. Despite the advantages of ANN-based control, these systems have limitations, such as requiring substantial computational resources for training, the risk of overfitting, and the need for large amounts of labeled training data.

Reinforcement learning (RL)

Reinforcement learning (RL) is an advanced AI-based technique that enables systems to learn optimal control policies through trial and error by interacting with their environment (Bușoniu et al., 2018; Sutton & Barto, 2018). RL operates by using an agent that makes decisions based on a reward signal, which evaluates the performance of its actions in achieving specific goals (Khan et al., 2012), such as minimizing energy costs, balancing SOC, or maximizing the lifespan of storage units. Researchers have employed RL in HESS to tackle challenges such as managing fluctuating renewable energy inputs, responding to varying load demands, and enhancing overall system efficiency (Perera & Kamalaruban, 2021). (Xiong et al., 2018) proposed a real-time energy management using RL for HESS in plug-in hybrid electric vehicles (PHEV). By learning current driving power information, their algorithm updates the strategy to reduce the energy loss of the HESS.

RL algorithms, like Q-learning and Deep Q-Networks (DQN), are effective in these applications as they can handle high-dimensional state and action spaces and adapt to changing system dynamics in real-time (Kofinas et al., 2018). The main advantages of RL in HESS include its ability to learn and improve control policies over time, adapt to new and unforeseen scenarios, and optimize performance without requiring explicit models of the system (Khan et al., 2012). However, RL is limited by its need for extensive training data, computational resources, and susceptibility to the choice of hyperparameter values (Henderson et al., 2018).

Case studies of successful implementation of HESS

Numerous HESS projects have been successfully deployed, demonstrating their viability and effectiveness in transitioning towards a more sustainable and resilient energy infrastructure. Table 4 presents an overview of successful HESS implementations in different parts of the world, illustrating the various applications and configurations employed. By leveraging advanced storage technologies and smart grid integration, these projects have successfully reduced greenhouse gas emissions, enhanced grid stability, improved energy efficiency, and ensured a reliable power supply.

Challenges and future directions

Figure 6 presents an overview of the current challenges, progress, and future direction of HESS. Advancements in HESS have been rising in recent years, driven mainly by the development of renewable energy sources, advanced energy storage devices, advanced control strategies, and microgrid infrastructure. However, to advance the development of HESS, the following challenges must be addressed:

- Effective strategies for integrating HESS with existing grid infrastructure: Integrating HESS with existing grid infrastructure is challenging. It requires the development of standardized protocols for communication and control. The bidirectional flow of energy and information between the grid and storage systems needs to be managed in real-time to ensure synchronization and efficient energy dispatch.
- Improving energy density and efficiency of storage technologies: The energy density and efficiency of storage technologies need significant improvement. Current materials and technologies often fall short of the desired performance, and advancements in these areas are crucial for developing more effective HESS.
- Compatibility between different ESDs: Compatibility between different ESDs within a hybrid system is complex due to the varying operational principles, management systems, and performance characteristics of each ESD. These differences can lead to inefficiencies and operational difficulties, making seamless integration and efficient management challenging.
- High initial cost of HESS: The high initial cost of HESS is a significant barrier to widespread adoption. Advanced storage technologies, such as Hydrogen Storage systems, require substantial investment in infrastructure and technology, making them less viable for widespread use without significant financial support.
- Sizing of HESS: Accurately sizing HESS based on application requirements, cost, and performance constraints is critical. Improper sizing can lead to inefficiencies, either by over-sizing, which increases costs, or under-sizing, which fails to meet energy demands.
- Safety and reliable operation: Ensuring the safe and reliable operation of HESS, particularly when integrating different chemistries and technologies, is a critical challenge. Different components may have varying maintenance schedules and reliability concerns, such as mechanical wear in flywheels and battery degradation, requiring robust monitoring and predictive maintenance.

Table 4 Notable HESS installations across the world

HESS plant	Country	Start of operation	RES	ESD	Description	Refs.
Flinders island hybrid energy hub	Australia	2017	Wind and solar PV	Batteries, flywheels and dynamic resistors	The project installed a 200 kW DC solar farm, 900 kW wind turbine, 1.5 MW dynamic resistor, 850 kVA flywheel, and 750 kW/266 kWh battery	(ARENA, 2020)
Coober pedy hybrid renewable power station	Australia	2017	Wind and solar PV	Flywheel, resistors, and battery	This plant combines 4 MW wind generation, 1 MW solar generation, a 1 MW/500kWh battery and other integration technologies with the diesel power station as a backup	(EDL, 2024)
Braderup hybrid power plant	Germany	2014	Wind	Lithium-ion and vanadium redox flow batteries	2 MWh lithium-ion batteries and 1 MWh Vanadium redox flow batteries	(PressCenter.com, 2014)
Zhangbei national wind and solar energy storage project	China	2021	Wind and solar PV	Lithium-ion batteries, vanadium redox flow batteries	Combines 500 MW wind, 135 MW solar with 200 MW/500MWh lithium-ion and 100 MW/800MWh vanadium flow batteries	(Carmen, 2021b)
Notrees battery storage plant	USA	2018	Wind	Lithium-ion batteries, lead-acid batteries	36 MW lithium-ion and 25 MW lead-acid battery systems providing 9MWh storage capacity	(Duke Energy, 2013)
Zhong neng tongliang hybrid energy storage project	China	2021	Wind	CAES and lithium-ion batteries	Combines compressed air energy storage (10 MW/40MWh) with lithium-ion batteries (6 MW/6MWh) for wind power integration	(Liu, 2023)
Stillwater triple hybrid power plant	USA	2011	Geothermal, concentrating solar power, solar PV	Thermal energy storage (TES)	The plant consists of a 33 MW geothermal power plant, a 26 MW DC photovoltaic solar power plant, a 27 MW DC photovoltaic plant and a 2 MW solar thermal plant	(GeoEnergy, 2021)
Rokkasho village wind farm	Japan	2008	Wind	Lithium-ion and redox flow batteries	17 sets of 2 MW battery units monitored using smart grid monitoring and controls	(Carmen, 2021a)
Tehachapi wind energy storage project	USA	2014	Wind	Lithium-ion batteries, sodium-sulfur batteries	135 MW of wind power capacity integrated with a 32 MWh battery energy storage system	(Gano, 2022)
Laurel mountain wind farm	USA	2011	Wind	Lithium-ion batteries, ultracapacitors	97.6 MW of wind power capacity and 32 MW integrated battery-based energy storage system	(D'Ambrosio, 2011)

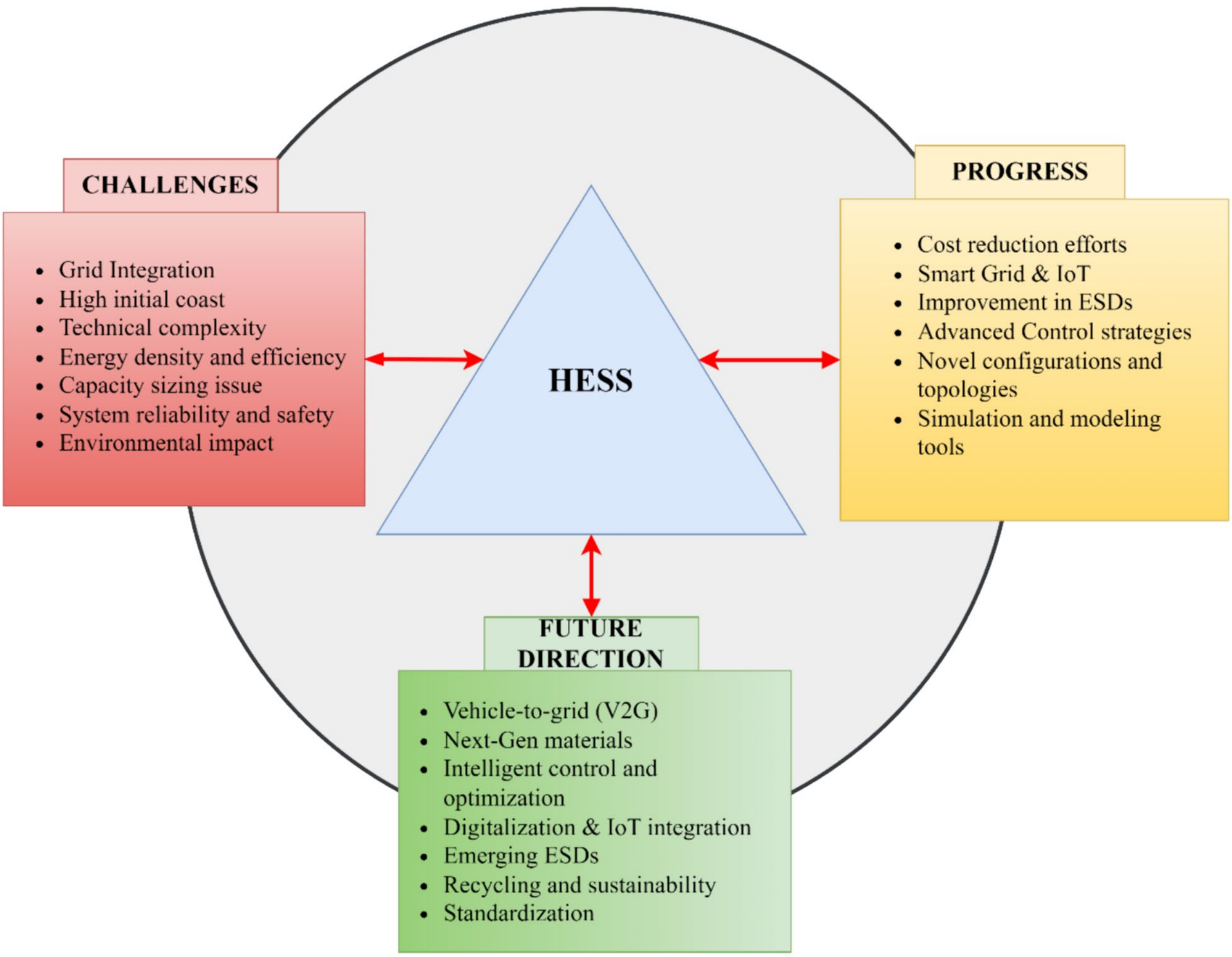

Fig. 6 Current challenges, progress, and future directions of HESS

- Developing sustainable materials and recycling processes: Developing sustainable materials and recycling processes is essential to mitigate the environmental impact of HESS. Current technologies often rely on materials that are not environmentally friendly or are difficult to recycle, posing significant challenges.
- Developing efficient control strategies and power management systems: This is crucial for the optimal operation and coordination of HESS. These strategies and algorithms are needed to balance load, predict demand, and optimize the charge–discharge cycles of the ESDs.

These challenges should be addressed to fully realize the potential of HESS in enhancing energy storage solutions. Overcoming these obstacles will require collaborative efforts in technological innovation, investment, and policy support to ensure HESS can effectively contribute to more widespread adoption and successful integration of HESS in various applications.

Several promising directions can drive the future of HESS. More efficient and safe HESS will become available by exploring new and emerging energy storage devices, such as solid-state batteries. Solid-state batteries offer benefits such as higher energy densities, improved safety, and longer lifespans compared to traditional batteries. Also, focusing on recycling and sustainable practices will help reduce the environmental impact of HESS. The advancement in vehicle-to-grid (V2G) technologies can enhance the flexibility and storage capacity of HESS. The development of intelligent control and optimization based on artificial intelligence will improve system performance, and increasing the integration of digital technologies and Internet-of-Things (IoT) will facilitate real-time monitoring and control. Establishing standardized testing and performance evaluation protocols will promote widespread adoption by ensuring consistency, reliability, and compatibility across different HESS technologies.

Concluding remarks

HESS has emerged as a promising solution to address the challenges of integrating renewable energy sources into the grid and ensuring a reliable and sustainable energy supply. By leveraging the strengths of various ESDs and employing advanced control strategies, HESS contributes to a more resilient and efficient energy infrastructure. This paper has critically reviewed HESS, highlighting its components, design considerations, topologies, control strategies, and practical applications. A comprehensive analysis of different energy storage technologies has been conducted, evaluating their features, design considerations, and performance characteristics. Significant progress in developing advanced control and optimization strategies for HESS integrated with RES has been discussed. Ongoing research and development efforts in advanced energy storage technologies, control strategies, and system optimization will further enhance the performance and cost-effectiveness of HESS, paving the way for widespread adoption and a more sustainable energy landscape.

Abbreviations

RES	Renewable energy source
PV	Photovoltaics
HESS	Hybrid energy storage system
ESD	Energy storage device
GHG	Greenhouse gas
BESS	Battery energy storage system
SC	Supercapacitor
FC	Fuel cell
SMES	Superconducting magnetic energy storage
UC	Ultracapacitor
CAES	Compressed air energy storage
TES	Thermal energy storage
PCS	Power Conversion system:
EMS	Energy management system
DC	Direct current
SOC	State of charge
DBC	Dead beat control
FBC	Filtration-based control
SMC	Sliding mode control
RBC	Rule-based control
MPC	Model predictive control
OPC	Optimization-based control
FLC	Fuzzy logic control
ANN	Artificial neural network
RL	Reinforcement learning

Acknowledgements
We gratefully acknowledge all the editors and reviewers for their constructive comments, which greatly improved the work.

Author contributions
All authors contributed equally in study conception and design, data collection, analysis and interpretation of results, and final draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability
No data was used for the research described in the article.

Declarations

Competing interests
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.

Received: 7 June 2024 Accepted: 27 June 2024
Published online: 20 July 2024

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